THE Next Wave

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20 years of emerging technology: What's next?

The National Security Agency's review of emerging technologies

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THE
Next Wave
The National Security Agency's review of emerging technologies

GUEST Editor's column

Deborah Frincke, PhD

It is my distinct privilege to introduce the 20th anniversary issue of *The Next Wave (TNW)*. The timing is striking for me personally because I finished my own PhD and began my first faculty job some 20 years ago. I, along with other newly minted PhDs that year, dreamed of technological changes in so many areas—faster computers, making the user experience safer and friendlier, embedding our beloved technical devices in our personal lives . . . the list goes on. Many of those dreams have been realized or exceeded, and you'll read about a few of them in this issue.

The world of 1993 believed 60 gigaflops[a] was blazingly fast and thought individual users would never have access to such speeds—or the need to use them. And we could begin to point out relatively affordable systems. After all, a Beowulf cluster in 2000 brought the cost of a gigaflop down to $1,300[b], quite remarkable given that in 1961 the estimated cost was over $8 trillion and in 1984 was around $33 million. Our world has gotten significantly faster since then; Lawrence Livermore National Laboratory's Sequoia supercomputer clocked in at 16.32 petaflops in June 2012, and Oak Ridge National Laboratory's Titan supercomputer achieved 17.59 petaflops just a few months later. Today it is possible to get a gigaflop for well under a dollar.[c]

Also important from a scientific perspective is our new, broader approach to setting expectations in this space. While the LINPACK measurement of peak floating point performance has long been used as a way to compare supercomputers, newer approaches are gaining traction. One such example is the Green500 list, which ranks machines by energy efficiency. A personal favorite is the Graph 500 approach, which pulls us into graph-based algorithms and, by extension, shows us how efficiently our modern computers will perform when used for analytics rather than solving linear equations.

The 1990s not only saw the emergence of the World Wide Web, it ushered in a decade in which we saw many pragmatic improvements in user interfaces. Text-based interfaces, like L-Gopher, gave way to Internet browsers Mosaic and Netscape. Fast forward to 2013, where we are pleased, though not entirely amazed, to learn that we can control our tiny smartphone screens through our gaze, where wall displays are reasonable choices for operational environments, and where tangible user interfaces (i.e., those allowing users to interact with their information through their physical environment) are part of our commodity gaming systems.

Nowadays we expect intuitive design and responsiveness, and we protest if the haptic screen on our pedometer-powered video games is not up to snuff. User experiences are less bound by the traditional keyboard and mouse and the one-size-fits-all constraints and are more apt to leverage increasingly subtle cues about how to tailor responses to an individual, whether through serving up interest-based advertisements or through periodically prompting a sedentary worker to get up and jog in the middle of the afternoon. Brain-controlled interfaces can also be found in games.

People are less users who interface with a specific computer than they are beneficiaries of a digital team, in which multiple devices and software are expected to work together smoothly to support the goals of the whole and even integrate with other digital teams to support social interaction. The ways to engage and the opportunities to improve are seemingly endless. Also, as we move into the next 20 years, it is worth pointing out that the challenges for those who seek to make user experiences safer and more secure are becoming harder, not easier—and it is even more important that we get this right.

There are always unexpected results when a society embraces a new concept and the commercial market races to meet the demand. As you'll see in the article "Radio noise: Global economic and political impact," our love of devices and the creative ways in which we use them has made the world of signals an extremely noisy, crowded, and messy place complicated by economic and policy conflicts. In 1993, my personal worries about radio noise involved wondering whether my new

a. CM-5, the number one supercomputer on the first TOP500 list, performed 59.7 on the LINPACK benchmark.
b. Amount is adjusted for 2012.
c. In 2012, an Advanced Micro Devices desktop with a quad-core processor sold for about 75¢ per gigaflop.

computer monitor would interfere with the neighbor's television set. (Sadly, it did, but the solution did not require nation-state summits—just moving furniture.) Modern conflicts over radio noise are much harder to resolve and have greater consequences.

The fourth idea explored in this special edition is single-photon detector technology. Here the future seems cloudiest. Will these technologies take off as spectacularly as wireless or as pervasively as the user interface? Will we see this turn into a widely used enabling technology, like high-performance computing? The authors from the Massachusetts Institute of Technology Lincoln Laboratory speculate about many possibilities. As with other technologies, the human wish to interact in new ways and in new environments is the real driver, and it seems safe to bet that if people need this technology, development could easily spike over the next 20 years.

One final thought: Whether the 40th anniversary issue of *TNW* touts a multi-zettaflop computer or introduces brain-controlled interfaces as old hat, the next 20 years are certain to be interesting ones. We'll still be weighing the needs of the many versus the one (e.g., radio noise), speculating about economic drivers that might accelerate innovation (e.g., single-photon detection), and redefining what makes one computer or interface better than another. Our technological dreams are an expression of our human selves, and we are complicated social beings who somehow seem to overcome theoretical limitations with new ways of thinking. Our technologies are the same way. Here's to the next 20 years—may they fill us with as much wonder as the last!

Deputy Director
Research Directorate, NSA

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Twenty years of technology: What's changed, what hasn't?

In 1992, the first issue of *Tech Trend Notes,* the publication that became *The Next Wave (TNW),* was published. *Tech Trend Notes* originated as a small, black-and-white internal newsletter for NSA's information security organizations. As described in the first issue, *Tech Trend Notes* was intended to "provide an executive summary of new technologies. . . . Each edition will offer several articles on new and emerging [information system] technologies" [1].

Twenty years later, *TNW* remains dedicated to disseminating technical advances and research activities in telecommunications and information technologies. During those years, *TNW* grew into a glossy, full-color magazine delivered to government, academic, and industry organizations throughout the US. In 2012, *TNW* became an online publication available to the world through NSA's website.

Like *TNW* itself, communications and information technology have evolved and expanded in ways undreamed of in 1992. Twenty years ago, most users were anchored to a desktop computer with a huge cathode ray tube monitor. Today, state of the art is the latest smartphone or tablet, allowing nearly ubiquitous computing. Even though mobile computing was growing quickly in 1992, it was still very much an emerging field, as evidenced in the point-by-point comparison of two Toshiba laptops in table 1.

In two decades, Toshiba's laptops became faster and cheaper. The screen became bigger with a finer resolution. The processor speed and memory grew by orders of magnitude while shrinking in size. Flash memory started to replace the hard drive. The electromagnetic floppy drive was replaced by an optical Blu-ray drive. From being routed through the user's mobile phone, wireless communication technology became integrated with the laptop and included audio and video links.

In the early 1990s, the world hovered on the brink of a new telecommunications era. Early *Tech Trend Notes* articles reported with great excitement on emerging technologies that seemed to make the "fantasy" possible, the "fantasy" being mobile, universal communication [2]. True to *TNW's* purpose of disseminating technical advances, the remainder of this anniversary issue contains forecasts on three of the technologies that made that fantasy real—user interfaces, photonics, and wireless communication.

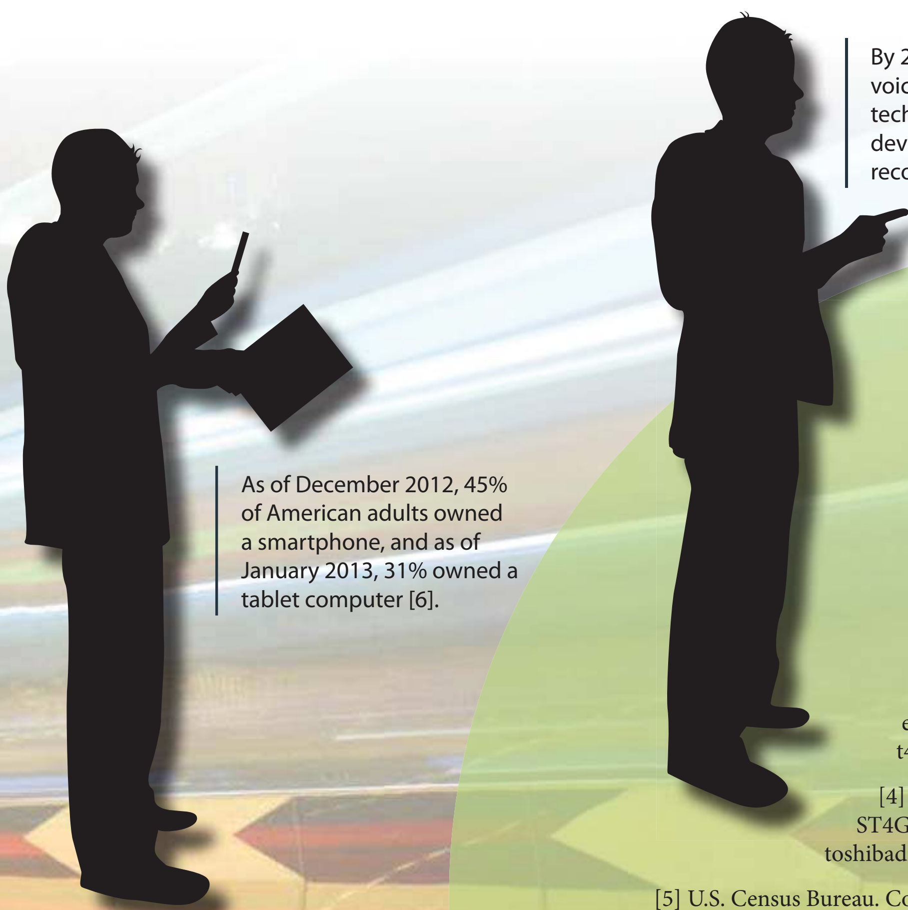
In 2008, 39% of American adults owned a laptop [6].

In 1993, 22.8% of US households had a computer [5].

TABLE 1. Comparison of Toshiba laptops from 1992 and 2013

	1992	2013
Model	T4400 SX portable computer [3]	Qosimio X875 (i.e., the company's top-of-the-line gamer laptop) [4]
Display	9.5 inch (diagonally) color liquid crystal display screen with 640 x 480 pixel resolution	17.3 inch (diagonally) color liquid crystal display screen with 1920 x 1080 pixel resolution
Processor	25 megahertz Intel 80486SX processor	3.4 gigahertz Intel Core i7-3630QM processor
Memory	120 megabyte hard drive, 1.44 megabyte floppy drive	2 terabytes of hybrid storage between the hard drive and flash memory
Additional Features	Optegra Global PC card V.34 modem plus GSM upgrade kit*	Blu-ray disc rewriteable drive, Intel 802.11 b/g/n wireless + wireless display, High-definition webcam and microphone
Measurements	11.75 x 8.33 x 2.33 inches	10.70 x 16.50 x 1.70 inches
Weight	7.75 pounds	7.50 pounds
Price (US)	$7,999	$3,000

* Upgrade kit allowed users to wirelessly transmit data through their mobile phones, which plugged into the laptop.



By 2017, expect movement, voice, and gesture recognition technology to lead to the development of interfaces that recognize emotion [pg. 7].

As of December 2012, 45% of American adults owned a smartphone, and as of January 2013, 31% owned a tablet computer [6].

References

[1] "Presenting Tech Trend Notes." *Tech Trend Notes.* 1992;1(1):1.

[2] "Soldier C3 program." *Tech Trend Notes.* 1993;2(1):11.

[3] Toshiba-europe.com. T-series T4400SX [updated 2001]. Available at: http://www.toshiba-europe.com/bv/computers/products/notebooks/t4400sx/index.shtm

[4] Toshibadirect.com. Toshiba Qosmio X870-ST4GX1 laptop [updated 2013]. Available at: http://www.toshibadirect.com/td/b2c/pdet.to?poid=2000053427

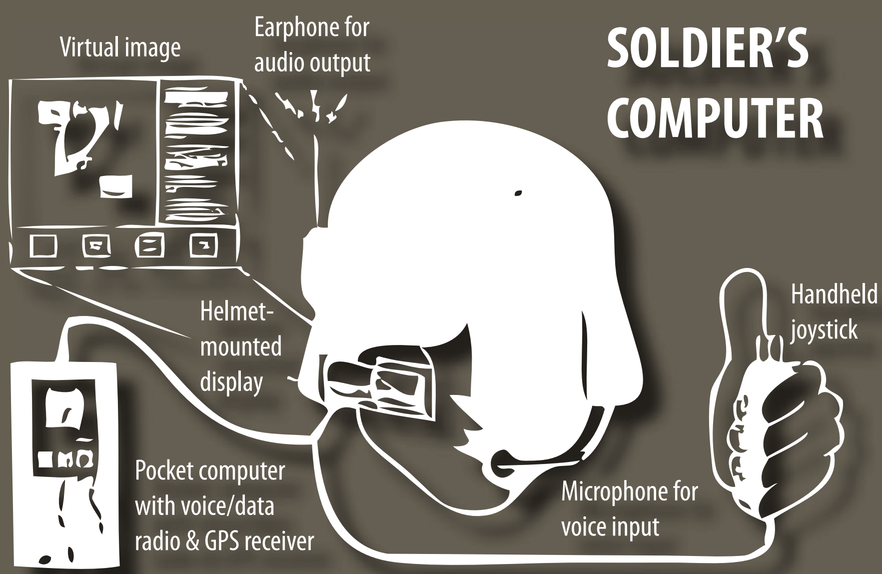
[5] U.S. Census Bureau. Computer use in the United States October 1993. Available at: http://www.census.gov/hhes/computer/files/1993/comp1.txt

[6] Pew Research Center. Device ownership: Pew Research Center's Internet & American life project [updated 2013]. Available at: http://pewinternet.org/Static-Pages/Trend-Data-(Adults)/Device-Ownership.aspx

User interfaces

Early *Tech Trend Notes* articles on user interfaces projected dramatic increases in communications effectiveness and efficiency for US forces. Some of those predictions were that soldiers would be able to communicate while on the move with any other soldier, terminal, or telephone [1]; computer-generated maps would change scale and overlay different types of information in response to voice commands; live video would be transmitted to remote commanders [2]; and warfighters would be able to get just the information that they wanted from a single display terminal [3].

Today, smartphones provide mobile communications, maps, and video to anyone who can afford the purchase price and can connect to the Internet. But what of the future? As pointed out by the authors of the proceeding article, new ways of interacting with electronic devices will be driven by the needs of mobile Internet users, who now exceed the number of desktop users [4]. The first change, they predict, will be the replacement of the keyboard with a more flexible and efficient input process.



