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Report to Congressional Requesters

May 2004

SPECTRUM MANAGEMENT

Better Knowledge Needed to Take Advantage of Technologies That May Improve Spectrum Efficiency

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GAO-04-666

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Highlights

Highlights of GAO-04-666, a report to congressional requesters

May 2004

SPECTRUM MANAGEMENT

Better Knowledge Needed to Take Advantage of Technologies That May Improve Spectrum Efficiency

Why GAO Did This Study

Recent advances in technologies that rely on the use of the radio-frequency spectrum have turned science fiction of the past into reality. Cellular telephones, wireless computer networks, global positioning system receivers, and other spectrum-dependent technologies are quickly becoming as common to everyday life as radios and televisions. Further, these technologies have become critical to a variety of government missions, including homeland security and strategic warfare.

However, with the increased demand, the radio-frequency spectrum—a resource that once seemed unlimited—has become crowded and, in the future, may no longer be able to accommodate all users' needs. As a result, there has been a growing debate among spectrum policy leaders about how to use spectrum more efficiently. To help inform these debates, GAO was asked to look at agencies' investments in spectrum efficient technologies and how the nation's spectrum management system may affect the development and adoption of these technologies.

What GAO Recommends

GAO is making six recommendations intended to facilitate greater investment by federal agencies in spectrum efficient technologies. Overall, the agencies indicated their commitment to promoting greater flexibility and more efficient use of radio spectrum.

www.gao.gov/cgi-bin/getrpt?GAO-04-666.

To view the full product, including the scope and methodology, click on the link above. For more information, contact Katherine V. Schinasi at (202) 512-4841 or schinasik@gao.gov.

What GAO Found

The nine federal agencies that GAO reviewed—which are among the largest users and investors in technologies and systems impacting spectrum use—have made some investments in technologies that provide improved spectrum efficiency. However, these investments have tended to occur when agencies needed to make greater use of available spectrum to meet a mission requirement—not by an underlying, systematic consideration of spectrum efficiency. For example, as a result of growing spectrum constraints, the Department of Defense (DOD), the Federal Aviation Administration, and the National Aeronautics and Space Administration began investing in technologies that would increase the throughput of information while using smaller segments of their available spectrum. However, agencies also consider other factors—including cost and technical and operational concerns—that may dissuade them from investing in spectrum efficient technologies. For example, DOD may need to use more spectrum to meet an operational requirement to field a jam-proof and accurate radar for military aircraft.

The current structure and management of spectrum use in the United States does not encourage the development and use of some spectrum efficient technologies. Because the spectrum allocation framework largely compartmentalizes spectrum by types of services (such as aeronautical radio navigation) and users (federal, nonfederal, and shared), the capability of emerging technologies designed to use spectrum in different ways is often diminished. For example, software-defined cognitive radios—radios that adapt their use of the spectrum to the real-time conditions of their operating environments—could be used to sense unused frequencies, or "white spaces," and automatically make use of those frequencies. It may also be possible to use software-defined cognitive radios to exploit "gray spaces" in the spectrum—areas where emissions exist yet could still accommodate additional users without creating a level of interference that is unacceptable to incumbent users—to increase spectrum efficiency. Currently, however, the spectrum allocation system may not provide the freedom needed for these technologies to operate across existing spectrum designations, and defining new rules requires knowledge about spectrum that spectrum leaders do not have. At the same time, there are few federal regulatory requirements and incentives to use spectrum more efficiently. While the National Telecommunications and Information Administration (NTIA) is responsible for managing the federal government's use of spectrum and ensuring spectrum efficiency, NTIA primarily relies on individual agencies to ensure that the systems they develop are as spectrum efficient as possible. Agencies' guidance and policies, however, do not require systematic consideration of spectrum efficiency in their acquisitions. The lack of economic consequence associated with the manner in which spectrum is used has also provided little incentive to agencies to pursue opportunities proactively to develop and use technologies that would improve spectrum efficiency governmentwide.

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Abbreviations

AGILE	Advanced Generation of Interoperability for Law Enforcement
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DOJ	Department of Justice
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FCS	Future Combat Systems
GHz	gigahertz
IWN	Integrated Wireless Network
JTRS	Joint Tactical Radio System
KHz	kilohertz
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
NEXCOM	Next Generation Air/Ground Communications
OMB	Office of Management and Budget
TTNT	Tactical Targeting Network Technology
TSAT	Transformational Satellite
UWB	ultra-wideband

G A O
Accountability * Integrity * Reliability
United States General Accounting Office
Washington, DC 20548

May 28, 2004

The Honorable Tom Davis
Chairman, Committee on Government Reform
House of Representatives

The Honorable Adam Putnam
Chairman, Subcommittee on Technology, Information Policy, Intergovernmental Relations, and the Census
Committee on Government Reform
House of Representatives

Over the past several decades, the development and use of telecommunications and information technology has expanded dramatically, greatly increasing the use of the radio-frequency spectrum. Cellular telephones, wireless computer networks, and global-positioning-system receivers are quickly becoming as common to everyday life as radios and televisions. Wireless communications have become critical to private industry and a variety of government missions—ranging from scientific research and public safety to homeland security and strategic warfare. As a result, the radio-frequency spectrum, which once seemed unlimited, has become crowded and, in the future, may no longer be able to accommodate all users' needs.

