

# Spectrum Access Technologies: The Past, the Present, and the Future

*This paper reviews the key technological advances and regulatory decisions over the past century that have helped to enhance the use of the radio spectrum, and “lessons learned,” and concludes by offering a bold vision of future spectrum access technologies.*

By JEFFREY H. REED, *Fellow IEEE*, JENNIFER T. BERNHARD, *Fellow IEEE*, AND JUNG-MIN (JERRY) PARK, *Senior Member IEEE*

**ABSTRACT** | This paper provides an overview of how our access to the electromagnetic spectrum has evolved and will continue to expand over time. We first focus on the historical origins of technological and regulatory choices, and provide some insight into how these choices have impacted the efficiency with which we currently utilize the spectrum, and how we can better use it in the future. In turn, we summarize the relevant technologies being discussed in today’s standardization and research and development efforts. Finally, we provide a vision for the evolution of spectrum access technologies that, intertwined with progressive regulatory and economic policies, will enable flexible and secure sharing of spectrum to deliver seamless mobility with ubiquitous service for users worldwide.

**KEYWORDS** | Cognitive radio; dynamic spectrum access; spectrum access; spectrum coexistence; spectrum sharing

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**J. H. Reed** and **J.-M. Park** are with the Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061 USA (e-mail: reedjh@vt.edu; jungmin@vt.edu).

**J. T. Bernhard** is with the Electromagnetics Laboratory, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801 USA (e-mail: jbernarh@illinois.edu).

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## I. INTRODUCTION

Engineers and scientists have been developing technology to help better utilize and manage the electromagnetic spectrum for more than a century. Never has this activity been more relevant than today, with the wide proliferation of wireless devices that began in the 1990s. Certainly, over the past decades, wireless systems have been an economic and social driving force, increasing the productivity and well being of people around the world and changing the social fabric in ways not dreamed of even five years ago. However, the ability of wireless technology to continue to advance the conditions of our society globally is challenged by *spectrum overcrowding*, that is, the plateauing capacity of available spectrum to support the ever-increasing volume of wireless data traffic. In fact, wireless data traffic has already eclipsed wireless voice traffic [1].

This plateauing capacity has led to an accelerated pace of research and development into methods for improving spectral efficiency over the past few years, but we are far from solutions that will future-proof the spectrum and eliminate spectrum overcrowding for the next generation. Therefore, we must adopt innovative technological approaches that will add more freedom to the way that we use and regulate spectrum, but at the same time, the complexity of how we access spectrum will greatly increase.

In this paper, we briefly review some of the key technological advances and regulatory decisions of the past that helped to increase our ability to better use the spectrum. We also consider what lessons we can learn from this history to improve the prospects for the future. Then, we

