SCANNING THE ISSUE

Future Radio Spectrum Access

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This special issue of the Proceedings of the IEEE focuses on the challenges and opportunities related to future access to the radio spectrum. The importance of this topic is underscored by the tremendous growth in spectrum-consuming technology, driven in part by the global growth in smartphones and tablets. But demand is also driven by an enormous variety of other important applications, such as command and payload signals for unmanned aerial vehicles; vehicular radars for improved safety on the roads; radionavigation-satellite applications including GPS and Galileo; TV and Internet service through terrestrial and satellite delivery; science applications such as remote sensing and radio astronomy; and countless others.

This Special Issue focuses on challenges and opportunities related to future access to the radio spectrum which is an extremely important topic underscored by the tremendous growth in spectrum-consuming technology.

Competition for use of radio spectrum resources is at an all-time high, and continues to grow. The common perception is that available bandwidth will soon be insufficient to meet demand. Whether the shortage of radio spectrum is real, or it is simply an artifact created by inefficient management of available bandwidth, is an active topic of debate. Common wisdom is that it is the latter: In most national regulatory frameworks, spectrum is managed today pretty much the same way it has been for the past 60+ years—each spectrum band is allocated to one or a few broadly defined services, and within each service, specific frequencies are assigned for the exclusive use of a single licensee in a particular geographic area. The process is akin to an entire highway lane being assigned to a single company, and the lane is reserved for that company at all times, whether they are using it or not. The gross inefficiencies in allocating resources in this manner are readily apparent.

Why not just open all highway lanes to shared use? For the very reason that spectrum has been managed in one particular fashion for so long, adopting new ways to deal with the artificial shortage is itself a daunting challenge. If you are a driver that has enjoyed your own reserved lane for many years, then opening the highway for shared access does not seem (to you) to be a good idea. There are many good ideas for improving the way bandwidth is allocated and assigned, but moving away from current practice is a major undertaking. It is not just engineering and physics that come into play, but also economics, law, public policy, social science, and human nature. The stakeholder community is also broad: the general public is a major consumer of bandwidth, but so are governments, public safety, industrial operations, and virtually every other sector of the global community.

As spectrum occupancy measurements show,[1] much spectrum appears to be unused for much of the time, even in densely populated urban environments. Such observations have been one component of the push toward dynamic spectrum access (DSA), in which policy and technology are being developed to allow secondary users to access momentarily unused spectrum, with the caveat that such use creates no (or minimal) impact to the primary user of the frequency. To be successful, spectrum sharing through

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[1] See, for example, Shared Spectrum Company, Spectrum Reports, 2004–2009, http://www.sharedspectrum.com/papers/spectrum-reports/

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DSA requires a variety of technology developments in hardware and software, and adoption of new and revised spectrum management policies that transcend traditional regulatory frameworks.

In the first paper of this special issue, Dudley *et al.* introduce some of the practical spectrum management issues that impact the adoption of cognitive radio technology. Cognitive radios are a prime component of DSA, allowing radios to understand and adapt to the environment in which they are operating. But traditional spectrum management policies typically presume that radio hardware capabilities are static and finite, and present-day service rules governing their operation have been written accordingly. Dudley *et al.* address considerations related to licensing models, hardware capabilities, policy and its enforcement in the cognitive radio context, and security, among other important topics.

Many of the concepts and policies that will dictate shared spectrum use rely on an understanding of what constitutes interference between radio systems. In the international regulations, and most national regulations, the concept of "harmful interference" has been formally defined. However, in an insightful contribution by Marcus, we find that the formal definition is woefully lacking from a technical and enforcement perspective. He further argues that uncertainty surrounding what exactly constitutes harmful interference may suppress the development and adoption of new spectrum-sharing technology.

Primary users of the radio spectrum who are faced with sharing their previously exclusive bandwidth with new secondary users, and secondary users who must share among themselves, are understandably concerned that new spectrum-sharing policies must be strongly enforced to avoid service degradation and interruption, either because of misbehaving devices or intentional hacking. Park *et al.* expand upon the importance that strong enforcement mechanisms, in addition to privacy and security issues, will play in future spectrum access paradigms.

The world's supply of available spectrum bandwidth for mobile wireless applications is both limited in quantity and fragmented across multiple noncontiguous spectrum bands. Typical smartphones in the United States, for example, currently use four separate bands ranging from 700 to 2100 MHz for third- and fourth-generation data services. As DSA opens additional shared spectrum bands, the ability to operate in a multitude of bands will either become a requirement or a distinct advantage for wireless devices. But such capabilities come with challenges, including the ability for cognitive radios to quickly sense the local spectrum environment across a wide bandwidth. Hattab and Ibnkahla address these challenges in their contribution on multiband spectrum access.

