Spectrum Resource Optimization in Context

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> If you want real growth, you have to have new technologies and you have to have the will to use them [1].
>
> Michael Mandel

> The more novel an idea, the less likely it is to conform to the existing FCC rules–which, after all, were written for the technologies that came before . . . if a device is sufficiently original—i.e., if it fails to comply with the existing technical rules—its prospects for fast approval are bleak [2].
>
> Mitchell Lazarus

If, as the quotations above suggest, new technologies create growth but radio regulation exhibits no will to use them, then our economic progress and general well being will be less—perhaps substantially less—than they would be otherwise. The radio spectrum resource is an essential part of today's modern economies—contributing to trillions of dollars of economic activity every year. The traditional spectrum management process often fails to react quickly to changes in technology or in user needs. New mechanisms, specifically property—right regimes and shared, unlicensed bands—are tools to that permit both more rapid innovation and the deployment of more efficient uses. The papers in this special issue explore various aspects of more efficient spectrum use.

Paradoxically, advances in technology have made radio spectrum both more abundant and more valuable than ever before. Improvements in electronic devices, modulation, data compression, protocols, and other related technologies allow us to extract far more value from the radio spectrum than could our predecessors and to pack a substantially larger quantity of communications into each megahertz of spectrum than could be done a few decades ago. But, those same improvements have increased the demand for radio spectrum by lowering the cost of radio gear and expanding the supply of complementary products—such as personal computers, PDAs, and electronic games. We are not aware of any study that reliably estimates the economic and social contributions to modern societies from the use of the spectrum—but whatever that figure, it is enormous. More than half the world's telephone lines are wireless; wireless is essential to modern air transportation; radio broadcasting, over-the-air television, and satellite television are key systems for the delivery of news and entertainment; modern navigation is almost entirely based on radio systems.

Given this enormous importance of the radio spectrum to modern life and the natural limits on the range of radio frequencies that are most effective for wireless applications, it is natural to address the problem of efficient use of the radio spectrum—to optimize our use of the radio spectrum.

The papers in this special issue illustrate a variety of methods for moving toward more nearly optimal spectrum use. Some of these methods, such as that presented in the paper by Y. S. Hyuck *et al.* regarding optimum carrier spacing for IMT-2000 and the paper by V. F. Milas and P. Constantinou analyzing spectrum sharing between high-altitude platforms and terrestrial microwave, are technical approaches that support more efficient spectrum engineering. Other approaches to spectrum efficiency, such as those discussed in the papers by J. M. Butler and W. T. Webb and by M. Marcus, mix technology and regulation to create institutions and incentives designed to permit the discovery and use of more efficient patterns of spectrum utilization.

In this overview, we first consider the definition of the spectrum resource itself. We then turn to the various measures of efficiency—what is it that we wish to optimize? After that we consider traditional models of spectrum management and mechanisms that have been proposed to improve the efficiency of spectrum management. Along the way, we reference the papers in this special edition and put them in perspective.

Although arcane to the lay person, radio engineers know what the spectrum resource is—the band of radio frequencies extending from approximately 100 kHz to 100 GHz that can be used for wireless communications, position location, radar, microwave ovens, and a host of other applications. The radio spectrum is an unusual resource—indeed some people even deny that it is a resource. If it is a resource, it is an unusual one. The spectrum is a flow resource—continuously renewing itself—like sunlight or wind; it is not a stock resource like oil or minerals. The radio spectrum is often analogized to land but with a third dimension. Thus, several administrations authorize users to operate radio transmitters over a specific band of frequencies within a specified geographic area. In practice, it turns out to be quite difficult to define reasonable units of the spectrum resource. It is an inescapable rule of physics that radio transmitters emit radio signals outside their assigned frequencies. Similarly, radio receivers respond to signals outside the band or channel carrying the signal of interest. Consequently, any spectrum boundaries must accommodate the incursions of out-of-band emissions and must deal with the problems of receivers responding to undesired signals.

But, whatever the complications of defining the spectrum resource, the underlying issue is the control of radio interference. Rights to use the spectrum resource are an expression of the rules governing the operation of radio transmitters and receivers. Anyone who is uncomfortable with the concept of a spectrum resource can just ignore the use of the word *resource* and look to the underlying rules governing use of radio transmitters and receivers.