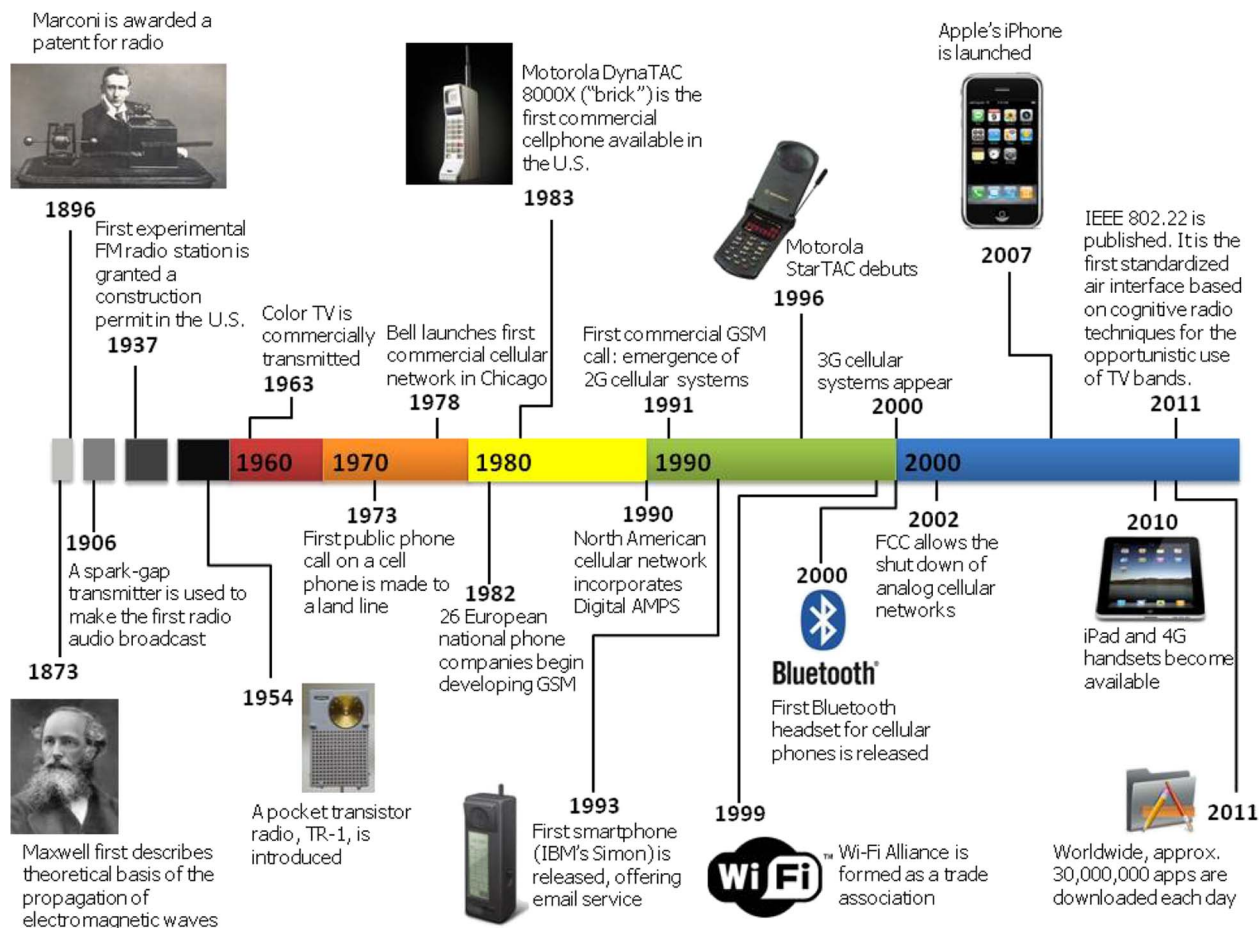


Fig. 1. A timeline of spectrum access technologies.

summarize the technologies being discussed in today’s research, development, and standardization efforts to address and improve spectrum efficiency. Finally, we imagine how spectrum access technologies of the future might banish spectrum overcrowding and enable truly seamless and ubiquitous wireless service.

## II. HISTORY OF SPECTRUM ACCESS TECHNOLOGIES

Over the past century or so, one of the major drivers of wireless technology development has been the quest for improved spectrum efficiency. A timeline of key technology innovations in spectrum access is illustrated in Fig. 1. Considering the first patented wireless communication device, the spark gap generator was patented by Marconi in 1896. The transmitter worked by creating a discharge that would create a corresponding signal at a receiving antenna.

Surely the spark gap generator was the first ultrawideband (UWB) device, creating significant energy from 10 kHz to 3 GHz, which, of course, ultimately limited it as a device for the next phase of wireless communication

technology that needed to serve more users. As the 100th anniversary of the sinking of the ocean liner Titanic approaches, it is worth noting that the signal-bleed characteristic of spark-gap transmitters played a role in the sinking of the ship.<sup>1</sup> What was needed was a more selective communications mechanism that allowed for multiple simultaneous transmissions. Amplitude modulation (AM) was the technical achievement that allowed this sharing, by varying the amplitude of a sinusoidal signal according to the volume level of the input audio signal.

In 1927, the International Radio Consultative Committee (CCIR) was founded, and in the same year, the CCIR recommended the ban on the use of spark-gap transmitters. This prescription provided the foundation for the band channelization approach to regulating spectrum that still exists today. Indeed, this was the only technically feasible approach in the 1930s when the regulatory framework for spectrum was being created. This is the

<sup>1</sup>On the fateful night of April 14, 1912, due to spark-gap transmitter-generated interference, the SS Californian—which was near the Titanic and aware of the icebergs in the vicinity—was unable to communicate iceberg warnings to the Titanic.

point in history when governments around the world began to strictly regulate transmissions, to designate which bands were used for which purposes, and to license the use of certain frequencies.

Research in the 1940s provided many of the key fundamental communications principles that would help in more fully addressing the issue of spectrum capacity (with assumptions imposed by the existing regulatory environment). Of course, the development of information theory by Shannon and others that derived fundamental bounds on the information capacity of a channel as a function of bandwidth and signal-to-noise ratio helped to define technology design goals by providing insight into what could be possible. By 1947, researchers at Bell Labs had grasped the concept of frequency reuse and its role for increasing capacity. This concept was clearly articulated in the 1950s, and finally implemented in the 1960s and 1970s. Cell reuse relies on signal attenuation and lower power transmitters to be able to reuse the spectrum spatially and support more users in a given area. It is the fundamental approach to providing increased capacity and even today remains the most powerful tool for increasing capacity under the existing regulatory framework.