Because of the growing demand for spectrum, there has been increased attention in spectrum management policy debates on ways to improve the efficient and effective use of spectrum. This has led to a growing interest in technologies that can provide more efficient use of spectrum. Therefore, you asked us to (1) determine whether federal agencies are investing in developing spectrum efficient technologies and the key factors they consider in making these investments and (2) determine the extent to which the nation's system for managing government and private sector use of spectrum facilitates the development and adoption of these technologies.

Our review focused on federal agencies that are among the largest users of technologies and systems impacting spectrum use—the Department of Defense (DOD), the Federal Aviation Administration (FAA) within the Department of Transportation, the Department of Homeland Security (DHS), the Department of Justice (DOJ), and the National Aeronautics and Space Administration (NASA)—as well as the National Science

Foundation (NSF), which funds research on spectrum-related technologies. To determine whether agencies were investing in technologies that might improve spectrum efficiency, we reviewed agency budget and investment planning documents and sought additional information from agency officials on specific programs and projects. To assess the key factors that influenced agency investment decisions, we interviewed agency officials and reviewed various documents and studies.

To determine the extent to which the nation's spectrum management system facilitates the development and adoption of these technologies, we interviewed officials at the two agencies responsible for spectrum management in the United States—the Federal Communications Commission (FCC) and the Department of Commerce's National Telecommunications and Information Administration (NTIA)—and reviewed these agencies' spectrum management policies and procedures. We reviewed processes established by the federal spectrum management system and individual agencies for addressing new technologies. We also met with officials at the agencies we reviewed to discuss the challenges of developing and adopting new technologies under the current spectrum management system. In addition, we interviewed experts and reviewed studies from private sector organizations that are examining spectrum policies and technologies—including the Center for Strategic and International Studies and the National Academy of Sciences—and attended several private- and government-sponsored conferences and forums on national spectrum management issues and new spectrum technologies.

We performed our work from June 2003 through May 2004 in accordance with generally accepted government auditing standards.

Results in Brief

The agencies that we reviewed have made some investments in technologies that provide improved spectrum efficiency. However, these investments have been primarily driven by the imperatives of their individual missions—not by an underlying, systematic consideration of spectrum efficiency. For example, as a result of growing spectrum constraints, DOD, FAA, and NASA began investing in technologies that would increase the throughput of information while using smaller segments of their available spectrum. These investments were needed to meet mission-specific requirements and goals, such as DOD's need for enhanced communications capabilities to meet its goal of information superiority and network-centric war-fighting, and FAA's need to meet growing demands for air traffic control communications. In addition to mission requirements, agencies consider other factors and tradeoffs—including cost and technical and operational concerns when making investment decisions. However, some of these considerations may dissuade agencies from investing in spectrum efficient technologies. For example, to meet an operational requirement to field jam-proof and accurate radar for military aircraft, DOD may need to use more spectrum.

The current structure and management of spectrum use in the United States may limit the development and use of some spectrum efficient technologies. Because the spectrum allocation structure largely compartmentalizes spectrum by types of services (such as aeronautical radio navigation) and users (federal, nonfederal, and shared), the capability of emerging technologies that are designed to use spectrum in different ways is often diminished. For example, technologies like software-defined cognitive radios can be adapted to operate in virtually any segment of spectrum and, in the future, may be able to adapt to real-time conditions and make use of underutilized spectrum in a given location and time. Currently the spectrum allocation system, however, may not provide the freedom needed for these technologies to operate across existing spectrum designations. Moreover, defining new rules to accommodate these emerging technologies requires knowledge about spectrum use that is not currently available. For example, NTIA and FCC do not have a sufficient understanding of the spectrum environment, including how and how much spectrum is used, and lack agreed-upon models to assess spectrum efficient technologies. At the same time, there are few federal regulatory requirements and incentives for agencies to use spectrum more efficiently. While NTIA is responsible for managing the federal government's use of spectrum and ensuring spectrum efficiency,[1] NTIA primarily relies on individual agencies to ensure that the systems they develop make as efficient use of the spectrum as possible. Agencies' guidance and policies, however, do not require systematic consideration of spectrum efficiency in their acquisitions. The lack of economic consequence associated with the manner in which spectrum is used has also provided little incentive to agencies to pursue opportunities proactively to develop and use technologies that would improve spectrum efficiency governmentwide.

[1] FCC has authority over all nonfederal spectrum use, including the use of spectrum by state and local governments.

We are making six recommendations to help facilitate greater consideration and investment by federal agencies in spectrum efficient technologies. Specifically, we are recommending that the NTIA Administrator and the FCC Chairman jointly take actions to build more flexibility into the spectrum allocation system where feasible and gain a better understanding of the current spectrum environment and spectrum efficient technologies to increase the use of these technologies. We are also recommending that the NTIA Administrator take actions to encourage agencies to use spectrum more efficiently. In commenting on the draft report, FCC supported our recommendations. The Department of Commerce also commented on the draft, though it did not specifically address our recommendations.