Optimizing use of the spectrum resource can be approached in three different ways:

- Improving the technical efficiency of radio systems,
- allocating spectrum to more valuable uses, and
- spurring innovation in radio systems.

Improving the technical efficiency of radio systems is the traditional undertaking of engineers. We have seen enormous progress on this front. For example, modern wireless telephony systems support approximately 20 times more subscribers per MHz than did the analog cellular systems. Much of the focus of radio engineering is on finding ways to squeeze more productivity out of a given block of spectrum—to increase technical efficiency.

Economists use the phrase *allocative efficiency* to refer to the employment of resources in their most efficient use—their highest and best use. Real estate in downtown Tokyo could be used to grow rice, but that real estate is more usefully employed to support streets, office buildings, apartments, and retail establishments. Ensuring allocative efficiency for the radio spectrum resource has proven to be difficult. Indeed, it is highly probable that the current pattern of uses of the radio spectrum resource in most nations is far from the efficient pattern of uses. For example, in the United States there are large blocks of spectrum that are still used for fixed microwave even though that spectrum is suitable for mobile wireless applications.

Innovation is a major key to economic progress. In the long run, the creation of an environment that facilitates and encourages innovation in spectrum-using systems will probably be the most important aspect of spectrum resource optimization. We use the term *innovation in spectrum-using systems* to refer to the development and adoption of new systems, such as direct broadcast satellites or wireless LANs, and not the incremental refinement of existing systems. Developing a better compression algorithm for use with existing direct broadcast satellites would be an example of such an incremental innovation.

Unfortunately, it is often quite difficult to change the fundamental architecture of radio systems and to thereby optimize use of the spectrum resource. Many radio systems are interconnected networks of thousands or millions of devices owned by many different individuals and corporations and that span national borders. Thus, the television broadcast standards that were adopted around 1950 still support the bulk of television today. There have been some marginal improvements—such as stereo sound and the transmission of text—but fundamentally the systems have changed very little. Recently, standards for digital television have been defined and digital television broadcasting is beginning to be adopted. But, this sudden change, after a half-century of near stasis, demonstrates how hard it is to change massive radio systems with distributed ownership.

In contrast, some radio systems such as point-to-point microwave and fixed satellite easily accommodate incremental changes in technology. Satellite systems moved from single to dual polarization, from analog to digital modulation, and from global beams to spot beams over a period of a few decades.

Interference is an unfortunate fact of life in radio engineering. Practical receivers can function less well or fail in the presence of signals other than the desired signal of interest. Consequently, it is necessary to have mechanisms that coordinate spectrum use in order to avoid or limit interference. Furthermore, radio signals travel far beyond national borders so the coordination of spectrum use is not merely a national concern; rather, coordination must be regional and global.

Over the last hundred years, we have gained substantial experience with the problems of interference. The primary initial uses of radio were for safety of life at sea, for military applications (particularly naval applications), and by amateurs. These initial operations were at low frequencies—less than 30 MHz. Radio waves at these frequencies often travel far beyond the horizon. The social and physical characteristics of early radio are substantially different from those than those for the bulk of radio spectrum applications today. Nevertheless, the world continues to cope with interference problems—to manage the spectrum resource—using institutions and mechanisms designed to deal with this initial environment.

The political and social institutions designed for management of the spectrum resource have, from the very beginning, been used to deal with other concerns such as competition policy, media regulation, and the adoption of system standards. Charging the spectrum regulators with these other tasks has often confused the process and obscured the fundamental problems of spectrum management.

Until recently, radio regulation consisted of a three-part process whereby national governments, following rules established by regional and global agreements, would *allocate* blocks of spectrum for specific uses (e.g., in most nations the block from 88 to 108 MHz is allocated to FM aural broadcasting). Next, specific subblocks (often denoted frequencies) would be *allotted* to specific locations or subuses (e.g., the frequency 103.5 MHz is allotted by the FCC to the Washington, DC, region for a use by a broadcast station). Finally, national regulatory authorities would *assign* specific allotments to individual operating entities.