Early attempts at mobile communications were a far cry from today's cellular systems—they were basically more like a radio dispatch system. Such early systems—sometimes referred to as precellular or zero-generation systems—include the Mobile Telephone Service in 1946, and Improved Mobile Telephone Service (IMTS) in 1964 that allowed for direct dialing, automatic channel selection, and reduced bandwidth. Other early examples of this technology include the 1952 launch of A-Netz in West Germany and the 1971 launch of Autoradiopuhelin (ARP) in Finland, both of which were the countries' first public commercial mobile phone networks. Still, these systems did not provide for sufficient capacity to meet demand.

Analog cellular systems [typically termed first generation (1G) technology] flourished in the 1970s, and cell splitting—reduction of power and adding more infrastructure—allowed more and more customers to be supported. In cell splitting, a cellular band is split into  $N$  subbands (called a reuse factor) and these bands are assigned to cells. Cells that use the same band are separated in distance by cells that are using different bands, thus minimizing interference between cells by virtue of propagation losses. If additional capacity is needed (which translates into the ability to handle more simultaneous calls), more cell sites are added, but the power of each cell site is reduced so that interference between sites does not occur. Thus, if the number of cell sites is doubled, the capacity in that area is also doubled. This approach, along with the development of new, more spectrally efficient technologies, has provided enormous gains in capacity to date, but unfortunately this approach may not be sustainable in the long run as the number of users and devices increases exponentially.

In 1979, Nippon Telegraph and Telephone (NTT) launched the world's first automated commercial cellular network (defined as using 1G technology) in Japan. Within the next five years, the NTT network was expanded to cover the entire population of Japan, and became the first nationwide 1G network.

In 1985, the U.S. Federal Communications Commission (FCC) provided unlicensed access to the industrial, scientific, and medical (ISM) bands [2]. This new approach to unlicensed, low-power access unleashed a flurry of new applications and technologies, including devices for WiFi, ZigBee, Bluetooth, and cordless phones. Before 1985, it was believed that these bands were nearly useless for communication due to interference from a number of sources, including microwave ovens and radio-frequency (RF) heating devices. Spread-spectrum modulation techniques, such as frequency hopping and direct sequence, which grew from military origins as mechanisms to thwart intentional jamming, made the ability to use these potentially polluted bands feasible. Spread-spectrum modulations often result in more efficient use of spectrum than simple channelization, and the introduction of these interference-robust technologies made the ISM bands useful and valuable for unlicensed device use. This example also provides powerful evidence of the technological, economic, and societal impact of shared spectrum access.

The 1991 launch of the first Global System for Mobile Communications (GSM) network in Finland ushered in the age of second-generation (2G) mobile phone systems. Switching to digital transmission with the advent of 2G cellular systems enabled huge gains in capacity. In analog cellular systems, a single RF channel corresponded to one voice connection. Digital systems allowed multiple-access techniques such as time division multiple access (time sharing of an RF channel) so that multiple users could share an RF channel. In the case of GSM, up to eight users were able to share a single RF channel using TDMA. Code division multiple access (CDMA), a form of direct sequence spread spectrum, was another approach for users to share a single RF channel, separating users through implementation of unique spreading codes. CDMA was used in the 2G system IS-95 as well as in third-generation (3G) systems such as CDMA 2000 and W-CDMA (which followed the GSM standard). Spread-spectrum techniques became attractive for 3G systems because of capacity gains that were possible, since the interference robustness of spread spectrum allowed all channels to be used at each cell site.

Digital 2G systems also allowed other innovations for improving spectral efficiency. Use of source-coding techniques (termed vocoders) reduced the amount of data that needed to be transmitted to reconstruct the voice signal. Basically, instead of sending digitized voice, a model of the voice was sent so that it could be reconstructed, which enables a much lower data rate to support voice. As vocoders improved, as many as 16 users could be