Background

The radio-frequency spectrum supports a vast array of government and commercial services, including radio and television broadcasts, personal communications services, satellite communications, wireless local area networks, public safety communications, air traffic control, scientific research, and radar-based weather forecasting. The radio spectrum spans a range of frequencies within the electromagnetic spectrum from about 3 kilohertz (kHz) to 300 gigahertz (GHz), but most of its use is concentrated in the lowest 1 percent of these frequencies—sometimes referred to as the "beachfront property" of the radio spectrum.[2] Advances in technology have greatly expanded the usable portions of the radio-frequency spectrum and have led to more efficient means of using the available spectrum. Simultaneously, these advances have created opportunities to provide new spectrum-dependent services, which have led to even greater demand on the limited available spectrum.[3]

[2] Radio waves are a form of electromagnetic energy, propagating through space at the speed of light. The number of waves that pass a given point per second defines the frequency of a radio wave in cycles per second, or hertz. Kilohertz (kHz), megahertz (MHz), and gigahertz (GHz) describe frequencies of thousands, millions, and billions of hertz, respectively. The radio spectrum above 100 MHz and below 3 GHz has propagation characteristics that are well suited for services such as mobile phones, radio and television broadcasting, some satellite communication systems, radars, and aeronautical telemetry systems.

[3] Nearly 30 years ago, GAO reported that technology was creating demands for spectrum faster than it was creating methods to meet those demands. See U.S. General Accounting Office, *Information on Management and Use of the Radio Frequency Spectrum—A Little-Understood Resource*, B-159895 (Washington, D.C.: Sept. 13, 1974).

The spectrum is managed to maximize the benefits derived from this limited resource, while mitigating interference among various users.[4] Within the United States, the spectrum is managed jointly by the NTIA, within the Department of Commerce, and the FCC. NTIA is principally responsible for developing and articulating domestic and international telecommunications policy[5] and for managing the federal government's use of the radio spectrum. FCC has authority over all nonfederal spectrum use, including the use of the spectrum by state and local governments.

In managing the spectrum, FCC and NTIA have largely used a "command-and-control" approach, which dictates how each segment of the radio spectrum can be used and who can use it. This approach generally involves five steps: allocation, adoption of service rules or technical standards, certification, assignment, and enforcement. Table 1 describes each step.

[4] Interference occurs when two or more radio signals interact in a manner that disrupts or degrades the ability of these signals to convey information successfully to their intended receivers. However, the extent and impact of interference depends on the technologies used both to transmit and receive radio signals, and the types of services and applications supported.

[5] Each country makes its own allocations of spectrum use; therefore, allocation decisions may differ in other regions of the world and in other countries. However, because radio wave propagation obeys the laws of physics and cannot be forced to respect national borders, spectrum management decisions (particularly allocation decisions) generally have been coordinated internationally. The International Telecommunication Union (ITU), a specialized agency of the United Nations, holds World Radiocommunication Conferences every 3 to 4 years to coordinate spectrum decisions and address other pressing international spectrum management issues.

Table 1: Five Steps Associated with the Command-and-Control Approach to Spectrum Management

Step	Actions taken by FCC and NTIA
Allocation	Particular segments, or "bands," of the radio spectrum are designated for specific types of services—for example aeronautical radio navigation—with bands of varying widths.
Adoption of service rules or technical standards	Rules and standards specify the required technical and operational characteristics of the radios (or other radio-frequency devices) that will use the allocated band, such as radiated power limits, channel bandwidth and location, levels of acceptable interference, and other service-specific or band-specific rules.
Certification	Major federal systems that directly use the radio-frequency spectrum must be certified by NTIA, as required by the Office of Management and Budget (OMB) Circular A-11, to be assigned a bandwidth. An agency first determines if the system it proposes to field is "major"—that is, the system could cause significant impact on the radio-frequency spectrum—then conducts the necessary technical studies of the proposed system, selects potential frequency bands, coordinates with other agencies involved, and prepares and files a certification application to NTIA for review. FCC similarly certifies nonfederal systems.
Assignment[a]	Once service rules and technical standards have been established, portions of the allocated band are assigned—typically, to individual users or service providers operating within a certain geographic area through a variety of mechanisms.
Enforcement	Spectrum monitoring, interference reporting, and other regulatory mechanisms are used to enforce allocations, technical standards and service rules, and unique geography-based assignments.

Source: GAO.

[a]Not all spectrum use requires an assignment. For example, many familiar "unlicensed" wireless devices—such as cordless phones, baby monitors, garage door openers, and wireless Internet access devices—are allowed to operate within certain spectrum bands provided they do not cause harm to assigned users and accept any interference received.