Although the traditional spectrum management model described above worked reasonably well in many circumstances, a number of flaws have been identified in it—the most severe flaw being that the system led to highly inefficient patterns of spectrum use. The primary sources of inefficiencies were (1) inefficient allocations of spectrum and (2) impaired incentives to innovate.

These two inefficiencies are related—technical innovation and changes in consumer and social needs are factors that make exiting spectrum allocations inefficient. The system of allocating blocks of spectrum for specific purposes created two types of inefficiencies. First, the initial allocation of blocks of spectrum might well be inefficient—for example, it is likely that either too much or too little spectrum was given to TV broadcasting when TV broadcasting was first established. Second, reallocation of spectrum to new or different uses is a slow and time-consuming political process that often takes place years after technology and user needs have changed.

The traditional spectrum regulatory system also erected, indeed still erects, substantial barriers to technical innovation. New radio services required allocations of new spectrum—a process that takes years or decades and substantial time and effort by the supporters of the new technology. The struggle by Major Armstrong to develop commercial FM broadcasting exemplifies the difficulty and delay that the traditional regulatory system imposes on innovation.

The traditional allocation process is illuminated by the paper by Yoon *et al.* They describe an implementation of a spectrum demand forecasting method that can be used in support of traditional spectrum allocation analysis.

The traditional analysis needed for the regulatory packing of applications or services together in the same frequency blocks is illustrated by three papers. The paper by Milas and Constantinou analyzes the coexistence between radio systems on high-altitude platforms and terrestrial microwave; the paper by Hyuck *et al.* studies the optimal spacing of carriers in an IMT-2000 system; and the paper by Jo *et al.* considers the coexistence of OFDM-based mobile systems (systems beyond 3G) with fixed microwave systems.

Recent decades have seen a flurry of changes to the regulatory system in order to counteract these flaws. Three of the most important reforms are flexible licenses, use of property-right mechanisms, and flexible, unlicensed bands.

Traditional radio licenses restricted licensees to a specific application and technology. One simple reform is to give the licensee technical flexibility to use any technology so long as the licensee creates no more interference to others than before. Thus, for example, a land mobile licensee that used 25 kHz FM channels to carry a single voice conversation might convert its channel to a TDMA digital channel carrying three voice conversations. With careful attention to signal format and power levels, such a digital signal would create no more interference to co-channel and adjacent channel users than did the original FM signal.

A second, and more difficult, reform is to replace administrative control of the radio spectrum by a system similar to real estate property rights. Under such systems, a rights holder would have a right to operate transmitters in a given block of spectrum over a specified geographic region. The concept is easy to state but hard to implement. New Zealand implemented a version of such rights packages in its 1989 Radio Communications Law [3], [4]. That law also introduced a second reform, the use of auctions rather than administrative choice (beauty contests) to select radio users in regions of the spectrum where entry is limited. Auctions are now used throughout the world to assign spectrum rights.

The argument for such property rights systems is simple: There is substantial theoretical and empirical evidence that markets are often more efficient tools for allocating resources and stimulating innovation than are government planning bureaucracies. Thus, defining spectrum property rights mechanisms that permit markets to be used for the management of spectrum resources may substantially enhance efficiency.

Such a property rights system is likely to work well only if the property owner (1) has sufficient spectrum rights to permit it to internalize the interference between many transmitters; (2) has flexible rights that permit the owner to choose the technologies and uses for the spectrum—always conditional, of course, on observing constraints that control interference to others; and (3) has rights that permit the owner to engage in market transactions with owners of adjacent spectrum regarding changes in interference obligations. Efficiency is also enhanced if the owner can subdivide or repackage its rights to create new rights packages and authorize others to use those packages.

Two of the papers in this special issue address the definition of such rights packages. Matheson's paper "Principles of Flexible-Use Spectrum Rights" provides an overview of a possible rights package and contrasts the incentives for innovation and enforcement problems with those of traditional spectrum regulation. The paper by Butler and Webb in large part addresses the same problem as does Matheson. However, their viewpoint not as abstract—rather, they consider the problem from the point of view of a national spectrum manager (in their case Ofcom in the U.K.) that wishes to transition to a more flexible, market-based regulatory regime while avoiding unacceptable interference. Consequently, their paper considers issues such as transparency, simplicity, and administrative cost. A third paper, "Real Time Spectrum Markets and Interruptible Spectrum" by Marcus, describes an innovative system that can be based on traditional radio licensing but that achieves flexibility and serves efficiency.