supported by GSM in a single RF channel. Note that the data rate did not improve, rather it was an improvement in the *effectiveness* of the data that gave the appearance of a capacity increase. Likewise, scheduling techniques (being able to provide data in a time slot representing an idle point of a voice conversation) provided more effective data transfer and have become a very important aspect of today's communication protocols. Sophisticated techniques have been developed to match channel quality and availability and the application quality of service (QoS) needs to the physical-layer resources at hand. Errors caused by impairments of the RF channel can cause inefficiencies in data transfer because of the need to retransmit corrupted data. Methods such as hybrid automatic repeat request (H-ARQ), which allowed only a partial retransmission of data, greatly reduced this inefficiency. Adaptive modulation and coding allowed transmission to occur at a rate that could be effectively handled by the current channel conditions. Adaptive sizing of packets was an innovation that allowed the packet size to be long and efficient in good channels, or shorter, to be more responsive and require less overall overhead in poor channels. The lesson from this experience with 2G systems is that the traditional spectrum efficiency metric of capacity in bits per second per hertz (a metric predicated on the availability of dedicated bandwidth) is inadequate, and a more *useful* metric is the number of useful bits per second per square meter of area while ensuring the QoS requirements of a variety of users' needs. In other words, a better metric should capture whether users can all obtain the necessary spectrum capacity to achieve their goals—for communication, entertainment, education, or any other purpose. Such metrics have yet to be defined.

As the demand for data services (such as access to the Internet) and greater data speeds grew, it became clear that the 2G technology was inadequate to meet these needs. With the advent of 3G systems, such as the Universal Mobile Telecommunications System (UMTS), significant improvements in capacity and data speeds were possible. The primary difference that distinguishes 3G technology from 2G technology is the ability to better handle data.

### III. STATE OF SPECTRUM ACCESS AND NEAR-TERM TRENDS

The explosive growth in the demand for high-throughput data applications has driven the need to develop 4G networks. 4G systems, such as long-term evolution (LTE) and WiMAX, adopted new strategies for improving spectrum utilization using orthogonal frequency division multiple access (OFDMA) and multiple-input–multiple-output (MIMO) approaches (which are also used in WiFi). OFDMA can be viewed as multiple carriers (hundreds, or even thousands) each spaced the minimal distance from the other carrier and modulated with data. The aggregate data rate can be quite high with OFDMA and scheduling

users' traffic can be done both in frequency and in time, giving a great deal of flexibility to accommodate many users with a target QoS. MIMO relies on transmitters and receivers, each with multiple antennas that take advantage of propagation path diversity in high-electromagnetic-scattering environments to deliver parallel, statistically uncorrelated channels. Much of the work in MIMO occurred in the 1990s, but its roots can be traced back to the 1970s [3], [4]. The most commonly used standard that allows for MIMO implementation today is 802.11n. Cellular systems are just emerging that utilize MIMO approaches.

Research over the past ten years has pointed to a new path for improving spectrum efficiency. Pioneering work by the Shared Spectrum Company [5] and the University of Kansas in their survey of spectrum usage showed that the average occupancy of spectrum was quite low. Additionally, their results indicated that although spectrum in some areas could be heavily used, in other areas it may be very underutilized. The conclusion drawn from this research was that rigid allocation of spectrum created this inefficiency. The Defense Advanced Research Projects Agency (DARPA) neXt Generation (XG)<sup>2</sup> program sought to examine how spectrum could be used on a more adaptive basis [6]. The basic idea was that transmissions could be scheduled on an *ad hoc* basis, and by sensing the energy in the spectrum, channels could be selected to avoid causing or receiving interference. This approach is generally termed dynamic spectrum access (DSA). Also during this time, a framework for adding intelligence to communication systems, called cognitive radio, was being developed [7]. Often, cognitive radio and DSA are used synonymously, but they are not equivalent. In a cognitive radio, intelligence is incorporated into the radio resource management, which might include selection of operating frequency but could also include other parameters as well. DSA provides agility to use the spectrum in a way to avoid interference, but it may or may not incorporate system intelligence capabilities into this process. Both of these concepts blend well with the new concept of adaptive spectrum management, in contrast to current compartmentalized spectrum allocations, and also point to a metric of spectrum efficiency that accounts for apparent capacity gains achieved through spectrum sharing rather than simply bits per second per hertz.

The increasing importance of transitioning research results into deployable systems has brought about a heightened emphasis on experimental research. Noteworthy projects include the Global Environment for Network Innovations (GENI) project [8] and the Cognitive Radio Experimentation World (CREW) project [9]. GENI is a project spearheaded by the U.S. computing community

<sup>2</sup>The XG program is a technology development project sponsored by DARPA with the goals of developing both enabling technologies and concepts for dynamic spectrum access as well as novel waveforms to enhance military communications.



with support from the U.S. National Science Foundation. The primary goal of this program is to improve experimental research capabilities in networking and distributed systems, and to expedite the transition of the research findings into products and services. CREW is a European experiment-driven research thrust on cognitive radio technology. CREW uses an infrastructure of federated testbeds to address challenges specific to cognitive network and dynamic spectrum access research, and the results of this testbed work are expected to greatly impact the design of future systems.

