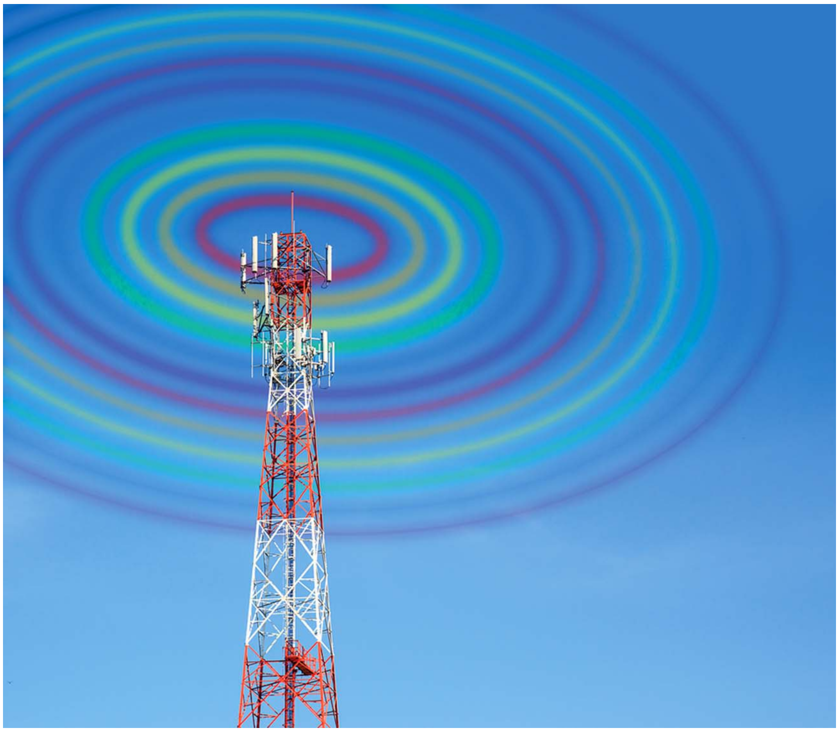
The Role of New Technologies in Solving the Spectrum Shortage

BY JEFFREY REED

MARIUS VASSILIOU

SYED SHAH



I. INTRODUCTION

A. Spectrum Is a Resource

Communications spectrum—that is, the set of electromagnetic frequencies suitable for communications and radar—is a precious resource. Like oil, it is limited and has a far-reaching impact on economic activity and national security. However, unlike oil, it cannot be stored for later use, and it cannot be exported, although it can be reused [1]. Depending on the licensing regime, spectrum can have the characteristics of a private good or a common good [2]. Spectrum can also be locally traded, and it can, by application of scientific creativity, be made more productive. Much research needs to be done in order to achieve the fullest possible productivity.

B. Spectrum Is Valuable

Communications spectrum is immensely important economically. Recent estimates indicate global annual revenues of over a trillion dollars for mobile wireless, $320 billion for broadcast TV, and $63 billion for broadcast radio. The estimated consumer surplus[1] associated with mobile wireless is around $1.4 trillion, and for broadcast television $2.5 trillion [4]. Auctions in the 700–800-MHz bands conducted in the United States, Germany, and France between 2008 and 2010 suggested a value of roughly $1 per megahertz per person living in the country [5]. An auction in the United Kingdom in 2013 in the 800-MHz and 2.6-GHz bands netted a lower amount [6], of around $0.23 per megahertz per person. The most recent U.S. auction, for Advanced Wireless Systems-3 (AWS-3) in the 1695–1710-, 1755–1780-, and 2155–2180-MHz bands, netted about $41.3 billion [7], suggesting an average value of nearly $2 per megahertz per person.

[1]In economics, the consumer surplus is the amount by which consumers value a product over and above what they pay for it [3]. The equilibrium price is determined by the intersection of supply and demand curves; it does not correspond to the only price consumers are willing to pay. If supply is more restricted, they may be willing to pay higher prices, according to the demand curve. The consumer surplus is thus the area under the demand curve and above a horizontal line at the actual or equilibrium price.

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II. SPECTRUM IS GETTING SCARCE

A. Increasing Demands

Demands on spectrum have been increasing for decades, and continue to do so at a rapid rate. In 2001, there were 15.5 mobile cellular subscriptions for every 100 people in the world; by 2013 there were 96.2 [8]. Mobile broadband Internet service on smartphones was virtually nonexistent before 2008. By 2013, there were 74.8 mobile broadband subscriptions per 100 people in the developed world, and 29.5 per 100 people in the world as a whole [8]. The developing world has perhaps benefited the most from the wireless revolution. The emerging Internet of Things, in which a plethora of enabled electronic devices, including sensors, will be increasingly accessible over the Internet [9], will only exacerbate the situation. These latest applications also have implications for traffic models, in that they may involve a redistribution of spectrum resources devoted to the uplink versus the downlink.