In 1993, *Tech Trend Notes* (vol. 2, issue 1) featured this figure of a combined computer and radio enabling soldiers to communicate with one another over long distances; the technology was predicted to be available by 1999.

The next user interface

Sandia National Laboratories

Not long ago the state-of-the-art telephone was a heavy contraption with a sluggish rotary dial. The top-of-the-line television was a bulky console without a remote control. The world's best cameras were tricky gadgets filled with photosensitive film. All of that has changed. Technology transformed these common products, and it is about to transform another. In the next decade, the keyboard and mouse will be replaced by active "haptic interfaces" that respond to body and eye movements. Multimodal inputs will replace key inputs and mouse movements.

The transformation will occur gradually. First the keyboard and mouse will merge. Then the merged interface will transform into a peripheral device that responds to voice, gestures, and eye movements. The process will be enabled by improvements in materials and batteries and by the growth of wireless—ever smaller mobile devices powered by a new generation of batteries. No longer will people be tied to the stationary workstation. The days of ubiquitous computing have arrived.

The next ten years

To predict the shape of the next-generation user interface, we at Sandia National Laboratories developed a methodology for assessing trends in three areas essential to ubiquitous computing—keyboard technologies, virtual computer controls, and thin batteries. Our findings indicate that the future is mobile and the days of traditional interfaces, such as keyboards, are limited.

In the coming decade, humans will interact with their desktop and mobile devices in entirely new ways. The new ways of interaction will inspire technological changes that lead to further innovations. Much of the change will be driven by the needs of mobile Internet users, who now exceed the number of desktop users [4].

The hardware component most certain to change is the keyboard—a design that was introduced over 130 years ago as part of the mechanical typewriter. Although the keyboard's extraordinarily long life testifies to its usefulness, it is inherently inflexible and inefficient. It is neither portable nor adaptable to the mobile computing devices that will dominate the future.

Desktop users will not disappear, and they will need a more flexible interface—a simpler way to input information. That interface will be a multimodal peripheral device. At first, it will be equipped with feedback mechanisms (e.g., the sounds of keystrokes) to instill the same level of user confidence that the keyboard currently provides. After a while, the interface between human and machine will begin to blur. As it does, more novel control interfaces will appear. Clothing, furniture, print advertisements, packaging, even drug encapsulations might contain computing power and responsive interfaces. Future interfaces will be diverse and diffuse.

Keyboard technologies

Today's keyboard will not disappear overnight. But with the emergence of multitouch mobile devices, electronic paper, and flexible display technologies, the keyboard will transform. Yesterday's typewriter interface will become more virtual.

The needs of wireless users will stimulate disruptive changes in human-computer interactions for the next decade. As the number of mobile Internet users surpasses that of desktop users, new ways to input information will be needed. The dominant force driving change will be the demand for a virtual keyboard for use with mobile devices. The desktop will remain, but a steady transition will occur in the keyboard and mouse interface.

In the near term (i.e., one to three years), pointing tasks will be incorporated into the keyboard interface as the mouse is replaced by multitouch trackpads. Productivity will increase because finger motions will enable faster and more versatile pointing. In the mid-term (i.e., three to five years), the entire keyboard surface will become touch-active, with no boundary between keyboard and trackpad (see figure 1). Ultimately, a virtual-like keyboard will be printed or projected on an active surface. In the far-term (i.e., five years and beyond), the keyboard will be completely realized on a flexible surface that will allow for any key layout a user wants, and it will be powered by a thin battery.

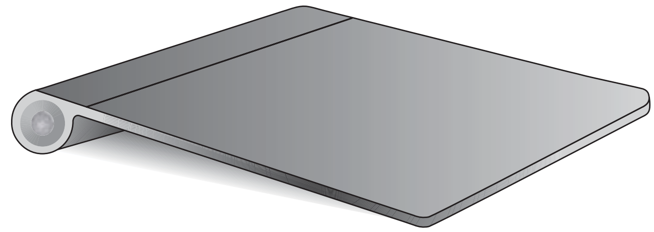


FIGURE 1. Within the next five years, the keyboard and mouse interface will be replaced by a keyless, touch-active surface with a multitouch trackpad.

Virtual computer controls

The technologies that will replace today's keyboard and mouse—virtual computer controls—include such devices as touch screens and wireless game controllers. Our assessment focused on the key component of virtual controls—tracking. Tracking systems enable the computer to determine a user's head or limb position or the location of a hand-held device that interacts with a virtual object. In the past, tracking for gesture recognition was implemented via worn devices such as gloves or bodysuits. Recent advances in passive techniques (e.g., cameras and sensors) allow for a more ubiquitous interface. The market for these interfaces has expanded in recent years; in fact, the top three video game console makers have integrated motion detection and tracking into their units.

The resulting virtual environments provide users with direct manipulation and interaction with multisensory stimulation. This flexibility enables a broader range of users (e.g., varying ages, skill levels, and languages). This blurring of the user interface, where the keyboard and mouse disappear completely, was once a costly endeavor; for example, three-dimensional depth mapping technologies ranged from $10,000 to $15,000. But Microsoft has been active with gesture-controlled interfaces that convert motion into on-screen action and control, and today their Kinect hardware package for Xbox 360 costs about $110.

Kinect operates by projecting an infrared laser pattern onto nearby objects. A dedicated infrared sensor identifies the laser position and determines the distance for each pixel. The corresponding information is then mapped to an image from a standard RGB camera (i.e., a camera that uses the red, green, blue additive color model), resulting in an RGB-D image where each pixel has a color and a distance (the D stands for "depth"). One can then use the image to map out body positions, gestures, and motion. Coupling body, face, and motion recognition with a multi-array microphone enables a complete virtual interface like none ever experienced outside of a laboratory.

Our analysis examined open-source publishing trends in the research and development of new tracking capabilities in recent decades. We discovered that more than 75% of the global research has been focused on body- and hand-tracking topics. Eye-tracking research represents most of the remaining research. Gesture recognition will also play a critical role in interface design, since it is a critical link between conceptualizing thought and linguistic expression.

The dominant force driving change in the area of virtual computer controls will be the demand for tracking technologies that convert human motion into computer responses.

For the near term, we can expect to see rapid expansion of Microsoft's Kinect platform. This inexpensive platform will encourage professionals, academic communities, and do-it-yourselfers to develop innovative applications limited only by the imagination. Additionally, transforming the current stationary hardware onto a mobile device will be an active area of development. In the longer term, as the technologies of gesture-, body-, and eye-tracking advance and as the resolution capabilities increase alongside machine learning, we can expect to see signs of *affective* human-computer interactions. For example, the ability to develop machine-level recognition of facial expressions combined with emotion signatures via audio would enable a progression toward affective interfaces.

Thin batteries

Our final area of interest is thin batteries. Our findings indicate that these batteries will become the power sources for the next generation of user interfaces. Today's batteries function by chemical storage. They are reliable but limited by packaging and energy density constraints; as the batteries shrink, their energy density falls. To meet the need for very small batteries to power future interfaces, new methods for thin battery manufacture are starting to appear. These methods fall into two categories: printed and sputtered. Printed batteries can be integrated on paper and flexible surfaces. Sputtered batteries are often deposited on rigid surfaces. Sputtered batteries are processed at high temperatures (i.e., greater than 500°C), thus offering manufacturing integration possibilities such as lamination with significantly reduced thicknesses.

We searched the literature for both printed and thin batteries. Our search identified research in these areas:

1. Printable lithium and other batteries based on liquid electrolytes,
2. Microbatteries based on microelectromechanical systems and thin film integration,
3. Sputtered batteries based on various chemistries, and
4. Solid electrolyte batteries using established chemistries like lithium phosphate.

A number of commercial suppliers of these batteries already exist, but because of the current economic environment, most are not investing in research and development. Rather, they are supplying products for specialized "gimmicky" markets like greeting cards, toys, cosmetic patches, and other novelties.

The near-term strategy for most manufacturers and researchers in thin batteries will be to improve energy densities and performance in an incremental and stepwise manner. For the mid-term, efforts will address considerations for rate engineering—for example, the design of very high continuous or pulsed current densities. In the far-term, packaging innovations are expected to reduce dimensions. Packageless devices may even be possible with the emergence of anode/cathode chemistries that are stable in air (e.g., lithium titanate and lithium iron phosphate). Studies have shown that theoretical capacities of about 88% are possible; however, systems to date are limited by low voltage potentials and several processing restrictions. The ability to deposit batteries on demand regardless of location is an extremely attractive prospect, but significant hurdles need to be overcome in basic science research and development before that can happen.

One recent development is worth noting: Dynamics Inc. has been advertising a new credit card product in which more than 70 components have been mounted on a printed circuit board and embedded in a credit card. The device includes a number of peripheral management circuits that are directed to power management, timing, and control. Accordingly, a number of peripherals (e.g., buttons) may be added to the platform to allow a user to enter information into the card. Displays might allow users to receive information from the card. The device is designed to be thin, flexible, durable, and able to operate for three years on a single battery charge.

Conclusions

To predict the shape of the next-generation user interface, we developed a methodology for assessing trends in keyboard technologies, virtual computer controls, and thin batteries—three areas essential to what is called "ubiquitous computing."

Our findings indicate that the next user interface will be shaped by developments in flexible electronics and displays and in manufacturing technologies that embrace printable electronics. Ubiquitous computing will be enabled by processing chips that bend, flex, and stretch. Commercial manufacturers already have the capacity to print conductors, resistors, capacitors, primitive sensors, and displays onto flexible surfaces. In the next decade, manufacturers expect to develop cost-effective methods for integrating thin devices (e.g., battery, electronics, and display) into a single product. Several commercial battery manufacturers are aligning their capabilities with this vision. For the market to materialize, however, manufacturers must develop diodes, sensors, transistors, displays, and electronic components that are compatible with printable and flexible manufacturing technologies and processes. But the trend is evident. Just as the rotary phone transformed into today's smartphones, so will the keyboard transform into tomorrow's haptic interface.

About the author

Since 1949, **Sandia National Laboratories (SNL)** has developed science-based technologies that support national security. SNL is a federally funded research and development corporation and a government-owned, contractor-operated facility. Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, manages SNL as a contractor for the US Department of Energy's National Nuclear Security Administration. SNL works with other government agencies, industry, and academic institutions to support national security in the following strategic areas: nuclear weapons; defense systems and assessment; energy, climate, and infrastructure security; and international, homeland, and nuclear security.

References and further reading

[1] "Soldier C3 program." *Tech Trend Notes.* 1993;2(1):11.

[2] "The information warrior." *Tech Trend Notes.* 1996;5(1):1.

[3] "C4I for the warrior." *Tech Trend Notes.* 1992;1(2):8.

[4] Meeker M. "The mobile Internet." Dec 2009. Morgan Stanley.

Department of Defense. "Technology Readiness Assessment (TRA) deskbook." Jul 2009. Office of the Director, Defense Research and Engineering. Available at: http://acqnotes.com/Attachments/DoD%20Technology%20Readiness%20Assessment%20Deskbook.pdf

Sato K, Tachi S. "Design of electrotactile stimulation to represent distribution of force vectors." In: *2010 IEEE Haptics Symposium;* Mar 2010; Waltham, MA. p. 121–128. DOI: 10.1109/HAPTIC.2010.5444666

Wang Y, Mehler B, Reimer B, Lammers V, D'Ambrosio LA, Coughlin JF. "The validity of driving simulation for assessing difference between in-vehicle informational interfaces: A comparison with field testing." *Ergonomics.* 2010;53(3):404–420. DOI: 10.1080/00140130903464358

Kim S, Sohn M, Pak J, Lee W. "One-key keyboard: A very small QWERTY keyboard supporting text entry for wearable computers." In: *Proceedings of the 18th Australia conference on Computer-Human Interaction;* 2006; Sydney, Australia. p. 305–308. DOI: 10.1145/1228175.1228229

Foxlin E. "Motion tracking requirements and technologies." In: Stanney KM, editor. *Handbook of Virtual Environments: Design, Implementation, and Applications.* Magwah NJ: Lawrence Erlbaum; 2002. p. 163–210.

Yamamoto M, Sato H, Yoshida K, Nagamatsu T, Watanabe T. "Development of an eye-tracking pen display for analyzing embodied interaction." In: Salvendy G, Smith MJ, editors. *Human Interface and the Management of Information. Interacting with Information.* Springer, 2011. p. 651–658. (Lecture Notes in Computer Science, 6771).

Image on the bottom of the following page is an angled view of a portion of an IBM chip showing blue optical waveguides transmitting high-speed optical signals and yellow copper wires carrying high-speed electrical signals. IBM silicon nanophotonics technology is capable of integrating optical and electrical circuits side-by-side on the same chip. (Courtesy of International Business Machines Corporation. Unauthorized use not permitted.)

Photonics and optical communication

***"Photonics is the optical equivalent of light. Photonic systems use light, instead of electricity, to process, store, and transmit energy. Photonics is a pervasive technology, which is capable of significantly influencing communications and information systems worldwide"* [1].**

The author of that *Tech Trend Notes* article eagerly anticipated new photonic systems and devices that would increase network capacity and secure the optical communications flowing over those networks. Indeed, photonics in the form of fiber-optic technology helped enable the expansion of the early Internet from a support service for scientific researchers to a worldwide communications network [2].

Securing the data, however, has been an ongoing struggle. Traditional encryption is based in part on mathematical problems, such as factoring extremely large numbers. But as computers became more powerful, concern increased about their ability to break traditional cryptographic codes, and researchers looked for alternative ways to protect transmitted data.

Quantum cryptography, which depends on principles of quantum physics instead of mathematical problems, has become the holy grail of protection.

The theory of quantum cryptography was originally proposed in 1982, the technology and protocol were first demonstrated experimentally in 1989 [3], and the first commercial quantum cryptography technology in the US was installed in 2012 [4]. As with many theories, commercial development of quantum cryptography had to wait for the supporting technologies. (Even the scientists who propounded the theory of quantum cryptography in 1982 thought of it as science fiction because the technology required to implement it was out reach at the time [3].)

One of those supporting technologies, single-photon detectors, is discussed in the following article both as a key technology for quantum cryptography as well as for other methods of communication in extreme conditions.

Forecasting single-photon detector technology

Massachusetts
Institute of
Technology
Lincoln
Laboratory

Since they cannot be generated, controlled, and measured easily, photons (i.e., light pulses) have been used to transmit information throughout recorded history. The optical communications pulses used today to transport information in the global Internet contain several hundred to a few thousand photons per information bit. The fiber-optic and free-space technology needed to generate, control, and measure the optical pulses containing such large numbers of photons is very mature, and there are numerous commercial and military optical communication systems that utilize this technology.