Today, we have generally two methods for managing and accessing spectrum. One is licensed access, and systems in this category include land mobile radio (LMR) systems, such as radios used by emergency services; satellite communication systems; and, most commonly, cellular communication systems. Typically, these systems are characterized by strict requirements on usage of the band, exhaustive planning to reduce interference and enhance reliability, and homogeneous networks. On the other hand, unlicensed access, for example, consists of systems such as WiFi, Bluetooth, cordless phones, ZigBee, and others. Typically, these systems are characterized by low power, short range, and at times spotty reliability, particularly since heterogeneous systems share the same bands. Ironically, since cellular service providers are running low on spectrum resources, several have sought to offload a portion of their wireless traffic onto local WiFi systems to combat spectrum overcrowding in densely populated areas.

A third category of access is currently emerging, which is termed “managed access.” Notionally, managed access can exist in a framework of licensed users and/or unlicensed users where access to the spectrum is directed by a set of policies. Policies may include giving priority to legacy or licensed users or restriction on when and where certain devices can be used. Permission to use the spectrum might be granted by some geographical database and/or by the device’s policy engine that uses observations of the spectrum utilization before it permits the device to transmit (such as the case for DSA). This approach has its advantages and disadvantages, mixing characteristics of both licensed and unlicensed approaches. Advantages include the ability to utilize spectrum, perhaps even spectrum that is currently designated for legacy users, when it is idle. Mixing access between licensed and unlicensed users, spectrum utilization may be more effective, even with priorities given to licensed users. In some planned embodiments, managed access also provides a modest amount of coordination between heterogeneous networks. In the managed access paradigm, heterogeneous unlicensed and licensed wireless devices/networks may operate in the same frequency band within interference range of each other. All of this potential has not gone unnoticed, and several recent standardization activities have incorporated managed access concepts. Some of these standardization activities are listed in Table 1.

Table 1 Standardization Activities Relevant to Managed Access

Standard	Description	Web Reference
DySPAN-SC (formerly SCC41)	Standards for dynamic spectrum access systems and networks with a focus on improved use of spectrum.	[10]
802.11af	It is an amendment that defines modifications to the PHY/MAC layers of 802.11 to meet the requirements for spectrum access and coexistence in TV white spaces.	[11]
802.22	It defines the air interface of point-to-multipoint wireless regional area networks (WRAN) operating in TV white spaces.	[12]
ECMA 392	It specifies PHY and MAC layers for a wireless personal area network (WPAN) that is used for multimedia distribution and Internet access.	[13]
Cognitive TD-LTE	Requirements and case studies are being developed by the Wireless Innovations Forum to be able to use white space.	[14]
802.19	It is the Wireless Coexistence Technical Advisory Group (TAG) within the IEEE 802 LAN/MAN Standards Committee. The TAG deals with coexistence between unlicensed wireless networks.	[15]

In the near-term, perhaps the most interesting and highest impact of these standardization efforts is in third-generation partnership project (3GPP) with the ongoing standardization of LTE-Advanced. Two initiatives stand out: self-organizing networks (SONs) and LTE coordinated multiple point (CoMP). SON works to prevent faults, and optimize the network performance for capacity, reliability, and coverage, all with minimal human intervention. This is especially important since capacity growth under this operational model relies again on a familiar idea—cell splitting—and hence will require smaller and smaller cells. The notion of increasing capacity by using smaller cells is being instantiated in another way—viz., femtocells [16]. A femtocell, also called a home base station, is a data access point installed by home users to improve indoor wireless coverage. The strategy of increasing capacity by deploying a greater number of base stations with smaller coverage areas and the widespread adoption of femtocells are expected to exponentially increase the operational cost of configuring and optimizing the parameters of these networks. These trends in radio access networks are the main motivation for SONs.

LTE CoMP is being developed in LTE-Advanced as a mechanism for using multiple base stations (eNBs) to coordinate scheduling, transmissions, and joint processing of the received signal to improve reception to reduce interference and increase throughput, particularly at cell edges. A variety of techniques and algorithms are used to accomplish this, including simultaneous transmission/reception of user

data from multiple eNBs to individual devices. “Macro-diversity” is used at the base stations to combine the signal from the mobile devices received across multiple base stations to increase signal power and reduce interference (similar to the softer handover techniques used in CDMA2000). According to a recent report commissioned by the Office of Communications (Ofcom),<sup>3</sup> spectral efficiency for LTE-Advanced has the opportunity to greatly increase capacity with the eventual deployment of CoMP [17]. This philosophy of coordinated base stations will continue to be a theme in emerging systems.