A third reform is the use of flexible, unlicensed bands—sometimes called spectrum commons. Again, the details vary but the basic concept is to set aside a block of spectrum with minimal rules, for example, limits on power and power spectral density, and allow users to operate any gear they wish in that band providing the gear is designed to meet the rules. Such flexible bands were proposed no later than the late 1970s by analysts at the U.S. Federal Communications Commission (FCC) [5]. Several years later, the FCC took a step toward implementing such bands when it adopted liberal rules permitting the use of unlicensed spread spectrum radio systems at 902–928, 2400–2483.5, and 5725–5850 MHz [6]. Over time these rules have evolved. The requirement that spread spectrum be used has been relaxed; today the FCC permits any digital modulation to be used subject to limits on power and power density. The current FCC rules parallel the policy proposals of the late 1970s. However, the use of spread spectrum for such unlicensed operation was probably essential to the political acceptance of such relatively high-powered unlicensed operation. Spread spectrum, which was well understood by few in the policy community, distinguished the proposal from a simple, low-power unlicensed service.

The paper by Sahin and Arslan considers a related approach to increasing spectrum efficiency—the authorization of low power transmitters that can share the spectrum with existing applications without interference. Such additional operations are often called overlay or underlay operations. Sepcically, Sahin and Arslan consider a cognitive UWB system—one that listens before transmitting on a number of wide subbands—and they conclude that such an architecture facilitates sharing between traditional systems and such underlay/overlay operations.

The radio spectrum resource is an essential building block for modern economies. Improvements to the efficiency of the use of the spectrum resource generate substantial benefits. Large benefits will come from reforms that improve allocative efficiency and free up innovation. Engineers—people who understand the mechanisms by which radio systems work and fail—can make essential contributions to such reforms.

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Charles L. Jackson received his undergraduate degree in applied mathematics from Harvard College and the Ph.D. degree in electrical engineering from MIT.

He has worked at SRI-International, Signatron, CNR, the FCC, and the Commerce Committee of the U.S. House of Representatives. He has worked as a consultant since 1980. He has served on the adjunct faculty at Duke University and George Washington University.

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Michael J. Marcus received S.B. and Sc.D. degrees from the Massachusetts Institute of Technology in electrical engineering. After serving in the U.S. Air Force and working at the Institute for Defense Analyses, he joined the Federal Communications Commission and worked there for nearly 25 years. He proposed and directed the development new policies that resulted in the ISM spread spectrum band that is home to both Wi-Fi and Bluetooth. Later, he had a similar role with respect to new bands from 60-90 GHz. Based in Paris, France, he is now Director of Marcus Spectrum Solutions, a consulting firm. He is a Fellow of the IEEE.

Fredrick Matos is Acting Chief, Strategic Spectrum Planning and Reform Division, with the Department of Commerce's National Telecommunications and Information Administration (NTIA), Office of Spectrum Management. The Division is engaged in carrying out the President's spectrum policy initiative. Dr. Matos has been with NTIA for over 20 years.

During June 2003–April 2004, Dr. Matos was detailed to the Coalition Provisional Authority (CPA) in Iraq where he was a senior staff member at the CPA Ministry of Communications where he had a major role in the CPA's nation building efforts. He was the national telecommunications regulator and director of all Iraqi national spectrum management, including licensing and policy making for all spectrum-related services. He drafted the cellular telecommunications licenses for the three cellular operators, and negotiated the license provisions.

In previous positions at NTIA, he developed policies and participated as a member of the U.S. delegation to international spectrum management treaty conferences of the International Telecommunication Union where he negotiated various complex issues. Prior to NTIA, he was a spectrum engineer and project manager at the Department of Defense Electromagnetic Compatibility Analysis Center (ECAC).

Dr. Matos served as senior telecommunications policy adviser and Legislative Assistant to U.S. Congressman Tom Tauke in 1986–88 where he supported the Congressman's activities on the House Subcommittee on Telecommunications.