However, several optical communication scenarios of interest to the government and military must measure far fewer than hundreds of photons in a single pulse in order to decode a communication bit. Presently, applications requiring a single or, at most, a few photons per bit for detection are being developed and deployed. These limited photon number communication applications can be divided into the following categories: 1) stressed free-space optical communication, 2) low probability of intercept (LPI) optical communication, and 3) quantum communication.

Single-photon detectors are the key technology underlying all of these limited photon number communication applications. Single-photon detectors are devices that can reliably detect the presence of optical pulses containing only a single photon by absorbing a photon and converting its energy into a measurable electrical signal. While commercial single-photon detectors are presently available, they are expensive and have limited performance characteristics. Fortunately, single-photon detector technology is currently an area of active research, and dramatic performance improvements have been demonstrated in the laboratory. Future development and deployment of optical communication systems designed to effectively utilize a limited number of photons per bit will require the continued advancement of single-photon detector technology.

Single-photon detector technology provides detection of time-varying optical signals with performance approaching the quantum noise limit. Single-photon detectors digitize each photon detection event and its associated timing, thereby overcoming the readout noise encountered in typical photodetection schemes. This digitization provides a significant performance benefit to applications that require detecting the presence or absence of photons during many short time periods rather than measuring the total number of photons during an integration period.

For example, single-photon detectors enable very sensitive optical communication receivers for intensity-modulated signals. Additionally, most quantum key distribution protocols rely on single-photon detection. Despite these advantages, the challenges associated with single-photon detection have limited the technology's adoption and capabilities. This article summarizes the current state of single-photon detector technology, identifies optical communication scenarios that can benefit from it, and forecasts future technology advancements.

A wide range of single-photon detector technologies are likely to continue to be developed due to the different strengths of each technology and the widely varying requirements for different applications. Consequently, the technologies are likely to develop in different ways for each application, and the most appropriate scenarios to consider are application-driven ones.

Three distinct categories of optical communication can benefit from further development of single-photon detector technologies. First, stressed free-space optical communication can benefit from the improved sensitivity offered by photon-counting receivers, particularly in situations where it is challenging to couple the received optical signal into a single spatial mode. In this application, the driving requirements are the efficiency, speed, and active area of the detector. In some cases, the size, weight, and power (SWaP) of the detector system is also relevant. Second, low probability of intercept (LPI) optical communication can also benefit from photon-counting receivers' sensitivity and from their ability to collect an optical signal from a wide field of view. In this application, the driving requirements are the SWaP, the active area/array capabilities, the dark count rate, and the detection efficiency. Finally, various quantum communication applications require single-photon detectors with high efficiency, low noise, and high speed.

FIGURE 1. Single-photon detectors are already the technology of choice for the longest distance optical communication links, such as data transmission between a satellite in space and a receiving station on Earth.

The wide variety of requirements imposed by different applications and the drawbacks associated with each individual technology has lead to the development of many different types of single-photon detectors. The available technologies include detectors based on the photoelectric effect, electron-hole pair generation in a semiconductor, and excitation of an electron out of the superconducting state. Each of these technologies offer different performance advantages and drawbacks in terms of detection efficiency (i.e., optical loss), speed, noise, scalability to arrays, reliability, size, weight, and power. The evolution of each detector technology will vary depending on their application.

Stressed free-space optical communication

In stressed free-space optical communication, the extreme conditions under which communication needs to take place are the factors determining the number of photons available at the receiver. In this category, the encoded optical pulses are generated at the transmitter with a very large number of photons per pulse but, because of the nature of the link between the transmitter and the receiver, by the time the encoded optical pulse reaches the receiver, there are only a very few remaining photons available for detection.

One example of such a communication application is a satellite orbiting the moon transmitting data to a receiving station on Earth. In this application, the extreme distance of the communication link greatly reduces the number of photons per bit available at the receiver. As the link distance increases, the sensitivity of the communication receiver becomes more important and the data rate that can be supported ultimately decreases. Consequently, single-photon detectors are already the technology of choice for the longest distance (i.e., interplanetary) optical communication links (see figure 1).

Another example is communication in extreme optical environmental conditions—such as fog, smoke, or under water—where the scattering losses caused by the environment dramatically reduce the number of photons per bit available at the receiver. Depending on the system constraints and the required data rates, single-photon detectors can also be attractive for much shorter distance links. The acceptance of single-photon detectors for these applications is likely to improve as the technology and packaging mature and performance improves, particularly in terms of speed and detection efficiency as well as radiation tolerance for space applications.

The interest and acceptance of free-space optical communication systems in general is increasing, with a notable number of demonstration systems utilizing photon-counting receivers. This large and growing area should continue to support research and development of single-photon detector technologies and will thus likely play an important role in determining the evolution of single-photon detector technology.

Low probability of intercept (LPI) optical communication

In low probability of intercept (LPI) optical communication, the defining factor is the desire for communication security. In these applications, the transmitter deliberately generates encoded optical pulses that only contain a single or, at most, a few photons. For example, in LPI optical communication systems, the number of photons per transmitted bit is deliberately kept very low to minimize the probability that an adversary will be able to detect the presence of the communication link.

Single-photon detector technology provides many important attributes for enabling LPI optical communication. Specifically, this technology enables implementing a high-sensitivity receiver in a compact and scalable package, which can be designed to collect optical signals from a large number of modes. For links in which the collected optical power is limited, due to absorption, scattering, or limited power at the transmitter, the features provided by single-photon detectors can be important even for short-distance links.

In contrast to the stressed free-space optical communication application, there is a wider range of desired performance attributes for specific systems within this application. Some systems make use of the significant scattering and background-free environment available at ultraviolet wavelengths, while others may be designed to employ low-scatter, line-of-sight geometries at shortwave infrared wavelengths. In general, this application area is focused only on compact, noncryogenic technologies that can provide large active areas and/or array formats with low noise. The acceptance of single-photon detectors in this application is likely to depend on the availability of a technology that can be mass produced with high-enough performance and low-enough cost to justify widespread adoption.

Quantum communication

Quantum communication involves the transfer of quantum information between two locations. Here, the defining factor is the requirement to maintain the quantum nature of the information being transmitted. Most quantum communication systems require single-photon detectors. The most widely known and only commercially available application in this category is quantum key distribution (QKD). In QKD, ideally each optical pulse only contains a single encoded photon. Having only a single photon per pulse allows the QKD system to exploit the quantum properties of photons to provide a secure means to establish a shared secret encryption key between the transmitter and the receiver locations. (See figure 2 for a diagram of the first QKD protocol, BB84, developed in 1984.)

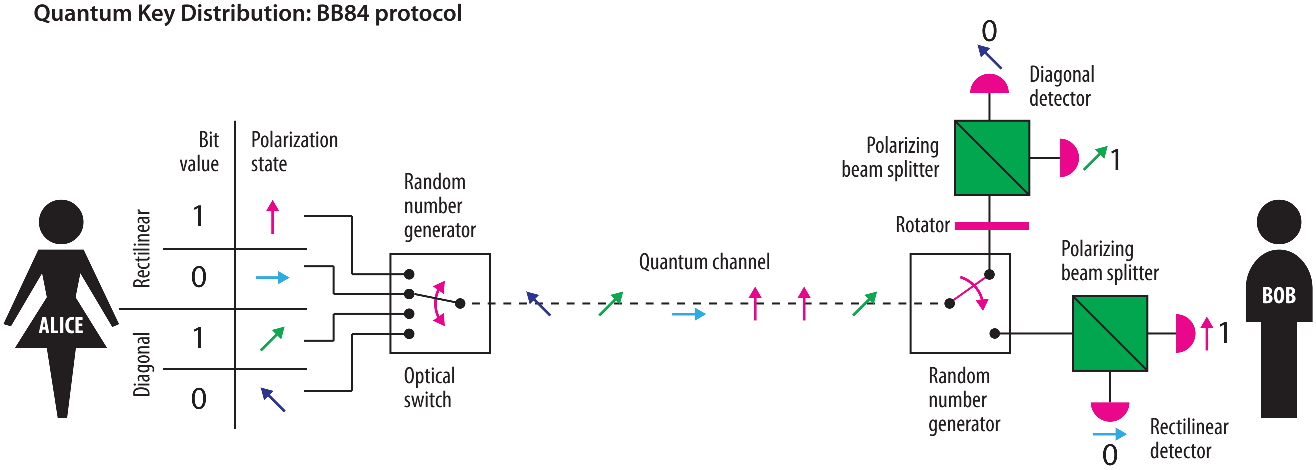
These systems have been an important area of research for over two decades. As a result, the evolution of single-photon detector technology has been driven more by the requirements of this application than by the classical (i.e., nonquantum) optical communication applications. The most important detector parameters for this application are the detection efficiency, the speed, and the noise. The performance requirements can be very challenging, particularly for some protocols or long-distance links. Single-photon detector technology development is likely to continue to steadily overcome these challenges to meet the desired performance levels.

Although the acceptance of single-photon detector technology within QKD systems is high, the growth in the adoption of these systems has been slower in recent years than some experts initially projected. More widespread deployment of these systems, beyond the initial fielded demonstrations, will likely require lower-cost systems (including the detectors) and increased security benefits relative to competing key distribution approaches.

Commercial adoption and implementation

The economic and market forces influencing single-photon detector technology are limited, particularly for optical communication. This limited influence from commercial markets can be understood given the optical communication scenarios that are likely to adopt single-photon detector technologies. Specifically, single-photon detector technology is not well suited to most commercial optical communication applications, such as fiber-optic communication systems, and

Quantum Key Distribution: BB84 protocol



Quantum transmission & detection	ALICE sends photons	↖	↗	→	↑	↑	↗	↖	↑
	ALICE's random bits	0	1	0	1	1	1	0	1
	BOB's detection events	↑	↗	↖	↑	↗	↗	↖	↖
	BOB's detected bit values	1	1	0	1	1	1	0	0
Public discussion (i.e., sifting)	BOB tells ALICE the basis choices he made	Rect	Diag	Diag	Rect	Diag	Diag	Diag	Diag
	ALICE tells BOB which bits to keep		✔		✔		✔	✔	
	ALICE and BOB's shared sifted key	–	1	–	1	–	1	0	–

FIGURE 2. This diagram shows the first quantum key distribution (QKD) protocol, BB84, developed in 1984. Although the acceptance of single-photon detector technology within QKD systems is high, the growth in the adoption of these systems has been slower in recent years than some experts initially projected.

is instead suitable for quantum communication and a subset of free-space optical communication links. There are a limited number of commercially available QKD systems that use single-photon detectors, but there are no commercially available free-space optical communication systems that employ photon-counting receivers. Consequently, most of the commercial adoption analysis will focus on the fiber-optic QKD scenario.

Several commercial companies are developing QKD systems and associated single-photon detection technologies. Both id Quantique and MagiQ Technologies have developed QKD products that use single-photon detectors. Additionally, several other companies including Toshiba Research, NTT, NEC, IBM, and Mitsubishi have developed QKD systems that are not available as commercial products but have been used in test beds or fielded technology demonstrations. In some cases, these companies have not only developed QKD systems but have also advanced single-photon detector technology or advanced the availability of packaged detector systems.

In particular, Toshiba Research and IBM have pursued new readouts and detectors, which advanced the performance of their QKD systems. Additionally, id Quantique offers a number of packaged Geiger-mode avalanche photodiode (APD) single-photon detectors that can be purchased as independent units. Despite commercial interest in these technologies, the market for QKD systems remains small and includes many research-oriented efforts to demonstrate the capabilities and to understand the vulnerabilities of these systems. Consequently, continued commercial efforts in this area will likely depend strongly on the availability of government funding to support the work and the ability of employees working on the projects to effectively advocate for internal research and development funding.

The worldwide acceptance of QKD systems that employ single-photon detectors has been slow. Although there have been some notable demonstrations of the technology in the US, Europe, Japan, and China, the technology has not been widely adopted in any region. The availability of government funding has been the primary driver in determining how the technology has been implemented as a function of time and geographic location since the cost-benefit equation governing market adoption of these systems has not changed significantly over the past few years. In the future, the system cost has the potential to change if single-photon detectors and other components for QKD systems could be integrated on a single chip with classical fiber-optic communication hardware.

As integrated photonics is more widely adopted in commercial fiber-optic communication systems, any subsequent efforts to integrate QKD functionality into those chips would be interesting to track. Additionally, the benefits provided by QKD systems would change if existing key exchange mechanisms are found to have new vulnerabilities or are subjected to new regulations. Small changes in the costs and benefits of QKD systems, including the forecasted changes in single-photon detector technology, are unlikely to generate significant market adoption of QKD systems employing single-photon detectors.

Finally, commercialization of single-photon detector technology for noncommunication applications may serve as a more powerful force influencing the development of the technology. Specifically, single-photon detectors are used in several types of instruments for measuring fluorescence from single molecules and biological samples, characterizing defects in very-large-scale integrated semiconductor circuits, and performing material analysis. Avalanche photodiode technology will benefit from governmental and commercial investments in photon-counting imaging systems that employ the same types of APDs used in optical communication systems.

The cost, complexity, and constraints imposed by current single-photon detectors can often be readily accommodated by larger-scale test equipment.

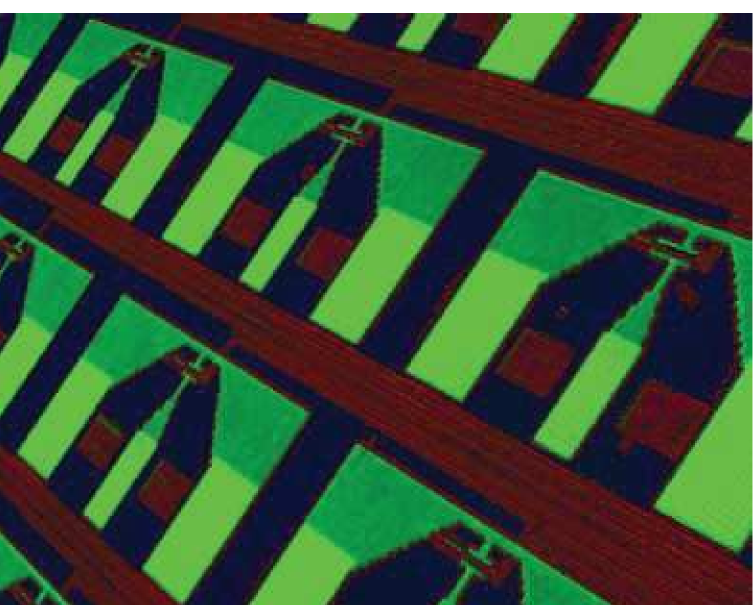


FIGURE 3. Optical microscope photographic image of an array of nanophotonic avalanche photodetectors on a silicon chip. (Courtesy of International Business Machines Corporation. Unauthorized use not permitted.)