NTIA and FCC implement the command-and-control approach differently because of differences in their missions. For example, NTIA assigns spectrum resources through an administrative process that emphasizes interdepartmental advice and coordination among federal agencies, while FCC has used a number of administrative processes including comparative hearings and lotteries as well as its authority to assign spectrum through auctions.[6] However, because so much of the spectrum is shared between federal and nonfederal users, FCC and NTIA must coordinate their management of spectrum.[7]

For many decades, command-and-control has been the most commonly used approach for managing the spectrum. However, as both the usage of and demand for spectrum have exploded over the past decade, the disadvantages of the command-and-control approach have become increasingly apparent. For example, in October 2001, the FCC Chairman noted that it is becoming difficult for government officials to determine the best use for spectrum and to repeatedly adjust allocations and assignments of spectrum to accommodate new spectrum needs and new services. The President has similarly noted that the existing legal and policy framework for spectrum management has not kept pace with the dramatic changes in technology and spectrum use and can discourage the introduction of new technologies.

In June 2002, the FCC Chairman established a Spectrum Policy Task Force to help identify and evaluate changes in spectrum management policy and to provide specific recommendations to FCC for ways to evolve from the current command-and-control approach to a more integrated, market-oriented approach. In November 2002, the Task Force reported its findings and recommendations to FCC.[8] While noting that no single regulatory model should be applied to all spectrum, the Task Force recommended that FCC pursue a spectrum management policy that includes both exclusive spectrum usage rights granted through market-based mechanisms and creates open access to spectrum "commons," with command-and-control regulation used in limited circumstances. In January 2003, we issued a report recommending a commission be established to conduct a comprehensive examination of current U.S. spectrum policy. [9] In May 2003, the President signed an executive

[6] 47 USC § 309(j).

[7] For more information on how spectrum is managed, see U.S. General Accounting Office, *Telecommunications: Better Coordination and Enhanced Accountability Needed to Improve Spectrum Management*, GAO-02-906 (Washington, D.C.: Sept. 30, 2002).

[8] Federal Communications Commission, *Spectrum Policy Task Force Report*; ET Docket No. 02-135 (Washington, D.C.: Nov. 2002).

[9] U.S. General Accounting Office, *Telecommunications: Comprehensive Review of U.S. Spectrum Management with Broad Stakeholder Involvement Is Needed*, GAO-03-277 (Washington, D.C.: Jan. 31, 2003).

memorandum establishing the federal government's "Spectrum Policy Initiative" to develop recommendations for improving spectrum management policies and procedures for the federal government and to address state, local, and private spectrum use.[10]

Although work under the President's initiative is ongoing, the initiative recognizes, along with the findings of the 2002 FCC Task Force, that existing and emerging technologies create the potential for future radios and other radio-frequency devices and systems to use spectrum more efficiently.[11] Efficiency may be accomplished through improvements to a broad set of technologies and applications. Table 2 provides descriptions and key examples of such technologies and applications that can improve the utilization of spectrum.

[10] The initiative consists of two courses of spectrum-related activity: (1) an interagency task force to focus on improving spectrum management policies and procedures to stimulate more efficient and beneficial use of government spectrum and (2) a series of public meetings that will assist the Department of Commerce in developing a detailed set of recommendations for improving policies and procedures for use of spectrum by state and local governments and the private sector, as well as the spectrum management process as a whole.

[11] In addition, the NSF is currently sponsoring a study at the National Academy of Sciences on wireless technology advances and associated implications for spectrum management policy.

Table 2: Descriptions and Key Examples of Existing or Emerging Technologies That Can Improve Spectrum Utilization

Technology	Description	Key examples
Radio frequency component-level	Encompasses a broad set of radio-frequency components—transmitters, receivers, and antennas (and their enabling technologies)—that can improve spectrum utilization.	• "Smart" antennas that can selectively amplify desired signals while canceling out competing signals. • Modulation and channel coding can also influence how much spectrum is needed to transfer encoded voice data.
Other component-level	Encompasses a broad set of other (non-radio frequency) radio components including digital processors and associated algorithms to compress data, and batteries for handheld devices.	• More advanced algorithms to encode and digitally compress a human voice can greatly reduce the radio's data transfer requirements. • Improving the efficiency of a handheld radio's battery can allow it to accomplish more sophisticated data compression, modulation and coding, and thus indirectly, influence the radio's ability to use spectrum more efficiently.
Network-level	Technologies and related network or spectrum management practices that can significantly improve information transfer and spectrum efficiency as well as mission effectiveness.	• Improvements to an ad-hoc network's routing strategies can enable more efficient use of available network resources, including spectrum resources. • Advanced quality of service algorithms may enable a diverse set of network users with very different requirements and mission-driven priorities, to operate on a single network and share the spectrum resources of the entire network; these algorithms can grant high priority to the rapid transmission of critical communications and lower priority to routine message traffic.
Other enabling technologies	Includes investments in various technologies that may yield improvements to spectrum utilization and efficiency.	• Advancements in microelectronics and semiconductors have enabled greater processing power in smaller lighter weight packages. These advancements continue with the development of semiconductor technologies that may greatly improve upon the performance of today's radio-frequency components. • Research directed toward improving models of the ionosphere can lead to more efficient use of some frequency bands.
Off-loading technologies	Technologies that are being developed, which would facilitate "off-loading"—that is, relocating certain communications requirements from highly congested radio-frequency spectrum to higher radio-frequency bands and non-radio-frequency portions of the electromagnetic spectrum.	• Research is under way to further the use of lasers to communicate at very high data rates.