He initiated and teaches a course in radio frequency spectrum management at the George Washington University. He is the NTIA director of the spectrum management training course conducted with the United States Telecommunications Training Institute (USTTI), training spectrum managers from developing countries. He is the author of the book, *Spectrum Management and Engineering*, published in 1985. He was Director of Engineering for the MediAmerica Corporation, a chain of radio broadcasting stations. Dr. Matos holds Bachelor's and Master's degrees in electrical engineering, and is a licensed radio amateur, holding the extra class license.

His graduate school research was in computer communications networks. He is a Senior Member of the Institute of Electrical and Electronics Engineers (IEEE), a life member of the International Amateur Radio Club at the ITU in Geneva, and a life member of the American Radio Relay League.

In January 2001, Dr. Matos advised the government of the Arab Republic of Egypt by conducting an extensive evaluation of the spectrum management organization and processes. He was asked by the Egyptian government to review the draft new telecommunications law, and he made extensive comments in all areas of the law.

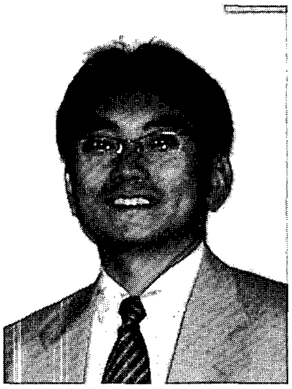
In May 1996, Dr. Matos coordinated and led a team of experts presenting a special seminar in radio frequency spectrum management to the Panama Canal Commission in Panama. In October 1996, he led another team of experts presenting a special seminar to the Ente Regulador, the newly established telecommunications and spectrum management regulatory agency of the Republic of Panama. Dr. Matos was an adviser to the Ente Regulador in establishing and organizing the spectrum management organization and its procedures, and it is now the most modern spectrum management organization in Latin America.

In May 1997, Dr. Matos was part of a team of experts presenting a spectrum management seminar in Tel Aviv, Israel that included participants from Israel, the Palestine Authority, and Jordan. In all of these cases, the team of experts provided consultation and advice on spectrum management.

William Webb joined Ofcom as Head of Research and Development and Senior Technologist in 2003. Here, he manages a team of 10 engineers providing technical advice and managing research across all areas of Ofcom's regulatory remit. He also leads some of the major reviews conducted by Ofcom including the Spectrum Framework Review and Ultra-Wideband Consultation. Previously, William worked for a range of communications consultancies in the UK in the fields of hardware design, computer simulation, propagation modelling, spectrum management and strategy development. William also spent three years providing strategic management across Motorola's entire communications portfolio, based in Chicago,

William has published eight books, sixty papers, and four patents. He is a Visiting Professor at Surrey University and a Fellow of the Royal Academy of Engineering. He is a Vice President and Fellow of the IEE. His biography is included in multiple "Who's Who" publications around the world. He sits on the judging panels of a number of awards including the Wall Street Journal "Annual Innovation Awards."

William has a first class honours degree in electronics, a Ph.D. and an MBA.



Kyu-Jin Wee is Director of Regulation Research Department of Radio Research Laboratory (RRL), MIC of Korea. He received the B.E. degree in Engineering in 1981, the M.E. degree in Electrical Engineering in 1983 and the Ph.D. degree in Electrical Engineering in 1988 from Yonsei University. Since 1989, he had been a research engineer in Electronic Material Lab of Oriental Chemical Industry and he joined RRL in 1991. Since 1995 he has been participating in WRC95, WRC97, WRC2000 and WRC2003 as a delegate of Korea. Since 1995, he is the Chairman of IMT-2000 Sub-Committee of the Telecommunications Technology Association (TTA), which is a telecommunications standardization organization in Korea. He was a chairman of ITU-R TG8/1 WG4 during 1997–1999 and is a vice-chair of ITU-R WP8F since 2000. As a TTA Chair, he is Head of Delegation to 3GPP and 3GPP2. He is 3GPP PCG Chair in 2004.

He is also participating in several work programs of Asia Pacific Telecommunity (APT) such as APG (APT Preparatory Group for WRC), ASTAP (APT Standardization Program), and AWF (APT Wireless Froum) and vice Chair of Management Committee of APT since 2002.

His current interest is spectrum management, radio wave propagation, CDMA technologies, and telecommunication standardization.