Over time, these tools will likely be used not only by researchers in a laboratory environment but also for industrial applications in manufacturing settings and for medical applications in clinical settings. This expanded market is likely to reduce the cost and increase the robustness of technologies that are utilized. It may also drive development toward more integrated readouts and packaging, larger arrays, and improved performance. This optimization is likely to be driven by the requirements of the target application, so unless the requirements are closely matched to those of optical communication systems or the communication application has flexible requirements, other markets may have limited impact on the technology development for optical communication.

Research directions

There have been multiple decades of worldwide research on single-photon detector technologies that are suitable for optical communication. In particular, research interest in quantum optics and QKD has motivated many efforts since the 1980s to improve both the detectors and their optical and electrical interfaces. Additionally, although the advantages of photon-counting receivers for highly sensitive classical communication have also been understood for decades, efforts to demonstrate and optimize these advantages have increased substantially in just the last 10 years. Research efforts have included industry, academia, and government-funded laboratories, with most of the funding in all cases being provided by domestic or foreign governments.

Current and future research efforts to improve single-photon detector technology are likely to vary greatly in terms of the associated risks and uncertainty. Many aspects of relatively mature technologies, including photomultiplier tubes, Geiger mode APDs, and superconducting nanowire single-photon detectors are well understood and can be accurately modeled, allowing future advances to be carefully engineered with relatively low risk. In general, these low-risk research efforts are not as useful when pursued solely as proof-of-principle experiments because there is little uncertainty about their viability and impact. Instead, these research efforts are most useful when they are geared toward detectors that are well optimized for the intended application so that any trade-offs and integration difficulties can be evaluated.

Oftentimes, pursuing these advances in industry or government-funded laboratories increases the likelihood that the approach will have impact beyond an initial demonstration. These efforts can include both government-sponsored programs and, in some cases, internally allocated research funding. Government agencies or companies that are interested in fielding systems or demonstrating new capabilities are generally more likely to succeed quickly by extending the performance of relatively mature technologies as opposed to funding early research in speculative technologies. Government funding for this type of research and development is provided by defense, intelligence, and space agencies, both domestic and foreign.

In addition to low-risk detector improvements, there are also more speculative potential advancements that can be made to both mature and emerging technologies. In this case, demonstrating the viability of new ideas is important, regardless of whether this demonstration is made on a record-breaking device by a leader in the field or by an unknown researcher on a nonoptimized detector. Such breakthroughs are much harder to predict, and they are often accompanied by new engineering challenges that delay the eventual impact on optical communication systems. Although it is impossible to forecast the exact form of these single-photon detector technology breakthroughs, the speculative areas with potential for breakthroughs include photon-counting linear-mode APDs, nanoinjector sensors, quantum dot detectors, microwave kinetic inductance detectors, and superconducting tunnel junction detectors.

There is also the possibility for breakthroughs in new materials or readouts for more mature single-photon detector technologies. Speculative research areas are almost always government funded because the commercial market for such developments is not large enough to justify private investment.

Due to the scientific nature of the work, new single-photon detector technology results are generally publicly available through scientific journals and conferences; however, some foreign countries and commercial companies are less open about new results. There are numerous review articles and several books published on single-photon detectors, including a special issue of the *Journal of Modern Optics* published every two years in connection with the Single Photon Workshop. These published results generally provide a much more complete picture of worldwide technical advances than does tracking individual efforts or funding sources, many of which are small or difficult to discover and track.

Finally, it is important to distinguish between early research results and fielded detector systems. The technical challenges in maturing a new single-photon detector technology or even integrating a new approach into an existing system are considerable, particularly given the relatively small scale of most efforts in this field. Also as a result of the small scale of this field, many research advancements depend on leveraging independently developed technologies, including material growth and characterization, lithography/ fabrication capabilities, readout circuits, and cooling/ packaging technologies.

While this article provides a somewhat uncertain prediction of the opportunities for breakthrough performance improvements, these scientific and research advancements are only the first, vital step toward impacting actual optical communication systems.

Conclusions

Single-photon detector technology has enabled new optical communication capabilities with particular relevance for national security and defense applications. Although the optical communication systems that employ single-photon detector technology are in the early stages of adoption, it is likely that acceptance of these systems will increase, particularly with further advances in single-photon detector technology. Significant improvements in the technology are technically feasible for both relatively mature and speculative technologies, but government funding is the dominant source of investment for this work, so progress will depend strongly on the level of investment the US and foreign governments choose to make in various technologies and applications.

Future investments in speculative technologies should focus on revolutionary improvements that can impact single-photon detector technology acceptance into optical communication systems. It is not only the detector performance that will limit adoption but also the cost, maturity, reliability, complexity, size, weight, and power of the detector systems. The performance of existing detector technologies is a moving target, with continued progress likely to occur. Additionally, mature technologies provide significant advantages over emerging technologies in terms of development and past investments that can be leveraged.

In order for speculative technologies to justify significant investment, initial research into these technologies should seek to evaluate the potential for revolutionary improvements either in performance or in other metrics, such as the manufacturability, scalability, and ease of integration into systems. Existing single-photon detector technologies, particularly those operating at cryogenic temperatures, can offer fairly impressive performance, but adoption of these technologies is limited to systems that justify the cost and operational constraints associated with existing technologies. Investments in speculative technologies will most likely take many years to translate into deployable systems, but these investments are justified if they can result in revolutionary advances in system performance or widespread adoption.

In contrast, more mature single-photon detectors offer relatively well-understood opportunities to improve the performance and acceptance of systems. For many applications, increased acceptance of single-photon detectors may simply require further optimizing a technology for a specific system. Significant past investment can be leveraged to engineer and realize the required changes, while accounting for the performance and operational trade-offs. This type of optimization is relatively low risk and can be readily justified; thus, many funding opportunities for this type of work exist.

However, there are also opportunities to improve detector performance for a wide range of applications with few trade-offs or drawbacks. In particular, improved optical coupling and packaging can improve performance and may even reduce costs or improve manufacturability. An example of this is a front-illuminated fiber-coupling approach developed at the National Institute of Standards and Technology that enables very low-loss coupling to single devices [5]. Detector arrays could benefit from additional investment in low-loss microlens arrays, which might also improve back-illuminated coupling to single-photon detectors. Also, although it would require a larger investment and would have less universal applicability, improved material quality could improve detector performance without trade-offs. These types of efforts are often more difficult to justify than application-specific optimizations, but they can offer a very significant return on investment.

In summary, the future evolution of single-photon detector technology is likely to be strongly motivated by optical communication requirements as the acceptance increases for both the detectors and the optical communication systems which use them. The application scenarios and the individual technologies have many unique attributes that will likely limit the feasibility of pursuing a single, dominant technology. However, a few technologies including APDs, superconducting nanowire single-photon detectors, and transition-edge sensors do provide compelling performance advantages for specific applications.

While pursuing breakthroughs in speculative technologies is worthwhile, it is important to recognize that advancing single-photon detectors from initial demonstrations to mature components requires significant government investments. In cases where less ambitious performance improvements are sought, many opportunities remain to further optimize technologies that are already used for those applications.

About the author

The **Massachusetts Institute of Technology Lincoln Laboratory** is a federally funded research and development center that applies advanced technology to problems of national security. Research and development activities focus on long-term technology development as well as rapid system prototyping and demonstration. These efforts are aligned within its key mission areas: space control; air and missile defense technology; communication systems; cybersecurity and information sciences; intelligence, surveillance, and reconnaissance systems and technology; advanced technology; tactical systems; homeland protection; air traffic control; and engineering. The laboratory works with industry to transition new concepts and technology for system development and deployment.

References

[1] "The rise of photonics." *Tech Trend Notes.* 1992;1(2):15–16.

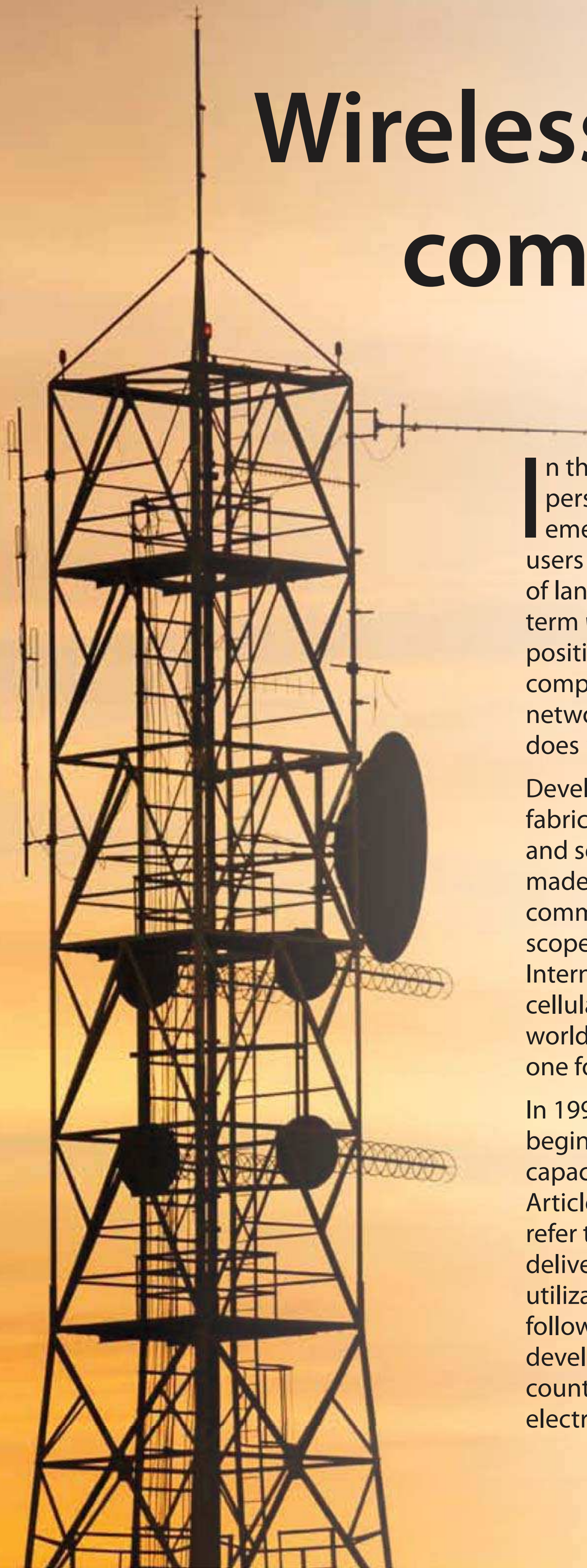
[2] Frazer KD. "NSFNET: A partnership for high-speed networking, final report, 1987–1995." 2004 Oct 26. Available at: http://www.merit.edu/documents/pdf/nsfnet/nsfnet_report.pdf

[3] Bennett CH, Bessette F, Brassard G, Salvail L, Smolin J. "Experimental quantum cryptography." *Journal of Cryptology.* 1992;5:3–28. DOI: 10.1.1.34.3599

[4] Batelle. "Battelle installing first commercial quantum key distribution in US" [Press release]. 14 Jun 2012. Available at: http://finance.yahoo.com/news/battelle-installing-first-commercial-quantum-145500986.html

[5] Miller AJ, Lita AE, Calkins B, Vayshenker I, Gruber SM, Nam SW. "Compact cryogenic self-aligning fiber-to-detector coupling with losses below one percent." *Optics Express.* 2011;19(10):9102–9110. DOI: 10.1364/OE.19.009102

Wireless communication



In the first issue of *Tech Trend Notes,* wireless personal computing was described as "a rapidly emerging technology [that] will enable computer users to access information without the restrictions of landline-based systems" [1]. Today, of course, the term *wireless* includes smartphones, tablets, global positioning systems, laptops, netbooks, wireless computer accessories, remote controls, wireless network cards, and pretty much anything that does not use wires to transmit information [2].

Developments in radio frequency circuit fabrication, advanced digital signal processing, and several miniaturization technologies have made it possible to "deploy and deliver wireless communication services at the scale and scope that we see today" [3]. According to the International Telecommunication Union, mobile-cellular subscriptions have grown from 22.8 million worldwide in 1992 to 6.8 billion in 2013—almost one for every person on the planet [4].

In 1992, even though the wireless boom was just beginning, rumblings about the need for increased capacity and effective use of spectrum were heard. Articles in the early issues of *Tech Trend Notes* refer to the need for more cost-effective service delivery, increased system capacity, and effective utilization of spectrum [5, 6]. As discussed in the following article, those early rumblings have developed into a worldwide struggle between countries and corporations over use of the electromagnetic spectrum.

Radio noise: Global economic and political impact |

Pacific Northwest
National Laboratory

The term *radio* often conjures up images of the early transistor receivers, sound bites from Franklin Roosevelt's inaugural address, and large antenna arrays used for broadcasting. These images do not reflect the modern truth that radios are ubiquitous and constantly employed in everyday life. Some common radios include mobile phones, wireless local area networks (e.g., Wi-Fi) , global positioning systems, satellite radio, Bluetooth, cordless phones, baby monitors, microwave ovens, remote controls, garage door openers, and most devices that are wireless. The recent proliferation of mobile devices and wireless Internet has dramatically increased the amount of electromagnetic energy being broadcast everywhere. This added energy creates noise or, more precisely, interference that can interrupt other signals operating at the same frequency. This noise can worsen analog signals or prevent the reception of digital signals altogether. Within the next five to ten years, the indirect effects of noise will likely result in worldwide decisions to free more bandwidth for mobile and industrial, scientific, and medical applications with an increase in the noise level. The effects of the continued spread of wireless technology may also lead to diverse economic, political, and military issues.

Introduction

Signal interference is one limiting factor in the spread of mobile devices and has recently become a juggernaut in driving economic decisions due the financial value of the billions of mobile phones that have entered the world market in the last 20 years. The shift from one-way communications, like broadcast television, to bidirectional information transmission services, like third generation (3G) cellular telephony, have created major consumer markets and dependence on mobile services.