B. Government-Dedicated Spectrum Is being Reallocated

One of the major collisions is between the needs of governments and the needs of the commercial marketplace. In the United States, the federal government has dominant access to about 32% of the spectrum from 225 to 3700 MHz. Nonfederal users have dominant access to about 33%, and about 35% is shared, with federal users having a primary allocation and nonfederal users having a secondary allocation [10]. Various federal agencies have over 240 000 frequency assignments. The agency with the largest amount of allocated spectrum is the U.S. Department of Defense, with 37.3% of the federal total. When combined with other agencies involved in national security or public safety, the total rises to nearly 61% [11]. Governments in Europe also hold a fairly large share of spectrum. In a typical Western European country, commercial uses account for about 50% of the spectrum from 108 MHz to 6 GHz (with a 15% slice for mobile services), and government for the other half. Defense accounts for somewhat over half of the government use (27.2% of the total). Broken down another way, radars and navigation account for 29.3% and military communications 19.0% [12].

The large share of spectrum controlled by government, as well as the relatively uncrowded nature of the government bands, has led to a continuing process of reallocation from government to commercial uses. Between 1992 and 2010 in the United States, the federal government agreed to give up access to 412.5 MHz of spectrum. This was the result of cumulative national decisions (the Omnibus Budget Reconciliation Act of 1993 [13], [14] and the Balanced Budget Act of 1997 [14]) and international agreements (the World Administrative Radio Conference of 1992 [15], [16] and the World Radio Conference of 1997 [17], [18]). Furthermore, a U.S. Presidential Memorandum of June 14, 2013 [19] called for "continued efforts to make more spectrum available for wireless broadband applications." It built on an earlier Presidential Memorandum of 2010 [20] that established the goal of repurposing 500 MHz of spectrum from existing government uses to commercial broadband use within ten years. The AWS-3 auction mentioned above was one instance of progress toward this goal. Similar trends are being observed throughout the world. For example, the 700-MHz band is being repurposed to cellular use throughout Europe, following decisions of the World Radio Congress [21], [22]. Many countries (including, as examples, the United States, the United Kingdom, Canada, Colombia, Malawi, The Philippines, Singapore, South Africa, Kenya, Ghana, and Indonesia) are in varying stages of repurposing unused very-high-frequency (VHF) and ultrahigh-frequency (UHF) spectrum originally designated for television broadcasting ("Television White Space") [23].

C. National Security Can Be Affected

The repurposing of government-dedicated spectrum can pose national security concerns. In the United States, the squeezing of the military's available spectrum has occurred while the military's own spectrum needs have actually increased, with the advent of net-centric operations, increased use of unmanned systems, increased sensor use, and increased bandwidth demands of military radars. The U.S. Department of Defense projects that bandwidth needs may exceed 300 Mb/s per 5000 military service members by 2020, compared to a usage of roughly 50 Mb/s per 5000 members in Operation Iraqi Freedom during the early and mid-2000s, and less than a fifth of that amount during Operation Desert Storm in 1991 [24]. This is a serious problem for the U.S. military, which ideally would like to operate its communications and train personnel in peacetime in a way not too different from how it operates in war. This problem is not unique to the United States; all countries are looking for additional spectrum for commercial applications, and transitioning military spectrum is being considered as a potential way to achieve this needed commercial spectrum. For example, the U.K. Government has decided to release 500 MHz of spectrum, much of which is being used by the Ministry of Defence, by 2020 [25].

III. TECHNOLOGY OFFERS A WAY OUT

Perhaps the only way out of this conundrum is new technology. Spectrum sharing technology will be required not only for efficient commercial use, but also for sharing between commercial systems and government. Note that such technology will be needed even if governments eventually vacate certain bands completely. The timelines for transferring government spectrum to commercial use can be long. In

Europe, the process can take six to ten years [26]. In the United States, to take the example of the AWS-3 auction mentioned above, transition times vary from one to ten years, depending on the agency and system in question. Technology will still be needed to allow coexistence and facilitate early commercial entry during the transition [27].

Technologies for more efficient spectrum use, that is, supporting more users in a given bandwidth, hold much promise. The switchover from analog to more efficient digital television broadcasting, which freed up between 72 and 164 MHz of spectrum, depending on global region, is one example. Spectrum sharing is also becoming a key part of new mobile communications systems. Fifth-generation (5G) cellular will be the first mobile communication system designed from the ground up with spectrum sharing in mind. Fig. 1 shows the goals for key capabilities in 5G systems as compared with fourth generation (4G). Among these are a threefold increase in spectrum efficiency and a hundredfold increase in area traffic capacity. Some of the other goals, such as energy efficiency, make spectrum efficiency and traffic capacity improvements all the more difficult. Achieving the goals will involve considerable new technology development. Such new developments, and others, will also help national security systems coexist with commercial ones.