Source: GAO.

Many spectrum efficient technologies have both component-level and network-level attributes. For example, some "smart" antennas can pinpoint the source signal and selectively amplify it while canceling out competing signals. In addition, because smart antennas direct transmitted power toward desired receivers, the level of interference experienced by other spectrum users is reduced. This adaptive behavior may be controlled by local sensors but may also be cued by information provided through the radio's network. Similarly, software-defined radios, unlike traditional radios, have operating parameters (such as the operational frequency and modulation type) that are determined by software, meaning they can be programmed to transmit and receive on many frequencies and to use any desired modulation or transmission format within the limits of their hardware designs; as with smart antennas, the programmed operating parameters of the radio may be controlled internally or may be cued through the radio's network.

FCC and NTIA are both charged with promoting the efficient and effective use of the radio spectrum. NTIA has told us that ensuring efficient use of the spectrum is a major NTIA goal reflected throughout most of its spectrum management processes, which include

- setting standards for equipment that use the radio spectrum,
- certifying that proposed new systems conform with existing spectrum allocations and associated standards, and
- requiring justification of frequency assignment requests and continuous review of existing frequency assignments.

Additionally, NTIA is responsible for conducting spectrum analyses and research to keep abreast of the latest spectrum efficient technologies that are appropriate for government use and for developing and adopting automated information systems that support the spectrum management processes and facilitate appropriate spectrum conservation measures.

Agencies' Decisions to Invest in New Technologies Are Generally Driven by Factors Other Than Achieving Spectrum Efficiency

Federal agencies have made some investments in technologies that may provide improved spectrum efficiency. However, their decisions to invest in those technologies are primarily driven by their individual missions—not by an underlying, systematic consideration of spectrum efficiency. Agencies generally do not identify spectrum efficiency as a distinct category of technology investment. Other considerations that influence agencies' technology decisions include technical and operational concerns and costs that may make spectrum efficient technologies impracticable.

Agency Mission Is a Key Factor in Determining Investments in New Technologies

Determining investments that may improve spectrum efficiency is difficult because agencies do not clearly identify spectrum-related investments in their budgets. However, using published budget and other information provided to us by each of the nine agencies, we identified projects that might result in improved spectrum efficiency and spoke with agency officials about their technology investments. Based on this review, we identified 335 fiscal year 2004 federally funded projects that potentially included funding for spectrum efficient technologies.[12] Funding for these projects totaled approximately $1.8 billion.[13] These investments cover a wide range of technologies that can affect spectrum use, including the compression of raw source data, advanced radios, and network improvements. The military services and Defense Advanced Research Projects Agency (DARPA) combined are by far the largest federal investors in new technologies that use the spectrum. In contrast, the Departments of Justice and Homeland Security have small research and development budgets and tend to rely on technologies that are commercially available. Table 3 provides the total fiscal-year-2004 funding identified for each agency's projects related to spectrum efficiency and highlights major areas of investment.

[12] Amounts included for NSF are based on funds provided grantees in 2003.

[13] We did not verify the reliability of the funding information, however, it comes from published agency budget documents and program officials.

Table 3: Agency Research and Development Investments in Technologies That May Improve Spectrum Efficiency

(Dollars in millions)

Agency	Areas of major investment related to spectrum efficiency	Total funding for fiscal year 2004
DARPA	Antenna technologies, laser communications, transistor technologies, and cognitive communications	**$339.7**
U.S. Air Force	Software defined radio/laser communications	**649.4**
U.S. Army	Software defined radio	**381.9**
U.S. Navy/Marine Corps	Software defined radios	**172.4**
NASA	Optical (laser) communications	**41.8**
DOJ		**0**[a]
DHS		**0**[b]
FAA	Air traffic control communications and digital radar	**165.8**
NSF	Interference avoidance and measurement, networking, antenna technologies, data compression, error correction, and cognitive radio research	**14.8**[c]

Source: GAO.

Note: Investments include amounts invested in projects undertaken with a stated goal of improving radio-frequency spectrum and projects where spectrum efficiency is not a stated goal but a possible outcome (including enabling technologies like software defined radios). These investments also include projects to off-load/achieve communications in non-radio portions of the electromagnetic spectrum, for example, laser communications. Because of the difficulty identifying relevant projects and quantifying relevant investments in projects where spectrum efficiency may be only a small component, actual investment numbers may be higher or lower.

[a]DOJ focuses on the acquisition of commercial-off-the-shelf equipment.

[b]While DHS is not currently funding research and development into technologies to provide improved spectrum efficiency, it expects to in the future.