Another potential innovation for LTE is carrier aggregation (or channel aggregation). Carrier aggregation has many benefits for spectrum utilization, where the aggregated channels may be contiguous in the spectrum, disjoint in the same spectrum, or in completely different bands. Without carrier aggregation, the smaller bands have limited utility, since they cannot support the user data rates or overall system throughput needs. This is especially true when transitioning technology. An example would be the possibility of repurposing some GSM channels in an active band, and filling in sections of this spectrum with LTE using carrier aggregation. Of course, this approach poses some interesting challenges for both the hardware and software that have yet to be resolved.

Finally, with heterogeneous devices, the coexistence problem is complex, and standards for defining the techniques and mechanisms for coexistence among dissimilar devices/networks are needed. IEEE 802.19 is the Wireless Coexistence Technical Advisory Group (TAG) within the IEEE 802 Standards Committee, which is tasked with defining such standards. The 802.19 TAG recently formed a new task group (TG) called 802.19 TG1. This TG has been chartered with the task of developing a standard for TV white space coexistence methods.

Obviously, what many consider the prime spectrum below 3 GHz has many desirable non-line-of-sight propagation characteristics that make it very suitable for a number of communication applications—hence, all of these aforementioned standardization activities try to squeeze as much capacity as possible from existing and newly vacated bands of spectrum. Of course, much of the spectrum in these bands has long been allocated and reallocated, and so it is natural to repeat history and go higher in frequency to find unallocated or underused spectrum. Certainly, going to higher frequencies is feasible in some cases, and is currently occurring under certain applications (such as high-throughput, short distance data transfers) (e.g., [18], [19]). However, there are just some operating scenarios, such as longer distance and outdoor

transmission in rural areas, that this spectrum will not support well without large expenditures in infrastructure.

#### IV. THE FUTURE OF SPECTRUM ACCESS TECHNOLOGIES

Our current method of rigid spectrum band allocations for specific purposes or systems such as broadcast television and radio, cellular systems, or radar was adopted as a way to manage interference from these dissimilar systems. The technological capabilities of the time dictated this approach. This regulation paradigm has now resulted in spectrum overcrowding that cannot be addressed in a sustainable way without significant adjustments in how spectrum is used and shared. We now need to develop more flexible and reconfigurable hardware and software to support this sharing. The electromagnetic spectrum is a resource, and the future holds tremendous promise for both greater access to and greater utility from this resource through new approaches to spectrum access that embrace spectrum sharing in its myriad forms.

Keeping the lessons of history and the current state of the art in mind, what is the outlook for spectrum access technologies? As the previous discussion has outlined, preliminary steps are being made in the research community to develop and demonstrate the potential of spectrum sharing technologies, but this is really only the beginning. As a starting point, one can certainly build upon the developments outlined in the previous section to implement managed access (or dynamic spectrum access) on a broader scale. Enabled by agile RF hardware (including antennas and radio front ends), this kind of spectrum access will allow our wireless devices to select operating frequencies, signaling properties, and protocols based on information obtained either through access to a locally sensed, locally updated database of available spectrum for that particular location [20], or using more sophisticated technology, sense their own electromagnetic environments with onboard hardware, and select unused channels.

Managed access, however, is an approach derived from a presupposition of exclusive use to a channel, ideally with no interference. However, next generations of spectrum access technologies will move toward interference-tolerant architectures, protocols, and hardware embodiments [21]. These new design approaches could include concepts from cognitive radio [7], where each wireless device learns about its electromagnetic and propagation environment through coordinated sensing with multiple antennas and/or collaboration with other devices. It will then be able to make decisions about how to behave based on this information as well as its own operational goals. One can imagine, then, that this cognition would leverage more than just simple frequency sensing and move into the spatial and time dimensions of the electromagnetic environment as well, perhaps even in collaboration with other similar devices in the network. For instance, information

<sup>3</sup>Ofcom is the government-approved regulatory authority that regulates the telecommunications and broadcasting industries in the United Kingdom.

about the direction of arrival of potentially interfering signals [22] could be used to adjust antennas and radio parameters of the receiving device and interfering device to reduce the levels of interfering signals [23], rather than finding an unoccupied channel at a different operating frequency. Transmission waveforms can be designed and coordinated between users so that they lend themselves to both straightforward mitigation at unintended receivers and robust detection at intended receivers. Sophisticated but miniaturized receivers, leveraging compact adaptive antenna arrays paired with wideband tunable filters and amplifiers could also be developed to sense, characterize, and mitigate interference as well as incorporate more interference-tolerant architectures and signaling protocols. Eventually, a “smart network” may even leverage continually updated propagation models, information about trends in spectrum usage, and a global picture of devices’ mobility and application demands to *anticipate* spectrum needs and provision spectrum resources accordingly. This is a particularly salient issue for the development of future radar and remote sensing systems, which currently occupy many bands below 3.5 GHz—frequency bands that could be ripe for sharing in the medium term if new designs for these systems and wireless devices are made more interference tolerant.