An additional challenge for adaptable radios is the ability to quickly change filtering characteristics through a combination of software and reconfigurable hardware. Such capabilities are an integral component of so-called "software-defined radio" (SDR) devices, which will be one enabler of cognitive radios for DSA. Chappell *et al.* concentrate on the filtering aspects for SDR in their contribution, and expand on some of the innovative techniques and complicating factors that enter into creating frequency- and bandwidth-agile filters "on the fly." Larson argues the need to replace the traditional narrowband radio-frequency (RF) transceiver and circuit designs with broadband design approaches for future radio spectrum access, and takes a broad look at some of the circuit design challenges related to adaptable and broadband low-noise amplifiers, frequency converters, filters, and transmitter techniques, including cost and power consumption.

While spectrum sharing and DSA are important components of future radio spectrum access, additional complementary work on alternative network topologies is being pursued as another avenue for improving spectrum efficiency. One example is moving from macrocells that cover large areas to networks that utilize a multitude of small low-power cells with very limited coverage, as small as a few hundred feet. Small-cell networks allow the same frequency to be reused over short distances, and can provide significantly higher network data throughput when measured in bits per second per hertz per area. Fehske *et al.* review the challenges and opportunities of small-cell self-organizing networks, including a mathematical framework for analyzing small-cell network performance.

Doyle *et al.* explore an entirely different type of wireless network topology. In their vision, various improvements in wireless access technologies, crowdsourcing physical layer resources, and pushing the sharing domain up to higher network layers can all lead to much higher efficiency in the use of scarce spectrum resources. Their contribution discusses the opportunities and technical challenges behind a future of "spectrum without bounds, networks without borders."

The millimeter-wave band, which encompasses frequencies between 30 and 300 GHz and corresponding wavelengths of 10–1 mm, contains over 90% of the allocated radio spectrum, but is by far the most underutilized band. There are a number of reasons for this, including the relative maturity of technology in this frequency range and a propagation environment that has not traditionally been thought to be conducive to wireless mobility. Rangan *et al.* take a deeper look at wireless communications using the millimeter-wave band, particularly for small cell networks, and reach some promising conclusions about making better use of this vast bandwidth resource.

While the aim of many of the topics in this special issue is to improve spectrum efficiency by various means, quantifying what is meant by "spectrum efficiency" may be as difficult as applying the definition of harmful interference discussed previously. Rysavy takes a high-level look at different metrics for quantifying spectrum efficiency, and the relative merits of each.

Finally, Gergely discusses a very specialized use of the radio spectrum and how it will fit into the future spectrum architecture. Radio scientists employ a variety of passive (nontransmitting) sensing applications, including radio astronomy and remote sensing, which often require protected access to specific frequencies (due to fundamental physics) and usually employ extremely sensitive receivers. Gergely presents some of the history of passive sensing, and addresses challenges (and opportunities) for accommodating passive applications in a future DSA environment.

The suite of contributions to this special issue of the PROCEEDINGS can only scratch the surface of topics that are relevant to how the radio spectrum is accessed in the future. But we believe that the major concepts are represented, and by authors widely viewed as experts in their particular fields. The general topic area and the related technology are evolving quickly, while at the same time mired within a spectrum regulatory framework that is infamous for moving as slowly as a buffering video over a slow wireless link. The future of the world's airwaves will continue to be an important and fascinating topic for many years. ■

ABOUT THE GUEST EDITORS

Andrew Clegg (Senior Member, IEEE) received the B.A. degree in astronomy and physics from the University of Virginia, Charlottesville, VA, USA, in 1985 and the M.S. and Ph.D. degrees in radio astronomy and electrical engineering (minor) from Cornell University, Ithaca, NY, USA, in 1989 and 1991, respectively.

He recently joined Google, Mountain View, CA, USA where he works on spectrum engineering issues in support of the company's wireless projects. Prior to that, he was at the U.S. National Science Foundation (NSF), Arlington, VA, USA, for 11 years, where he created and ran the Enhancing Access to the Radio Spectrum (EARS) program. EARS is the first-ever NSF program dedicated specifically to research in the domain of radio spectrum efficiency and access. To date, the EARS program has provided support for more than 40 academic and small business research groups, and technology funded under the EARS program is beginning to find its way into innovative new wireless applications. Prior to joining NSF, he was a Lead Member of Technical Staff for Cingular Wireless (now AT&T Mobility, Atlanta, GA, USA), where he worked on a variety of engineering projects related to the company's spectrum holdings in the cellular, PCS, wireless communications service, and broadband radio service domains. He was also a Senior Engineer for Comsearch (a wireless consulting company), Ashburn, VA, USA and a research scientist for the U.S. Naval Research Laboratory, Washington, DC, where he conducted research in radio astronomy and remote sensing applications. He also created and maintains the SpectrumWiki.com website, which is an online crowdsourced resource for cataloging the myriad uses of the radio spectrum.

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