[c]NSF grants funded in fiscal year 2003. According to agency officials, NSF has recently initiated a number of spectrum efficiency projects, including a study of programmable wireless networking, on which it plans to allocate at least $8 million per year.

Agency investments in technologies that provide greater spectrum efficiency have tended to occur when agencies need to make greater use of available spectrum to meet a mission requirement and the additional spectrum is not readily available, as is the case with DOD. Specifically, DOD systems are requiring greater bandwidth to transmit intelligence and surveillance information, facilitate enhanced communications capabilities, and conduct electronic warfare—which DOD considers essential to meeting its key strategic goal of information superiority. As a result, DOD has made significant investments in new systems that, in part, address problems related to insufficient spectrum, as the following examples illustrate:

- **Joint Tactical Radio System (JTRS):** To address key communications shortfalls and significantly improve military capabilities, DOD has begun to make significant investments in software-defined radios, which offer the potential of more efficient spectrum use in the future without the need for expensive and complex hardware changes. In 1997, DOD initiated the JTRS program to develop and apply this technology and to bring together separate service-led programs into a joint software-defined radio development effort. JTRS radios are intended both to interoperate with existing radio systems and to provide military users with more flexible communications capabilities in the future.

- **Air Force's Transformational Satellite (TSAT) Program**: The Air Force is exploring new technologies that enable communications in higher radio-frequency bands, which are much less congested, and in non-radio-frequency portions of the electromagnetic spectrum. Non-radio-frequency technologies will enable next-generation military satellites to communicate at very high data rates using lasers. As a result, information can be transferred without relying on the radio-frequency spectrum.

- **DARPA's Tactical Targeting Network Technology (TTNT) Program:** TTNT program aims to demonstrate a high-capacity sensor data system that could enable networks of strike aircraft to accomplish their missions. In particular, certain missions require the rapid sharing of targeting sensor data among a large ad-hoc network of strike aircraft. Currently, the U.S. military's airborne tactical data links cannot support a large network of aircraft simultaneously due to spectrum constraints. TTNT is expected to provide a data rate 10 to 25 times higher than the current airborne tactical data link in an equivalent amount of spectrum.

Other agencies have made some investments in spectrum efficient technologies, and like DOD, these investments were largely driven by agency mission, as in the following examples:

- **NASA's Mars Laser Communications Demonstration Project:** NASA anticipates a significant increase in the near future in demand for long-haul communications services from deep space to Earth. As a result, it has undertaken the Mars Laser Communications Demonstration Project—a joint project with the Massachusetts Institute of Technology's Lincoln Laboratory—to develop a laser-based communications system that would transfer information without relying on the radio-frequency spectrum. Such a system would facilitate bandwidth-hungry instruments, such as imaging systems and radar to be used in deep space exploration.

- **Federal Aviation Administration's Next Generation Air/Ground Communications (NEXCOM) Initiative:** In 1990, FAA began the NEXCOM initiative in response to growing demands for air-to-ground air traffic control communications. By replacing current analog radios with digital radios, the program is expected to achieve greater spectrum capacity using the same spectrum currently allocated for air traffic control communications. Each of NEXCOM's 25 kHz channels will support four voice circuits, instead of the one circuit supported by the current system.

- **DOJ's Integrated Wireless Network (IWN) System:** While Justice is not investing directly in research and development into technologies to improve spectrum efficiency, it has undertaken a joint effort—the IWN system—with the Departments of Homeland Security and Treasury to provide improved interoperability of communications within the federal law-enforcement community. New equipment being acquired under the IWN system, such as new land mobile radios, will significantly increase spectrum efficiency.

Other Factors That Influence Agencies' Investment Decisions

Besides mission objectives, several other factors, such as technical and operational considerations and cost-effectiveness, influence agencies' technology investments. In considering these factors, agencies may determine that using more spectrum efficient technologies is impractical.

If an agency developed a system solely to minimize spectrum usage or optimize spectrum efficiency, the system may also include other less desirable or unacceptable operational characteristics—that is, characteristics that are incompatible with accomplishing an agency mission. For example, the Army's Future Combat Systems (FCS)[14]—the

[14] FCS is an information network linking a suite of 18 new manned and unmanned ground vehicles, air vehicles, sensors, and munitions.

centerpiece of the Army's plan to transform to a lighter, more agile, and more capable force—will rely on superior information to see and hit the enemy first. Future Combat Systems' capabilities depend, in part, on the ability of the Army's network to collect, process, and deliver vast amounts of information such as imagery and communications that will require much higher spectrum usage. Operational considerations also can affect radar aboard military aircraft. Such radars must operate in unfriendly and stressed conditions, including exposure to enemy jamming capabilities and flight speeds of up to 1800 to 2000 kilometers per hour. Aircraft radars must also function while the aircraft is conducting evasive maneuvers to avoid threats such as enemy missiles. According to DOD officials, the bandwidth used by aircraft radars is directly related to the radar's accuracy. As a result, limiting the radar's bandwidth could result in the aircraft engaging a wrong target or other unwanted consequences. Also, some federal agencies that intend to operate spectrum-dependent systems outside of the United States may have to compromise the application of more efficient technologies in order to acquire spectrum access in other countries. For example, in developing communications and radio navigation systems for aircraft, FAA is largely limited to using globally allocated bands that are designated for aeronautical services.