Even more exciting is the prospect of being able to rapidly introduce new devices and applications, a combination of truly reconfigurable hardware and software platforms with over-the-air upgradeable spectrum sharing and security policies.<sup>4</sup> This kind of “on-the-fly” adjustment of spectrum sharing policies and security protocols will be useful for incorporation and enforcement of new standards, regulations, and etiquettes. These policies and protocols could be based on incredibly diverse operational factors, such as local geography and electromagnetic propagation conditions, required actions to thwart potential hackers or rogue transmitters, policy rules that mandate operational coexistence with incumbent radar systems, and prioritized access for public safety personnel. Moreover, the ability to change policies, even after new equipment is developed, should reduce risks for both regulators and technology leaders, promoting widespread innovations in new technologies. This will also allow us to be more agile in both implementing more spectrum efficient technologies and retiring legacy systems.<sup>5</sup>

Extrapolating these kinds of ideas well beyond what is possible today, what will spectrum access technologies look like 100 years into the future? In its ultimate em-

<sup>4</sup>New spectrum access technologies create both security vulnerabilities and opportunities. See [24] and [25] for examples.

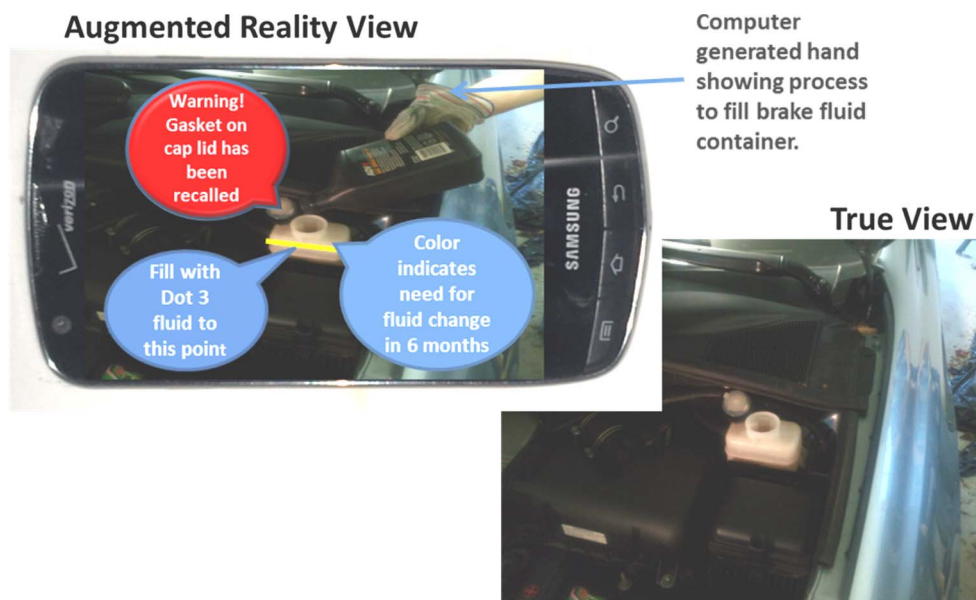
<sup>5</sup>It took over 50 years between the invention of spread-spectrum techniques and mass deployment in cellular products. Given the rapid growth in wireless communication applications, we cannot wait 50 years between an initial invention and its wide-scale commercial deployment. It took nearly 30 years before (spectrum-hungry) analog cellular disappeared in the United States and it will likely be 25 years or more after GSM’s first deployment before it disappears from the United States.

bodiment, the network itself (including all mobile devices and “spectrum access ports” equipped with advanced radio hardware and software) will be collaborative, self-configuring, self-monitoring, self-correcting, self-policing, self-maintaining, and self-optimizing. Hardware and software will be completely integrated and inseparable—separate domains for analog and digital hardware and signal processing will no longer exist, even at the antenna. Advances springing from physics-based modulation schemes, such as directional modulation (e.g., [26]), will provide both secure and interference-tolerant connections. Additional security and assurance could be based on local wireless channel conditions (e.g., [27]). Wideband, tunable radios with their starting point in this century (e.g., [28]) will enable seamless operation over decades of bandwidth based on reconfigurable electrical, mechanical, and material parameters. Advances in materials science and fabrication techniques with their origins in today’s innovations (e.g., [29] and [30]) will support development of structurally integrated and wearable (and washable) antennas and radios. Research and development well beyond today’s state of the art (e.g., [31]) in electronic materials, thermal management, and fabrication processes will make 3-D system integration the norm. Each wireless connection will have no predetermined capacity assumptions—the distinction between downlinks and uplinks will disappear, enabling new kinds of applications yet to be conceived (see Fig. 2 for a notional example.)