There are several promising technology areas that can help alleviate the spectrum bottleneck. They range from existing technologies that have not yet been extensively applied to spectrum sharing, to technologies that will require extensive and fundamental research. In rough order of increasing research requirements (decreasing readiness for use),[2] these are listed in the following sections.

[2]This ordering should not be taken too seriously, as each of the areas has scope for cutting-edge research.

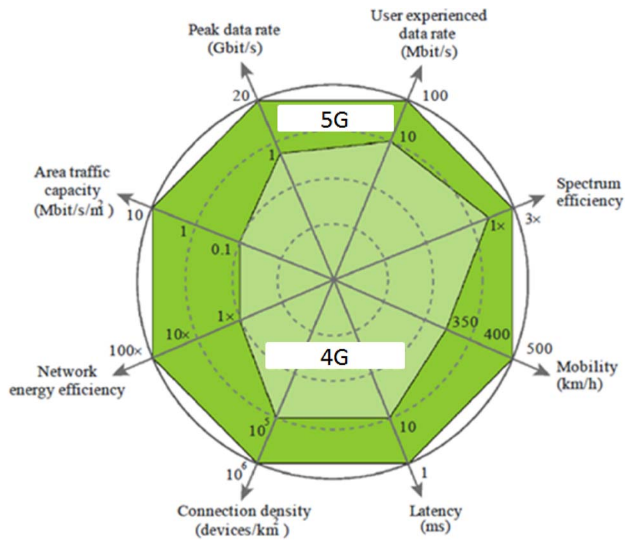

Fig. 1. *Goals for key capabilities in 5G systems as compared with 4G. 5G will be the first mobile communication system designed from the ground up with spectrum sharing in mind. Spectral efficiency and area traffic capacity improvements are crucial. These are goals set by commercial entities and standards bodies. Achieving them will require progress in all the technology categories discussed here. Similar technological progress will be needed to achieve broader public policy objectives for spectrum allocation and sharing. (Adapted from [28].)*

A. Small-Cell Technology

This refers to the use of smaller cells, served by more base stations, and operating at lower power, which can help avoid interference, and thereby increase spectrum efficiency and area traffic capacity [29]. Using a mixture of large cells overlaid with smaller ones is an important feature of third-generation partnership (3GPP) long-term evolution (LTE) and LTE-advanced (LTE-A) technologies [30]. Small-cell technology essentially amounts to taking the key principle of cellular technology, i.e., *cells*, to a greater extreme. It is also worth noting that millimeter-wave technologies (see below) being considered for 5G are well suited for small-cell deployment because of propagation limitations in that band. The profusion of cells will complicate system management. Another important issue is that of achieving low latency. Today, LTE latencies are on the order of 10 ms. For many applications, such as gaming or intelligent transportation systems, this will need to be reduced to about 1 ms. Overall, the frequency reuse achievable by making cells smaller is one of the more productive options in the short and medium term [31], provided costs can be controlled.

B. Smart Antennas

Smart antennas were introduced in second-generation (2G) mobile systems [32], but did not begin to catch on until 4G systems and the emergence of the multiple-input–multiple-output (MIMO) paradigm [33]. In a general sense, multiple antennas for transmission and reception allow for more propagation paths to be used, and hence increase the amount of data that can be transmitted in a given amount of spectrum.

A major research issue for smart antennas in the context of spectrum sharing is the coordination of interference through directivity control, such as putting nulls in the directions for which interference avoidance is most desirable. Advanced antenna technologies such as 3-D beamforming, active antenna systems, massive MIMO, and network

MIMO can help further reduce interference and increase spectrum efficiency. Such MIMO approaches provide antenna gain to overcome power amplifier inefficiency and high channel losses. We note that data throughput rates, computational requirements, and cost required to perform digital beamforming suggest instead analog approaches to beamforming, and the research needed to support those.

C. Spectrum Agility

A root cause of spectrum inefficiency is that mobile wireless devices in crowded spectral bands are impeded from using other bands that may be less crowded. This may be because of regulatory prohibitions, but it also arises from an inability to use other bands even when permitted, because of hardware, software, and system limitations. This has created a demand for spectrum-agile radios [34] able to operate across a number of different bands, even simultaneously.

Spectrum agility may enable a user to employ parts of different bands to support a high-data-rate communication link. This is already being implemented in LTE-A, but in future further research will be needed to support simultaneous use of bands having very different propagation characteristics. This would be the case in the combined use of cellular and millimeter-wave bands, where the latter needs near-line-of-sight but the former does not. Spectrum agility may also allow the creation of large virtual contiguous blocks of spectrum. This would help avoid the problem of moving out legacy users.