In addition, agencies need to make tradeoffs between spectrum efficiency and cost. For example, a new type of smart antenna, called an adaptive array, can extend the range of communications systems and minimize interference. Although more efficient in its use of spectrum, this new technology is generally more expensive than traditional antenna technology, and, as a result, these technologies may not be considered or developed unless justified by mission needs. Similarly, the Department of Justice's Advanced Generation of Interoperability for Law Enforcement (AGILE) program is coordinating the efforts of federal, local, state, and regional public safety organizations to achieve interoperable communications. However, local, state, and regional organizations may lack funding to replace their legacy radio systems and radio infrastructure with the most efficient systems available. As a result, these interoperability and funding concerns may dictate what technologies can be selected for use in new federal systems and may limit the degree of spectrum efficiency achieved.

Agencies' Technology Planning Processes Do Not Identify Spectrum Efficiency as an Investment Area

To help manage their investment decisions, some agencies have established science and technology planning processes to identify long-term technological needs, establish research and technology priorities, and coordinate research activities. These processes enable policy makers and implementers to adjust the allocation of agency resources to meet changing requirements for fulfilling agency missions. However, the agencies' science and technology planning processes that we reviewed do not specify spectrum efficient technologies as an investment area. For example, FAA's research and development strategy does not focus specifically on achieving spectrum efficiency; rather, it emphasizes improving the overall efficiency of the nation's air traffic control systems—which may require making better use of the spectrum. Similarly, the military services' science and technology planning processes emphasize achieving overall operational efficiency and effectiveness, which may or may not result in improved spectrum efficiency. A DOD official within the Office of the Assistant Secretary of Defense for Networks and Information Integration acknowledged that spectrum efficiency does not receive the same level of attention as science and technology efforts to improve more conventional weapons systems' performance requirements such as lethality and survivability.

However, DOD has taken initial steps to consider spectrum efficiency by revising its policy and guidance on spectrum management. Specifically, DOD's Electromagnetic Spectrum Management Strategic Plan—which was issued in December 2002 —has five core principles, including one that recognizes the need to invest in new spectrum efficient technologies. In addition, the strategic plan established a goal to improve spectrum utilization through technological innovation. As part of developing a strategy for DOD, the Defense Spectrum Office[15] has begun to study emerging technologies and future war fighter requirements. In addition, DOD convened a group of technologists last year to discuss spectrum technologies and how to link them more directly to DOD's science and technology planning process. Because these efforts are in their early stages, they have not yet resulted in policy changes or modifications to investment plans. Similarly, NASA is working on an electromagnetic spectrum management strategy, which is in the final stages of review before release.

[15] The Defense Spectrum Office has the responsibility within DOD for supporting the Assistant Secretary of Defense for Networks and Information Integration in establishing national and international strategies for new technologies that may affect how spectrum is used, occupied, or managed by the department.

Federal Spectrum Management System May Limit the Development and Adoption of Spectrum Efficient Technologies

The current structure and management of spectrum in the United States—allocating bands of spectrum to certain users for specific uses—may limit the development and adoption of some emerging technologies that promise improved spectrum efficiency. However, redefining this structure and management of spectrum to take full advantage of future opportunities to improve spectrum efficiency could be difficult due, in part, to the lack of flexibility in the spectrum allocation system, policy makers' limited knowledge about spectrum use and new and emerging technologies, as well as a lack of agreed-upon models to assess these technologies. At the same time, there are few regulatory requirements and incentives to encourage agencies to develop and use spectrum more efficiently. The current federal regulatory framework and system certification process tend to focus only on major systems that directly use the radio spectrum and their compliance with existing standards to avoid interference—not on spectrum efficiency. A lack of incentives to achieve spectrum efficiency also limits agencies' consideration of spectrum efficient technologies in the acquisition of systems. However, providing such incentives is challenging, in part, because financial considerations must be balanced with mission needs.

Current Spectrum Structure and Management Could Constrain Efforts to Use Spectrum More Efficiently

To manage the use of the radio-frequency spectrum in the United States, FCC and NTIA allocated the spectrum into federal, nonfederal, and shared bands and designated specific bands for specific uses, such as broadcast radio and television. Historically, this structure has served a valuable function. In addition to seeking to avoid interference among users, the structure has enabled spectrum leaders to balance government and commercial interests, provide stability and design certainty for equipment manufacturers, and accommodate a certain level of increased demand by apportioning spectrum for future uses. However, the current allocation structure has proven effective largely because technologies operated within a fairly narrow range of spectrum. While emerging technologies that use wider segments of spectrum or move across segments of spectrum may be able to operate within current demarcations, greater efficiencies may be achievable if these technologies were allowed to operate in an environment that provides more operational freedom than the current structure.