Moreover, spectrum access devices will be *infrastructure independent*, truly using whatever kinds of wireless connections are possible or likely to deliver the most appropriate quality of service (even multiplexing over wide swaths of the spectrum) to achieve their operational goals, within some negotiated or predefined constraints of etiquettes and economic arrangements. In other words, our grandchildren and great grandchildren will be accustomed to seamless mobility with ubiquitous service. A century from now, wireless connectivity will simply be a utility integrated seamlessly into our daily lives, along with electricity, energy systems for heating/cooling, and fresh running water. Just as we have many electrical outlets in a room today (and associated building codes), every built structure will have numerous radio ports in each room, flexible enough to accommodate any current or future radio within that room, and with an automatic spectrum management process for that space that will allow coexistence of numerous devices without the need for human intervention. A phrase that might best capture the essence of spectrum access technologies of the next century is “Unplug n’ Play.”

## V. CONCLUSION

History teaches us that spectrum access drives economic growth and productivity. The current approach to spectrum management started with the need to avoid



**Fig. 2.** An application that utilizes augmented reality as an aide in adding brake fluid to a car by enabling the superposition of computer-generated video information over the field of view of reality. Such applications will certainly challenge the usual wireless traffic model assumption that more information flows from a base station to the wireless device than vice versa. As these applications emerge, the fundamental assumptions of capacity needs and hardware capabilities for both ends of this notional link will need to be reconsidered. Flexible and agile spectrum access technology will simply be necessary to accommodate these kinds of disruptive applications.

interference with spark-gap transmissions. To solve this issue, we adopted rigid regulations and compartmentalization of spectrum, and our technology development followed. While this approach reduced the interference issue in the first century of radio, it does not now lend itself to efficient spectrum use. As we witness the ever-increasing rate of change in technology capabilities, we must find technological ways (matched with progressive regulatory and economic policies) to transition spectrum from being used exclusively by legacy technology to being used fluidly for new applications and devices as they emerge.

The next century of radio calls for new paradigms that support “coexistence spectrum management,” viewing spectrum as an open resource, perhaps not completely

free of interference, but a resource more effectively and efficiently used. Flexible utilization of the spectrum will lay the foundation for broad innovation and growth, not only in technology, but also, as history has shown, in the economic and societal benefits that come with this new technology. ■

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#### ABOUT THE AUTHORS

**Jeffrey H. Reed** (Fellow, IEEE) received the Ph.D. degree from the University of California, Davis in 1987.

He is the Willis G. Worcester Professor in the Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic and State University, Blacksburg. From June 2000 to June 2002, he was Director of the Mobile and Portable Radio Research Group. In 2005, he founded Wireless at Virginia Tech and is currently serving as Director. He is cofounder of Cognitive Radio Technologies, LLC and Power Fingerprinting, Inc. His area of expertise is in software radios, cognitive radio, wireless networks, and communications signal processing.

Prof. Reed is a Distinguished Lecturer for the IEEE Vehicular Technology Society.



**Jung-Min (Jerry) Park** (Senior Member, IEEE) received the Ph.D. degree in electrical and computer engineering from Purdue University, West Lafayette, IN, in 2003.

He is an Associate Professor in the Department of Electrical and Computer Engineering, Virginia Polytechnic and State University, Blacksburg, where he is the Director of the Advanced Research in Information Assurance and Security (ARIAS) Lab. He has held an industry position at Motorola Korea, Inc. His research interests include cognitive radio networks, wireless networking, network security, and cryptographic protocols.

Prof. Park is a recipient of a 2008 National Science Foundation (NSF) CAREER Award and a corecipient of the 2008 Hoeber Excellence in Research Award and a 1998 AT&T Leadership Award. He is a Senior Member of the Association for Computing Machinery (ACM).



**Jennifer T. Bernhard** (Fellow, IEEE) received the Ph.D. degree in electrical engineering from Duke University, Durham, NC, in 1994.

She is a Professor in the Electromagnetics Laboratory, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana. Her research interests include reconfigurable and wideband microwave antennas and circuits, wireless sensors and sensor networks, high-speed wireless data communication, and electromagnetic compatibility.

Prof. Bernhard is the recipient of a National Science Foundation (NSF) CAREER Award (2000) and the Wheeler Prize Paper Award (2004). She served as the President of the IEEE Antennas and Propagation Society in 2008.