Consumers are constantly demanding more information at faster rates with better reliability on mobile devices, which continues to increase noise. The demands create social and economic pressures that can drive major policy decisions, like the relicensing of some of the television frequencies for mobile data during the digital television shift in 2007. The already high economic value of the spectrum is projected to experience rapid growth in the next few years.

Communication and noise

Standard electronic communication occurs across a wide range of frequencies in the radio spectrum (i.e., frequencies less than 300 gigahertz) [7]. Typically, communication occurs when a sinusoidal electromagnetic wave, termed a *carrier*, is modulated with an information signal. When communication involves a single carrier frequency, the transmission mode is termed *narrow band* (as opposed to multiple carrier frequencies or wideband), and this is the form of almost every regulated communication currently conducted in the world.

To this end, the radio spectrum is broken into many narrow bands that are then assigned to specific activities such that the physical properties of electromagnetic waves at each frequency (e.g., atmospheric absorption) are suited to the particular communication or industrial use. Broadcasting in narrow bands cannot be perfectly achieved. This can result in some spillover that generates some undesired signal in adjacent bands. These undesirable signals are referred to as *spurious emissions,* and they are a common source of noise.

These communication waves can be interrupted by undesired changes to the signal. This electronic noise is a "random" electromagnetic signal at the frequency of interest that can be caused by natural sources. Noise is more likely due to another party using the same frequency for communication or for intentional jamming; this is typically referred to as *interference.*

While the physics of electromagnetic communication are complex, the basics are fairly analogous to sound. Consider a conference room that represents a single narrow band frequency. Broadcast communications, like television, are similar to a single speaker delivering a lecture in the room. People closer to the speaker will hear well because volume is louder, while listeners toward the rear of the room may miss words or entire sentences. In the same way, radio receivers closer to the station receive a strong clear signal, while distance receivers may have the station drop in and out of reception.

In that same conference room, there may be heating and cooling fans that are running, cell phones ringing, rustling movements and creaking as people adjust their chairs, or a plethora of other sounds. The collection of these sounds interferes with the listener hearing the speaker and represents natural noise sources, like lightning or cosmic radiation. Consider that the

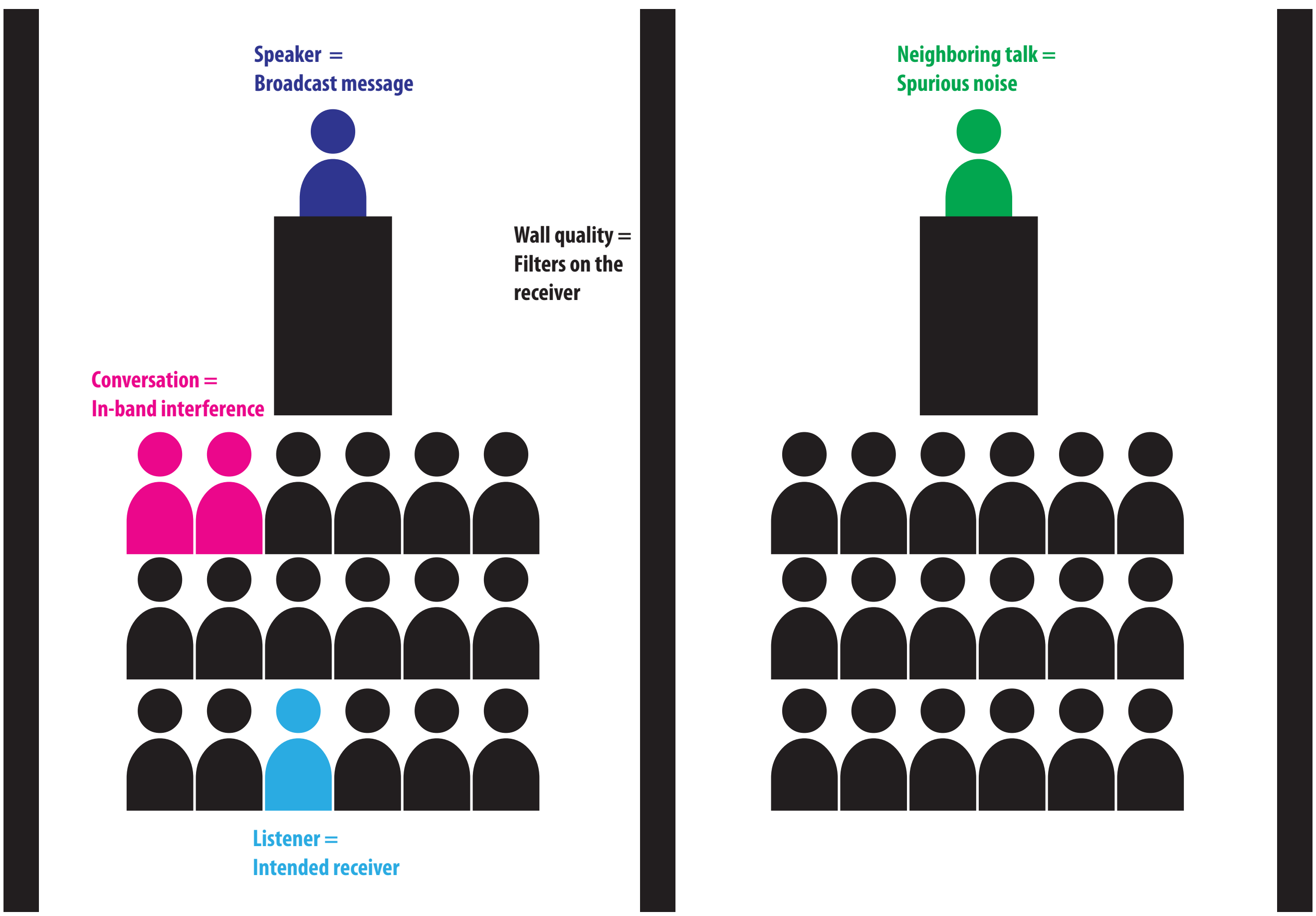


FIGURE 1. Communication across a narrow band frequency (e.g., broadcast television) is similar to giving a lecture in a room of a busy conference center. The speaker (dark blue) is transmitting a broad message to the receiver (light blue). A conversation at the front of the room represents in-band interference (pink). The walls represent the receiver's filter that reduces unwanted signals and prevents spurious noise (green) from adjacent narrow bands.

conference room is actually in a conference center with identical rooms on both sides (see figure 1). In each of those rooms, different speakers are also giving talks, and the walls are poor, allowing sound from their lectures to come into the conference room. The talks coming through the walls are a form of spurious noise, and the quality of the walls themselves represents the quality of the filter on the radio receiver.

Finally, some people are carrying on conversations at the same time that the speaker is talking. If the listener is nearby, the conversations can completely prevent him or her from hearing the talk and represents noise due to in-band interference. If the listener is involved in the conversation and not paying attention to the speaker, the speaker is a source of noise in the conversation. In this way, noise due to interference is completely contextual and depends on the specific communications.

Loosely applying this analogy to real issues can provide some insight into the impact that noise has on the world. Wireless Internet using the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standard (i.e., Wi-Fi) typically communicates in the unlicensed industrial, scientific, and medical (ISM) frequency at 2.4 gigahertz (GHz). This is the same frequency that Bluetooth, Zigbee, and a variety of other technologies also use.

Fifteen years ago, there were not many people using wireless Internet, and the data rates were lower than they are today. This is like a conference room with several tables and only a few people scattered throughout, each having quiet conversations with one another with very little difficulty. As time progressed, wireless local area network (WLAN) hot spots were installed in more places, wireless data rates increased, and technologies like Bluetooth began to see regular use. In other words, the conference room started to fill with more people having louder conversations, and some of those conversations were in different languages.

By 2011, the room was extremely crowded with everyone trying to carry on conversations at once. If someone is having trouble communicating in the room, they have three choices. They can: 1) increase their volume, 2) move closer to the other person in the conversation, or 3) move to another room. WLAN users experiencing interference have the exact same three choices. They can: 1) increase the communications power, 2) move closer to the wireless router, or 3) change frequencies. And all three behaviors are commonly seen in response to noise.

Unfortunately, those options are becoming less viable. There are power limits on transmission that prevent the "volume" from constantly increasing, and for practical reasons, one can only be so close or have so many wireless routers. That has historically led to migration to new frequencies (or empty rooms). That option is becoming less viable because technology has now been developed to cheaply utilize frequencies up to 6 GHz with relative ease. Due to the physical properties of electromagnetic waves, this represents the high end of the most desirable mobile frequencies. Basically, all of the conference rooms in the center are now claimed. The full conference center is a condition that will be realized by most urban centers in the world sometime before 2020.

Mobile phones and the ISM bands

The effects of interference that are the most pronounced in the frequency bands are the ones most heavily used. Mobile phone bands and ISM bands are the two sets of applications that are overwhelmed with users and have the greatest driver for increased demand. They are like loud, overcrowded conference rooms with lines at the door. The interference effects in these bands will be used as leverage to shift into other bands (similar to the digital television frequency auctions), and the finances associated with mobile devices will only continue to increase. For this reason, consideration of the future of the spectrum begins with mobile devices and then ISM band applications, like Wi-Fi.

Consumers worldwide are demanding more mobile devices with much greater connectivity. Currently there are approximately 6.8 billion cellular subscribers worldwide with a global shift away from fixed telecommunications infrastructure. In addition to an increasing user base, data demands are also growing. The bandwidth for these communication types will increase by about 100% every 4.4 years. This bandwidth trend is similar to earlier bandwidth gains found in broadband Ethernet and WLAN technologies (see figure 2 on the following page). Additionally, people are migrating from traditional voice and short message service (SMS) communication toward smartphones with significant data demands. By 2015 there will be about 738 million smartphones in use

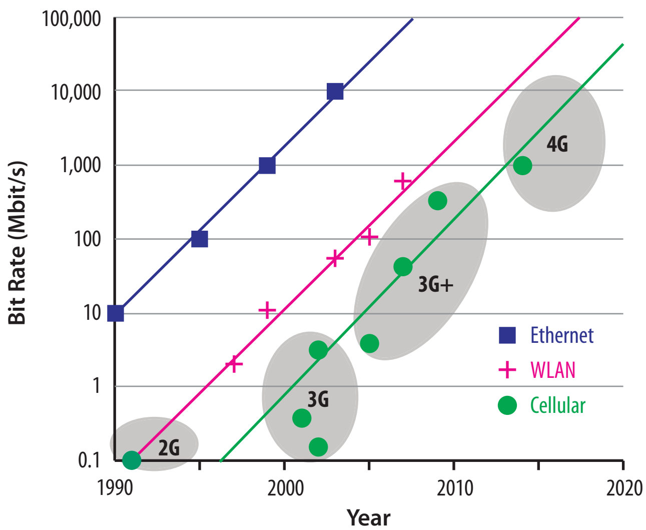


FIGURE 2. Pacific Northwest National Laboratory projects that, like Ethernet and WLANs, the maximum bandwidth for cellular data transmission technologies will increase by about 100% every 4.4 years. [Original figure created by PNNL.]

worldwide. Mobile phones will likely communicate at all ISM frequencies, all cellular frequencies, and all satellite location service frequencies with communication hardware adapting to meet changing standards.

Mobile devices have such a dramatic impact because of the economic value that the carriers can extract. This value drives frequency allocations and subsequently has a dramatic impact on interference. The enormous value of the spectrum coupled with a dramatic increase in demand for wireless data will have several likely effects. The high spectrum value creates inertia in band use by companies already operating in the market. This prevents governments from rapidly changing the purpose of an allocated license because of the extremely negative financial consequences. The same factor drives standardization from the International Telecommunication Union (ITU) for projected available bands that are often released a decade before they are implemented. The last expected outcome is a drastic increase in noise in all licensed communications bands and in all unlicensed ISM bands (e.g., those used for Wi-Fi) [8, 9].

There is a large consumer push to free up unlicensed or ISM bands to allow for free wireless communication instead of paying mobile operators. This creates political pressures because the most commonly used bands fall in the 900 megahertz (MHz) to 5.925 GHz range, which are also coveted by cellular companies [10, 11]. The ISM bands are the most utilized and allow for a wide variety of communication protocols [12–18]. This creates significant additional interference that cannot be as easily compensated for by a single carrier that controls the band. Some forms of ISM usage include WLANs, electronic toll collection, garage door openers, cordless phones, remote controls, Bluetooth, burglar alarms, and microwave ovens. The continued proliferation of ISM band uses is expected to create drastic interference in all current and any new ISM bands that are made available.

Current communication protocols are expected to evolve following historical trend lines. This suggests that the IEEE 802.11ac Wi-Fi standard will be adopted around 2015, Bluetooth will continue to evolve, and ISM bands may be used for wireless high-definition television transmission by 2017. Aside from these protocol improvements, the large driver of future ISM band interference will be information transmission [19–24]. The ISM bands are currently the primary frequencies used for short-range information transfers. Particularly, WLANs are expected to offload Internet traffic from portable devices when available. This has become more prevalent as mobile carriers have moved to pricing schemes in which they charge for data.

Also, the next decade will see an explosion of wireless sensors and supervisory control and data acquisition (SCADA) devices that are expected to use ISM band wireless communication to transmit data to a central node [25, 26]. ISM band noise is expected to be particularly pronounced in urban and developed environments, as these places tend to demonstrate the highest concentration of people and short-range infrastructure and will unlikely change rapidly due to the significant investment manufacturers and network providers have in the current ISM communication protocols.

Other radio uses

There are several other uses of the radio spectrum that do not involve mobile or ISM applications. Several of these applications such as television and radio broadcasting, navigation beacons, aerospace communications, emergency services, and certain military applications are very well regulated and unexpected to see significant changes before 2020. Other traditional radio uses like space-based communication and radio astronomy are more likely to be threatened by the economic emergence of corporations interested in spectrum.

The interference caused by the widespread use of wireless communication has been in constant conflict with radio astronomers who require extremely low background noise to measure anything of significance. This has led to the ITU and most countries adopting passive radio frequency device policies in which limited amounts of spectrum are set aside specifically for radio astronomy [27, 28]. Any interference in these bands is easily detected, and in some areas, the transmitting device is forcibly shut down.

A similar problem occurs with space-based communications, like global positioning system (GPS) signals or satellite radio. The best bands for satellite-to-earth communication are the same bands desired by mobile carriers and ISM band users. Additionally, the atmosphere dramatically attenuates the signal from space. This results in even weak interference being able to prevent communication from satellites; this is highlighted by the accidental jamming of GPS receivers by LightSquared and their fourth generation (4G) mobile communications [29].