Such abilities will require new developments in RF design. In the past, static spectrum planning allowed avoidance of adjacent channel interference without the need for very high-performance RF front ends. In the future, RF front ends must have greater dynamic range and better filtering capabilities, in order to cope with high and dynamic power variations in adjacent bands. Also, achieving agility will require duplexers/diplexers that can work across a variety of frequencies instead of being fixed to one band. Another needed improvement is the ability to match the antenna to the RF front end in order to optimize for the frequency being used, the presence of obstructions (such as the user's hand or head), etc. Spectrum agility will also require more efficient linear power amplifiers that work well across broad bands. This may involve breakthroughs in both circuit design and semiconductor processing technology.

D. Millimeter-Wave Technologies

The millimeter-wave band, between 27 and 300 GHz, is currently sparsely occupied, and represents an important source of new contiguous communication spectrum. Currently, operating in this band is difficult because its propagation characteristics dictate the need for near-line-of-sight visibility. Another problem is that there is relatively high signal attenuation, limiting range; this, however, can also be an advantage in minimizing interference. Successful exploitation of the millimeter-wave band will likely require massive MIMO for directivity and antenna gain, and also large-scale small-cell architectures, possibly with multihop relay for wireless millimeter-wave backhaul [35]. High antenna gains are required largely because power amplifiers are not terribly efficient at millimeter-wave frequencies; efficiencies can easily be as low as 8%. Making fundamental improvements in power amplifiers could have a large effect on the ability to exploit this band.

E. Extensive Spectrum Sharing and Cognitive Radio

An ultimate objective is to create intelligent cognitive radios that can automatically and seamlessly share spectrum, and to optimize their transmission parameters [35]. This will require research into cognitive engines, allowing radios to adjust parameters in order to identify and manage available spectrum, and even anticipate "holes" before they occur. One example of spectrum sharing where cognitive radios can make a very important contribution is in sharing between communications and radar. In the United States, radar can be found in bands ranging from high-frequency (HF) through millimeter wave. Radar systems are mostly fixed, and limited geographically. They also have predictable patterns that cognitive radios can exploit.

Cognitive radios may incorporate database management techniques for dynamic spectrum access and sharing. How these databases are stored, accessed, and maintained may constitute an important set of research issues. Should the databases be distributed or centralized? How can sensitive information about, for example, the operation of a radar system, be kept secure? Information assurance and privacy will be crucial issues when spectrum is shared.

Another advantage of cognitive radios is that they will make large-scale deployment of small cells more viable. Cognitive radios will perform automatic channel selection, and peer-to-peer coordination, thus reducing the need for human involvement in base station management and deployment.

Extensive spectrum sharing using cognitive radios will require the establishment of standards, and research into enforcement mechanisms, to make sure that users do not abuse their new and awesome capabilities.

F. Economic and Regulatory Models

In addition to the technical areas discussed in Sections III-A–III-E, research will also be required into the interaction of coexisting wireless technologies and various regulatory frameworks for managing spectrum access. As pointed out in a recent National Science Foundation Workshop, "This is illustrated by the on-going challenges of reconciling barriers to coexistence between wireless systems influenced by unlicensed versus license-anchored frameworks (e.g., Wi-Fi vs. LTE-U, respectively)" [36]. The workshop concluded that research will be needed to explore ideas of embedding economic and regulatory functionality explicitly in wireless system designs, and also to explore the transaction and efficiency implications of different regulatory regimes of varying degrees of centralization [36]. It is also worth noting that the imperatives of cost reduction may suggest the need for network, equipment, and spectrum sharing by various commercial providers; new economic models may need to be explored to ensure maintenance of a competitive environment under such conditions.

IV. CONCLUSION

In conclusion, new technologies have the potential to alleviate the spectrum shortage and create a situation where no one has to lose access—or, at least, fewer people have to lose much less. This will have an impact across military, commercial, and even diplomatic domains, particularly with the U.S. military's international presence. Since some of the needed technology will require fundamental advances, it is furthermore crucial to devote due attention to basic research. The U.S. Government is on the cusp of sponsoring considerable research into spectrum, using monies from the Spectrum Relocation Fund. As an example, the Spectrum Access R&D Program (SARDP), managed through the National Spectrum Consortium, is intended to spend \$500 million on projects mitigating transition and operational risks associated with the AWS-3 transition.[3] We contend that such programs are critical, but that significant funds should be set aside—from whatever source—for earlier stage basic and applied research, as well, to address some of the fundamental issues we discuss above, as well as others.

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