In the next five to ten years, the radio astronomy frequencies are expected to remain unchanged, but satellite communications channels will become more crowded as the navigation constellations of Russia (Global Navigation Satellite System, GLONASS), Europe (Galileo), and China (Beidou) all come online [30]. Additionally, amateur satellite bands are also likely to increase in use as private companies continue to develop space transportation.

There are several uses for the amateur and emerging bands aside from satellite communication [31, 32]. They are commonly used by amateur radio operators to attempt to communicate extremely long distances using short waves. Amateurs have been able to communicate using modems as well [33]. There are several other historic and emerging uses for spectrum that are specifically licensed for another application, not licensed at all (i.e., white spaces), or licensed for a new application. These include the numbered radio stations that broadcast patterns that are expected to be used for espionage communications [34–38], ultra wideband communications that communicate by raising and lowering the noise floor, or even high-frequency spectrum used for vehicle-to-vehicle and vehicle-to-road communications. These activities and others are expected to continue to proliferate and operate in segments of the spectrum for specific applications with limited interference from other unlicensed activity.

The exception to this is the expectation that electric grid communication will experience dramatic growth in both deployment and bandwidth within the next few years. Power lines are optimized to transmit high energy levels over long distances and are not designed for communications. As such, high frequencies transmitted along the power lines radiate at similar frequencies, as if being broadcast from an antenna. This is expected to become a significant problem in Europe, where power line Internet is a much larger industry than in other parts of the world. As communication frequencies are increased into the hundreds of megahertz, the radiated power is expected to begin to interfere with several wireless communication technologies in proximity to the power lines [39, 40].

While spectrum usage is expected to continue to expand at a rapid rate, there is no expectation of an increase in health risks. There have been several studies investigating the use of cell phones and potential links to cancer and other wireless health related hazards [41–47]. There is no substantial evidence that wireless devices inherently cause health risks. Research indicates that the greatest personal risk is due to the increase in automobile accidents as a result of distracted driving [48].

Future projections and alternative scenarios

There are two major factors in trend projections of the spectrum. The first factor is the increase in data demand and in the number of devices that communicate wirelessly. This results in an increase in the number of stations and the energy levels necessary to meet increased demand. This factor increases total noise. The second factor is the licensing of more bandwidth to mobile carriers and ISM services. This provides more spectrum to accommodate the demand and results in a decrease in total noise [49]. The most likely noise trends are outlined in table 1 on the following page.

TABLE 1. **Noise projections for 2011 through 2020**

Year	Total Utilized Bandwidth	Data Demand (norm.)	Data Efficiency	Spectrum Capacity	Hardware Data Gain Needed	Noise Increase
2010	700 MHz	1	1	1	0	0 dB
2011	750 MHz	3	1.26	1.35	2.22	3.45 dB
2012	800 MHz	9	1.59	1.817	4.593	6.57 dB
2013	900 MHz	18	2	2.571	7.001	8.42 dB
2014	1000 MHz	36	2.51	3.586	10.04	9.97 dB
2015	1100 MHz	54	3.16	4.966	10.87	10.33 dB
2016	1200 MHz	81	3.98	6.823	11.87	10.71 dB
2017	1300 MHz	121.5	5.01	9.304	13.06	11.12 dB
2018	1400 MHz	182.3	6.31	12.62	14.45	11.53 dB
2019	1500 MHz	273.4	7.94	17.01	16.07	11.95 dB
2020	1600 MHz	410.1	10	22.86	17.94	12.36 dB

Noise trends suggest that world governments should be expected to increase bandwidth allocated to wireless and ISM services by approximately 850 MHz between 2011 and 2020. It should also be expected that these opened bands (and current wireless and ISM frequencies) will all exhibit noise floors that are approximately 9 decibels (dB) above the 2011 noise floors of the wireless and ISM bands—especially in urban areas.

Assuming these projections are correct, there are also several key scenarios that may be of interest for specific frequencies and applications. The most likely future scenario is made apparent by the accidental jamming of GPS signals. LightSquared technology follows all bandwidth regulations for their spectrum license, but their communications interfere with GPS receivers because those receivers were built with less expensive filters that did not expect, and thus did not block, high energy levels in the adjacent bands. Simply put, the walls between the LightSquared and GPS conference rooms are thin, GPS is quiet, and LightSquared is very loud. Nobody in the GPS room can hear the talk because all they hear is LightSquared. This is not a major problem until other navigation satellites are launched because regulators will prevent LightSquared technology from being implemented if it will hinder satellite navigation. To prevent this, it is recommended that better filters be required on all GPS receivers manufactured from this point forward.

It is important to note that it is impossible to cancel noise in the spectrum. The only way to reduce interference is to prevent transmission in the first place. This creates an interesting scenario in which the only desirable bands (i.e., 500 MHz–5 GHz) that will have very limited interference worldwide will be those set aside for passive radio astronomy. Given the growing dependence on wireless communication for emergency response, interference to wireless communication could become a crippling threat. For this reason, it is expected that several entities may begin to develop secondary communication systems that are capable of operating in these "passive" protected bands, systems that are only activated in an emergency or major conflict.

The desirable mobile bandwidth of the spectrum is already extremely valuable. The economics of licensing, owning, and deploying devices have become influential; corporations ranging from Google to China Mobile significantly impact spectrum allocation decisions worth billions of dollars. The value of the spectrum in the third world is rapidly growing to match the developed world without the corresponding growth in domestic wealth. This could lead to a situation of economic imperialism where developed countries or global companies will be able to purchase huge amounts of spectrum in the developing world and monopolize the communication infrastructure there. Such shifts could generate political leverage in those regions and also create advantages for certain device manufactures that make products for those specific services.

In summary, radio communication has become a vital element of everyday life worldwide. Wireless communication is extremely commonplace and depended upon for a variety of activities ranging from phone communication to finding a restaurant for lunch. Interference noise caused by extensive use of the electromagnetic spectrum is constantly getting worse. This is causing significant economic and political pressures as mobile carriers and ISM band users try to acquire more spectrum to easily handle the greater usage and data rate demands. This is expected to cause an average of 850 MHz of more bandwidth to be allocated for ISM and mobile services worldwide between 2011 and 2020. Current and future frequencies used for consumer applications should still expect an average increase in the noise floor of about 9 dB above 2011 levels, and bandwidth will become so valuable that it will be better to use improved filters in applications like GPS than it is to maintain as much "white space" as is currently allocated to national interests.

About the author

Located in Richland, WA, **Pacific Northwest National Laboratory (PNNL)** is a US Department of Energy (DoE) national laboratory, managed by the DoE's Office of Science and operated by Battelle. PNNL's multidisciplinary scientific teams advance science and technology and deliver solutions to America's most intractable problems in energy, the environment, and national security. PNNL provides world-renowned scientists and engineers, facilities, and unique scientific equipment to strengthen US scientific foundations and advance scientific discovery through innovation.

References

[1] "Wireless personal computing." *Tech Trend Notes.* 1992;1(1):10.

[2] Pinola M. "What is wireless?" 2013. About.com guide [accessed 28 Mar 2013]. Available at: http://mobileoffice.about.com/od/glossary/g/wireless.htm

[3] Ghosh A, Zhang Z, Andrews JG, Muhamed R. *Fundamentals of LTE.* Boston (MA): Pearson Education; 2011. Chapter 1, "Evolution of cellular technologies"; p. 1–44. ISBN-13: 978-0-13-703311-9.

[4] International Telecommunication Union. "The world in 2013: ICT facts and figures." 27 Feb 2013 [accessed 28 Mar 2013]. Available at: http://www.itu.int/ITU-D/ict/facts/material/ICTFactsFigures2013.pdf

[5] "Advanced communications technology." *Tech Trend Notes.* 1992;1(1):7.

[6] "Synchronous Optical Networks (SONET)." *Tech Trend Notes.* 1992;1(2):13.

[7] International Telecommunication Union. *Radio Regulations, Edition of 2004,* Vol. 1. 2004. ISBN: 92-61-10661-7.

[8] International Telecommunication Union. "Frequently asked questions: What is meant by ISM applications and how are the related frequencies used?" Available at: http://www.itu.int/ITU-R/terrestrial/faq/index.html#g013

[9] US National Archives and Records Administration. "Operation in the band 433.5–434.5 MHz." *Code of Federal Regulations.* 47 C.F.R. Sec. 15.240 (2004).

[10] Signal Processing Group, Inc. "The ISM band—A review of the essentials." Available at: http://signalpro.biz/ism1.pdf

[11] Atheros Communications, Inc. "Worldwide Regulatory Progress for Wireless LANs." 2003. Available at: http://wirelesspt.net/arquivos/documentos/chips/Atheros_Regulatory_whitepaper.pdf

[12] Bluetooth. "Specification of the Bluetooth system." 2001;1. Available at: http://www.tscm.com/Bluetooth Spec.pdf

[13] IEEE. "Wireless medium access control (MAC) and physical layer (PHY) specifications for wireless personal area networks (WPANs), IEEE 802.15.1-2005." *IEEE Standard for Information Technology: Telecommunications and Information Exchange Between Systems—Local and Metropolitan Area Networks.* 2005.

[14] Norair JP. "Introduction to Dash7 Technologies." *RFID Journal.* 2009.

[15] OECD Directorate for Science, Technology, and Industry Committee for Information, Computer and Communications Policy. "RFID: Radio frequency identification. OECD Ministerial Meeting on the Future of the Internet Economy." Jun 2008, Seoul, Korea. Available at: http://www.oecd.org/sti/interneteconomy/40892347.pdf

[16] NFC Forum. "NFC activity technical specification." Nov 2010.

[17] Duckworth LL. "Advanced inventory and materials management at Pantex." In: *Proceedings of the 52nd Annual Meeting of Nuclear Materials Management;* Jul 2011, Palm Desert, CA: p. 2270.

[18] Bridgelall R. "Introducing a micro-wireless architecture for business activity sensing." In: *Proceedings of the 2008 IEEE International Conference on RFID;* Apr 2008, Las Vegas, NV: p. 156–164. DOI: 10.1109/RFID.2008.4519344.

[19] Cisco. "Cisco visual networking index: Global mobile data traffic forecast update, 2012–2017." Feb 2012. Available at: http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.html

[20] Industry Canada. "SP-5150 MHz—spectrum utilization policy for licence-exempt wireless local area networks in the 5 GHz Range." 2005;2. Available at: http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf01158.html

[21] McCann S, Ashley A. Official IEEE 802.11 working group project timelines. 2011 Nov 30. Available at: http://grouper.ieee.org/groups/802/11/Reports/802.11_Timelines.htm

[22] Wi-Fi Alliance. "Wi-Fi certified 802.11n draft 2.0: Longer-range, faster-throughput, multimedia-grade Wi-Fi networks," 2007. Available at: http://www.wi-fi.org/files/kc/WFA_802_11n_Industry_June07.pdf

[23] IEEE. "IEEE P802.11 Wireless LANs specification framework for TGac," 2011. Report No. IEEE 802.11-09/0992r21.

[24] Belanger P. "802.11n delivers better range." 2007 May 31. Wi-Fi Planet TechNet spotlight tutorial. *Wi-FiPlanet.com.* Available at: http://www.wi-fiplanet.com/tutorials/article.php/3680781

[25] Armstrong L, Fisher W. IEEE P802.11—Task group p—meeting update: Wireless accounts in vehicular environments (WAVE). Available at: http://www.ieee802.org/11/Reports/tgp_update.htm

[26] Farber D. [IP] [E-PRIV] [RFID] Dave Emory examines EZ Pass transponders. Interesting-People Message [personal communication]. 2004 Jul 9. Available at: http://www.interesting-people.org/archives/interesting-people/200407/msg00086.html

[27] Miller DF. *Basics of Radio Astronomy for the Goldstone-Apple Valley Radio Telescope.* Pasedena (CA): California Institute of Technology Jet Propulsion Laboratory. 1998. Document No. JPL D-13835.

[28] International Telecommunication Union. "Recommendation ITU-R RA.314-10: Preferred frequency bands for radio astronomical measurements." 2003 Jun. Available at: http://www.itu.int/dms_pubrec/itu-r/rec/ra/R-REC-RA.314-10-200306-I!!PDF-E.pdf

[29] National Coordination Office for Space-Based Positioning, Navigation, and Timing. "LightSquared and GPS." 2012 Sep 25. *GPS.gov.* Available at: http://www.pnt.gov/interference/lightsquared/

[30] Chong C. "Status of COMPASS/BeiDou development." Stanford University 2009 Position, Navigation, & Time Challenges and Opportunities Symposium; Oct 2009; Menlo Park, CA. Available at: http://scpnt.stanford.edu/pnt/PNT09/presentation_slides/3_Cao_Beidou_Status.pdf

[31] International Telecommunication Union. "ITU radio regulations—article 1, definitions of radio services." 2012 Oct 24. ICT Regulation Toolkit. Available at: http://www.ictregulationtoolkit.org/en/PracticeNote.2824.html

[32] Baruah S (VU2MUE, formally VU2MSY). "Frequency allocation to Amateur Radio Services." 2005 Jan 14. QSL.net. Available at: http://www.qsl.net/vu2msy/FREQ.htm

[33] Applegate AR. "A little amateur history." 2012 Dec 26. K0BG.com. Available at: http://www.k0bg.com/history.html

[34] Mäkeläinen M. "Monitoring Iraq: War of the airwaves." 2003 Feb 24. DXing.info. Available at: http://www.dxing.info/articles/iraq.dx

[35] Universal Radio Research. "Clandestine radio." 2003. DXing.com. Available at: http://www.dxing.com/clandest.htm

[36] Irdialani Limited. "The Conet project 1111: Recordings of shortwave numbers stations." 2012. Irdial-Discs. Available at: http://www.irdial.com/conet.htm

[37] Priyom.org [home page]. Available at: http://www.priyom.org/

[38] Sokol B. "Espionage is in the air." *Miami New Times.* 2001 Feb 8. Available at: http://www.miaminewtimes.com/2001-02-08/news/espionage-is-in-the-air/

[39] AMSAT: The Radio Amateur Satellite Corporation [home page]. Available at: http://www.amsat.org/amsat-new/

[40] Richards JC , Williams JV. "Potential interference from broadband over power line (BPL) systems to federal government radiocommunication systems at 1.7–80 MHz," 2007. National Telecommunications and Information Administration. NTIA Report 08-450.

[41] Lahkola A, Salminen T, Raitanen J, Heinävaara S, Schoemaker MJ, Christensen HC, Feychting M, Johansen C, Klaeboe L, Lönn S, Swerdlow AJ, Tynes T, Auvinen A. "Meningioma and mobile phone use—a collaborative case-control study in five North European countries." *International Journal of Epidemiology.* 2008;37(6):1304–1313. DOI: 10.1093/ije/dyn155

[42] Inskip PD, Hoover RN, Devesa SS. "Brain cancer incidence trends in relation to cellular telephone use in the United States." *Neuro-Oncology.* 2012;12(11):1147–1151. DOI: 10.1093/neuonc/noq077

[43] Khurana VG, Teo C, Kundi M, Hardell L, Carlberg M. "Cell phones and brain tumors: a review including the long-term epidemiologic data." *Surgical Neurology.* 2009;72(3):205–214. DOI: 10.1016/j.surneu.2009.01.019

[44] Sakurai T, Kiyokawa T, Narita E, Suzuki Y, Taki M, Miyakoshi J. "Analysis of gene expression in a human-derived glial cell line exposed to 2.45 GHz continuous radiofrequency electromagnetic fields." *Journal of Radiation Research.* 2011;52(2):185–192. DOI: 10.1269/jrr.10116

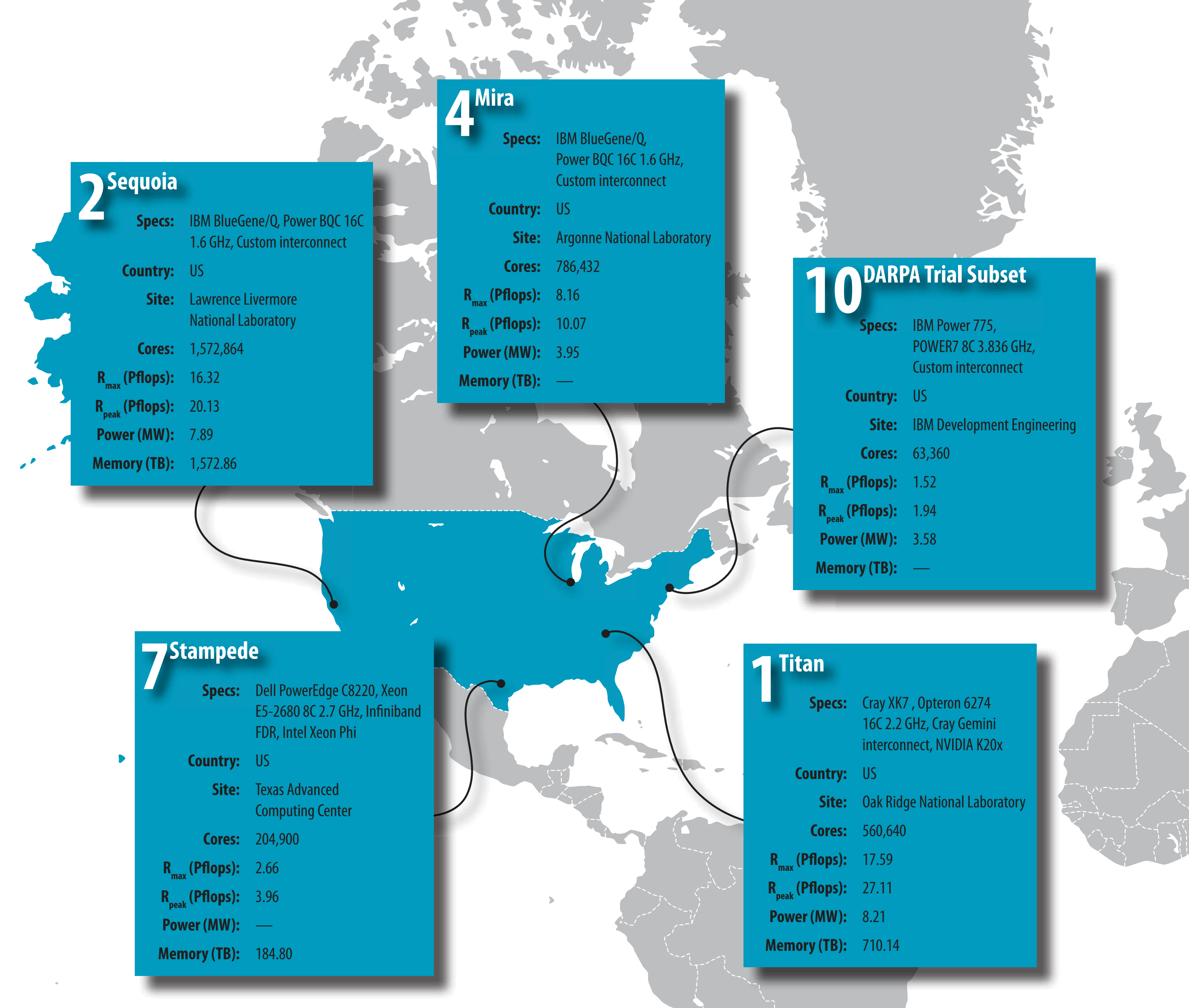
[45] Gerner C, Haudek V, Schandl U, Bayer E, Gundacker N, Hutter HP, Mosgoeller. "Increased protein synthesis by cells exposed to a 1,800-MHz radio-frequency mobile phone electromagnetic field, detected by proteome profiling." *International Archives of Occupational and Environmental Health.* 2010;83(6):691–702. DOI: 10.1007/s00420-010-0513-7

[46] Diem E, Schwarz C, Adlkofer F, Jahn O, Rüdiger H. "Non-thermal DNA breakage by mobile-phone radiation (1800 MHz) in human fibroblasts and in transformed GFSH-R17 rat granulosa cells in vitro." *Mutation Research-genetic Toxicology and Environmental Mutagenesis.* 2005;583(2):178–183. DOI: 10.1016/j.mrgentox.2005.03.006

[47] Lerchl A, Wilhelm AFX. "Critical comments on DNA breakage by mobile-phone electromagnetic fields." *Mutation Research-genetic Toxicology and Environmental Mutagenesis.* 2010;697(1–2): 60–65. DOI: 10.1016/j.mrgentox.2010.01.010

[48] Watkins ML, Amaya IA, Keller PE, Hughes MA, Beck ED. "Autonomous detection of distracted driving by cell phone." In: *Proceedings of the 14th International IEEE Conference on Intelligent Transportation Systems;* Oct 2011; Washington, DC; p. 1960–1965. DOI: 10.1109/ITSC.2011.6083026

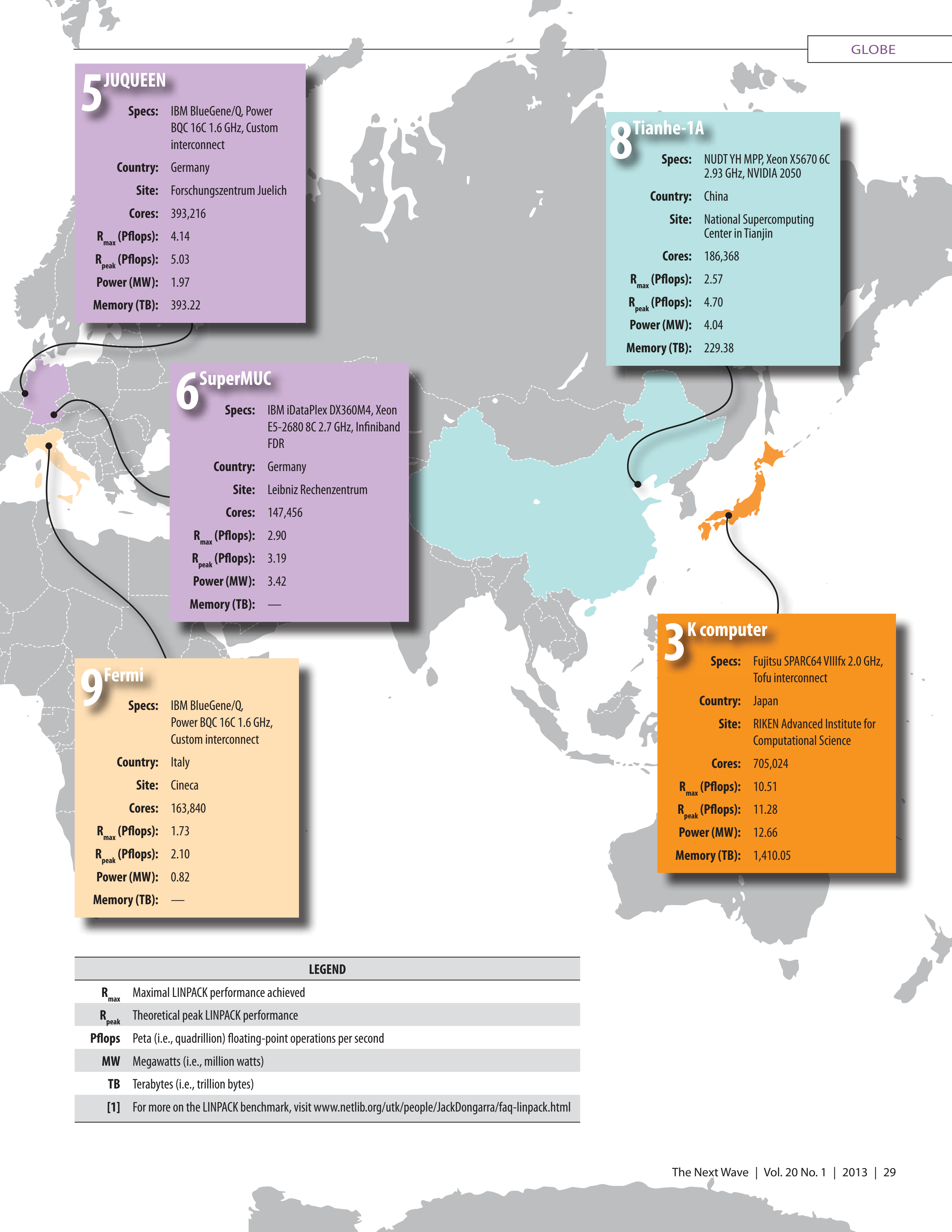
[49] International Telecommunication Union. "Estimated spectrum bandwidth requirements for the future development of IMT-2000 and IMT-Advanced," 2006. Report ITU-R M.2078.



GLOBE AT A GLANCE

TOP500's top 10 supercomputers

The TOP500 list ranks the 500 most powerful commercially available computer systems based on their ability to solve a dense system of linear equations (i.e., the LINPACK benchmark [1]). Therefore, any supercomputer—no matter its architecture—can make it into the list, as long as it is able to solve a dense system of linear equations using floating-point arithmetic. The following ranking is from November 2012. The list in its entirety is available at www.top500.org.



5 JUQUEEN

Specs: IBM BlueGene/Q, Power BQC 16C 1.6 GHz, Custom interconnect
Country: Germany
Site: Forschungszentrum Juelich
Cores: 393,216
R_{max} (Pflops): 4.14
R_{peak} (Pflops): 5.03
Power (MW): 1.97
Memory (TB): 393.22

8 Tianhe-1A

Specs: NUDT YH MPP, Xeon X5670 6C 2.93 GHz, NVIDIA 2050
Country: China
Site: National Supercomputing Center in Tianjin
Cores: 186,368
R_{max} (Pflops): 2.57
R_{peak} (Pflops): 4.70
Power (MW): 4.04
Memory (TB): 229.38

6 SuperMUC

Specs: IBM iDataPlex DX360M4, Xeon E5-2680 8C 2.7 GHz, Infiniband FDR
Country: Germany
Site: Leibniz Rechenzentrum
Cores: 147,456
R_{max} (Pflops): 2.90
R_{peak} (Pflops): 3.19
Power (MW): 3.42
Memory (TB): —

3 K computer

Specs: Fujitsu SPARC64 VIIIfx 2.0 GHz, Tofu interconnect
Country: Japan
Site: RIKEN Advanced Institute for Computational Science
Cores: 705,024
R_{max} (Pflops): 10.51
R_{peak} (Pflops): 11.28
Power (MW): 12.66
Memory (TB): 1,410.05

9 Fermi

Specs: IBM BlueGene/Q, Power BQC 16C 1.6 GHz, Custom interconnect
Country: Italy
Site: Cineca
Cores: 163,840
R_{max} (Pflops): 1.73
R_{peak} (Pflops): 2.10
Power (MW): 0.82
Memory (TB): —

LEGEND	
R_{max}	Maximal LINPACK performance achieved
R_{peak}	Theoretical peak LINPACK performance
Pflops	Peta (i.e., quadrillion) floating-point operations per second
MW	Megawatts (i.e., million watts)
TB	Terabytes (i.e., trillion bytes)
[1]	For more on the LINPACK benchmark, visit www.netlib.org/utk/people/JackDongarra/faq-linpack.html

POINTERS

SUPERCOMPUTERS

Supercomputers are extremely powerful, fast computers that are used for large-scale scientific calculations such as those found in quantum physics, weather forecasting, climate research, gas exploration, molecular modeling, and physical simulations (e.g., aircrafts and nuclear weapons). Twice a year since June of 1993, TOP500 has published a list that ranks the 500 most powerful commercially available supercomputers with help from high-performance computer experts, computational scientists, manufacturers, and the Internet community. TOP500 measures a supercomputer's performance based on its ability to solve a dense system of linear equations using floating-point arithmetic (i.e., the LINPACK benchmark).

In June of 1993, CM-5 was the number one supercomputer on the first ever TOP500 list. CM-5 performed 59.7 gigaflops on the LINPACK benchmark—that's approximately 59,700 billion floating-point operations (i.e., calculations) per second. Fast forward 20 years to November of 2012, and the number one supercomputer on the TOP500 list—Titan—performs 17,590 trillion calculations per second (i.e., 17.59 petaflops). Over the past 20 years, supercomputers have increased in performance at a rate of about 879,497 billion calculations per second per year. The systems listed in table 1 have occupied the number one position in the TOP500 list over that time.

TABLE 1. TOP SUPERCOMPUTERS FROM 06/1993–11/2012

Name	Country	Site	Manufacturer	Date in No. 1 Position
CM-5	US	Los Alamos National Laboratory	Thinking Machines Corporation	06/1993
Numerical Wind Tunnel	Japan	National Aerospace Laboratory of Japan	Fujitsu	11/1993, 11/1994, 06/1995, 11/1995
Intel XP/S 140 Paragon	US	Sandia National Laboratory	Intel	06/1994
Hitachi SR2201	Japan	University of Tokyo	Hitachi	06/1996
CP-PACS	Japan	Center for Computational Science, University of Tsukuba	Hitachi	11/1996
ASCI Red	US	Sandia National Laboratory	Intel	06/1997, 11/1997, 06/1998, 11/1998, 06/1999, 11/1999, 06/2000
ASCI White	US	Lawrence Livermore National Laboratory	IBM	11/2000, 06/2001, 11/2001
The Earth Simulator	Japan	Earth Simulator Center	NEC	06/2002, 11/2002, 06/2003, 11/2003, 06/2004
BlueGene/L	US	Lawrence Livermore National Laboratory	IBM	11/2004, 06/2005, 11/2005, 06/2006,11/2006, 06/2007
Roadrunner	US	Los Alamos National Laboratory	IBM	06/2008, 11/2008, 06/2009
Jaguar	US	Oak Ridge National Laboratory	Cray, Inc.	11/2009, 06/2010
Tianhe-1A	China	National Supercomputing Center in Tianjin	National University of Defense Technology	11/2010
K Computer	Japan	RIKEN Advanced Institute for Computational Science	Fujitsu	06/2011, 11/2011
Sequoia	US	Lawrence Livermore National Laboratory	IBM	06/2012
Titan	US	Oak Ridge National Laboratory	Cray, Inc.	11/2012

PERFORMANCE DEVELOPMENT

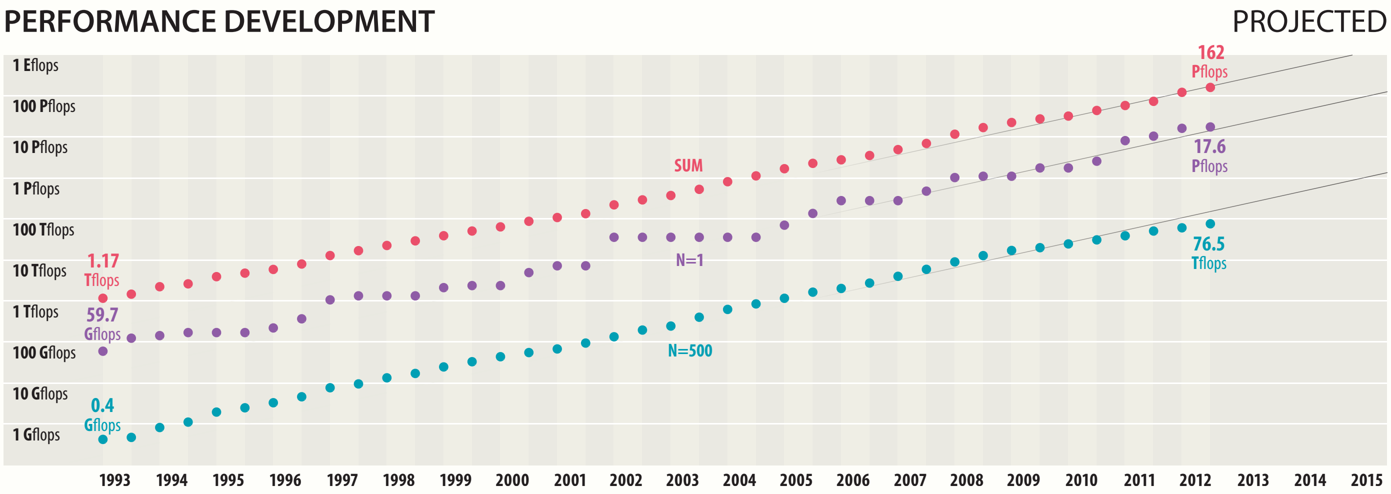


FIGURE 1. Over the past 20 years, supercomputer performance has increased from gigaflops in 1993 to teraflops in 1997 and then to petaflops in 2008. TOP500 projects that by 2018, the highest performing supercomputer will reach about 1 exaflops (i.e., quintillions of floating-point operations per second; not shown in figure).

The red data points show the sum LINPACK performance of all 500 supercomputers on the TOP500 list, the purple data points show the LINPACK performance of the top supercomputer (i.e., number one on the list) and the blue data points show the LINPACK performance of the bottom supercomputer (i.e., number 500 on the list).

ARCHITECTURES

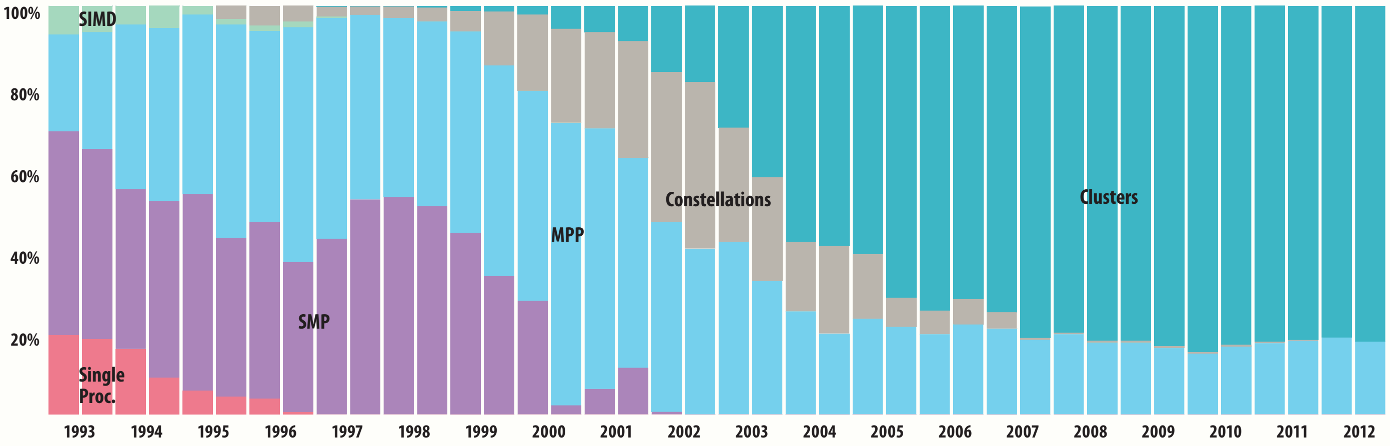


FIGURE 2. Since 2004, cluster computing has been the dominant computing architecture of supercomputers in the TOP500 list.

The number of processors and their configuration determine how a computer reads and carries out program instructions. A **single processor** allows a computer to carry out one instruction at a time. A multiprocessor allows a computer to carry out two or more instructions simultaneously.

In **symmetric multiprocessing (SMP)**, two or more identical processors are connected to a single shared main memory and controlled by a single operating system. In this kind of architecture, a computer system can execute multiple instructions simultaneously while drawing upon shared resources, which is useful for processes such as online transactions. In **massively parallel processing (MPP)**, two or more identical processors are each connected to a separate memory and are each controlled by a separate but identical operating system. An interconnect arrangement of data paths allows messages to be sent between processors. In an MPP architecture, the workload is essentially distributed across separate computers that communicate with one another so, for example, a number of databases can be searched in parallel.

Single instruction, multiple data (SIMD) processing is a form of parallel processing that lets one microinstruction operate at the same time on multiple data items, which is useful for processes involving multimedia applications. **Cluster computing** is another form of parallel processing that uses multiple separate computers, each having an SMP architecture, to form what appears to users as a single system. A cluster computing architecture is useful in handling traffic on high-traffic websites. **Constellation computing** is a cluster of symmetric multiprocessors.

*All figures are from TOP500 and have been modified for print.

The Oak Ridge Leadership Computing Facility is home to Titan, the world's most powerful supercomputer for open science (as of November 2012) with a theoretical peak performance exceeding 20 petaflops. That kind of computational capability—almost unimaginable—is on par with each of the world's 7 billion people being able to carry out 3 million calculations per second. (Image courtesy of Oak Ridge National Laboratory.)

CHIP TECHNOLOGY

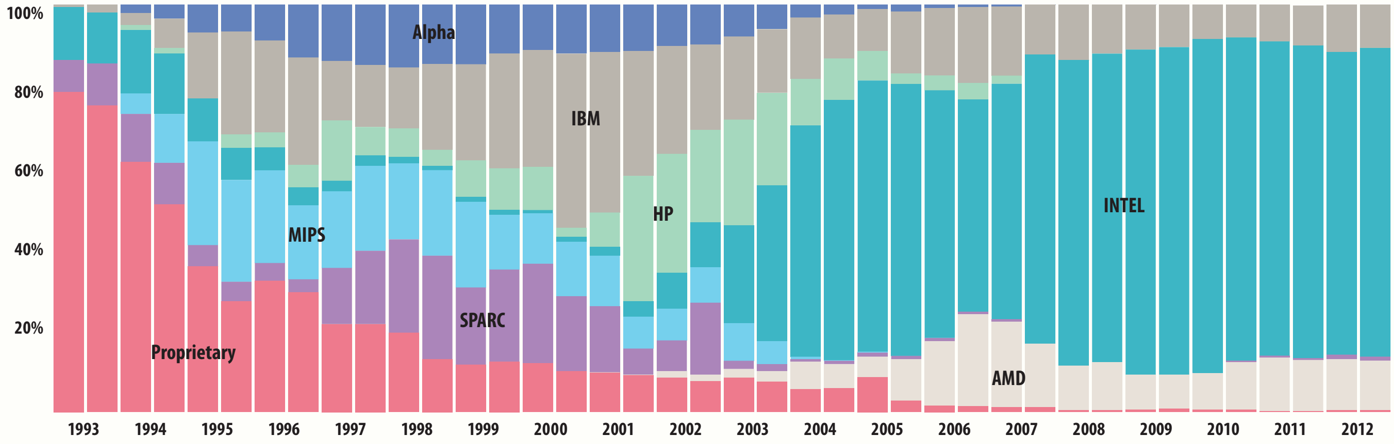


FIGURE 3. Since 2004, Intel Corporation has been the dominant manufacturer of chips in the supercomputers that made it into the TOP500 list.

INSTALLATION TYPE

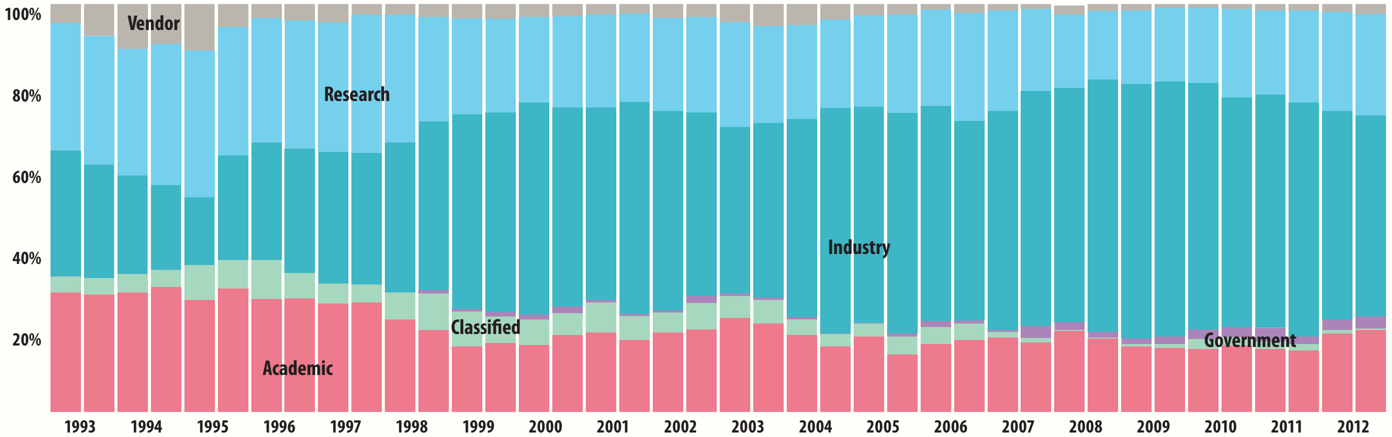


FIGURE 4. Supercomputers on the TOP500 list are used primarily in industry, research, and academia. Over 50% of them go to industry.

Twenty years of catching the next wave

The inaugural editions of *Tech Trend Notes,* the predecessor to *The Next Wave (TNW),* were small publications with few articles. Yet in their limited space, those early editions covered coming advancements in communications, networking, and information processing technologies. Perhaps most intriguing were articles on the revolution in wireless communications and personal computing that would lay the groundwork for the technological development of the next 20 years. For example, the first edition in June 1992 reported on the design and deployment of "multi-platform, multi-waveform radio," known today as software-defined radio. Unknown at the time, *Tech Trend Notes* was a look into the future.

Likewise, looking back 20 years at NSA's Technology Transfer Program (TTP), shows a small, struggling effort with a very limited portfolio of patented technology. A search of the US Patent and Trademark Office turns up only five (unclassified) patents issued between 1977 and 1992. However, these patents reveal a glimpse at what the portfolio has become today. For example, one patent issued in 1989 deals with planar optical logic, an optically controlled laser device for performing digital logic functions. Jump to 2012 and the TTP licensed a very large bundle of advanced photonics patents that describe breakthrough methods of silicon wafer manufacturing for optical devices.

The TTP now manages a portfolio of over 209 patents available for license in over 10 core areas including acoustics, advanced mathematics, communications, computer technology, information processing, microelectronics, networking, optics, security, and signals processing. From 2000–2011, NSA's TTP had a nationwide economic impact of $118 million including $70 million in value-added economic benefit, labor income of $58 million, and tax revenue of $17 million. Over 900 jobs were created or retained as a result of the TTP activities during this period.[a]

From its humble beginnings as *Tech Trend Notes, TNW* has matured into a professional electronic journal that highlights significant technical advancements within NSA's Research Directorate and beyond. In similar fashion, NSA's TTP has grown from a virtually unknown program to a highly successful mechanism for transferring taxpayer-funded research back to industry, providing economic income, and creating jobs. One can only imagine what *TNW* and the TTP will look like in 2033.

a. TechLink and Bureau of Business and Economic Research. "National economic impacts from DoD license agreements with U.S. industry 2000–2011." 2013 Feb. Available at: http://static.techlinkcenter.org/techlinkcenter.org/files/economic-impacts/DoD-Economic-Impact-Final-2.13.pdf

National Security Agency   Central Security Service

Defending Our Nation. Securing The Future