With nearly all of the spectrum allocated and access rights granted to users, such freedom tends to require increased "sharing" of the spectrum[16]—that is, allowing more than one user to transmit radio signals on the same frequency band.[17] In working to increase spectrum sharing, spectrum leaders will need to carefully consider the impacts on incumbent users' operations and define appropriate rules to mitigate those impacts.

However, attaining agreement on such rules may be difficult and could result in operational constraints that reduce the promise of increased spectrum efficiency. For example, radios that are largely defined by their software components could provide greater efficiencies if software enabled them to operate in a shared environment—as DOD hopes to do with JTRS. Currently, DOD is developing 34 waveforms[18] for use in JTRS radios. Of these, 33 waveforms are to be operationally identical to their respective, already fielded, traditional radio counterparts and, consequently, will be able to operate in the current spectrum structure. However, these waveforms will be no more efficient than their existing radio counterparts. While the remaining waveform promises to achieve greater spectrum efficiency in providing voice, video, and data services, it requires access to a wider swath of the spectrum, which JTRS program officials believe will challenge the current spectrum structure and certification process because it could impact other users' operations. JTRS program officials stated that for the near term, some of the concerns associated with the new waveform could be addressed by using software "lockouts" to ensure that sensitive bands are protected. However, to achieve greater efficiency, JTRS program officials believe that spectrum sharing issues will need to be worked out, and spectrum policies and rules will need to be adjusted.

[16] Greater freedom could also be achieved through "band clearing"—moving incumbent users to other parts of the spectrum. Because this reallocation could take significant time and funding to accomplish, band clearing is difficult to implement.

[17] In a shared spectrum allocation, "primary" users have priority over the use of a frequency and "secondary" users must defer to the primary user. Users may also be designated as "co-primary," in which the first operator to obtain authority to use the spectrum has priority to use the frequency over another primary operator.

[18] A waveform is the representation of a signal that includes the frequency, modulation type, message format, and/or transmission system. In general usage, the term waveform refers to a known set of characteristics, for example, frequency bands (VHF, HF, UHF), modulation techniques (FM, AM), message standards, and transmission systems. In JTRS, the term waveform is used to describe the entire set of radio functions that occur from the user input to the radio-frequency output and vice versa. A JTRS waveform is implemented as a re-useable, portable, executable software application that is independent of the JTRS operating system, middleware, and hardware.

As software-defined radios become more sophisticated, the challenge in employing them will become even greater. For example, software-defined cognitive radios—radios that adapt their use of the spectrum to the real-time conditions of their operating environments—could be used to sense unused frequencies, or "white spaces," and automatically make use of those frequencies. According to FCC, many portions of the radio spectrum are not in use for significant periods of time and that tapping into these white spaces—both temporal and geographic—could significantly increase spectrum available for use.[19] It may also be possible to use software-defined cognitive radios to exploit "gray spaces" in the spectrum—areas where emissions exist but that could accommodate additional users without raising the overall noise level in a band to a level unacceptable to incumbent users—to increase spectrum efficiency.[20]

However, employing the technologies needed to exploit these spaces could present significant problems of interference. Currently, FCC is exploring a new approach to cognitive radios and interference control and management[21] based on the concept of measuring "interference temperature."[22] Under this concept, the interference temperature in a given band would be measured, and devices receiving these measurements would restrict their operations in order to maintain the interference temperature at or below a prescribed limit for that band. In the simplest case, the entire process would take place within an individual device, such as a software-defined cognitive radio capable of measuring the interference temperature at its location and making a decision to transmit

[19] FCC *Spectrum Policy Task Force Report*; ET Docket No. 02-135 (Washington, D.C.: Nov. 2002).

[20] DOD's DARPA has a major effort under way (the Next Generation Communications Program) to develop enabling technologies and system concepts to dynamically use the spectrum through real-time sensing of the spectrum environment and adjustment of radio operations to take advantage of white and gray space opportunities. Its goal is to increase spectrum access by a factor of 10.

[21] FCC Notice of Proposed Rulemaking and Order In the Matter of Facilitating Opportunities for Flexible, Efficient, and Reliable Spectrum Use Employing Cognitive Radio Technologies; FCC 03-322 (Dec. 30, 2003); FCC Notice of Inquiry and Notice of Proposed Rulemaking in the Matter of Establishment of an Interference Temperature Metric to Quantify and Manage Interference and to Expand Available Unlicensed Operation in Certain Fixed, Mobile and Satellite Frequency Bands; FCC 03-289 (Nov. 28, 2003).

[22] "Temperature" refers to a measure of the undesired radio-frequency power in a particular band and location. FCC's Spectrum Policy Task Force developed the concept of an interference temperature to characterize and quantify undesired (interfering) transmitters' contributions to radio-frequency energy at a receiver's location.

or not transmit based on this measurement plus its own contribution of radio-frequency energy. However, the interference temperature concept is controversial and in the view of many has yet to be successfully demonstrated in a practical context. NTIA believes that more study is needed to determine what might be the "correct" tool for quantitatively controlling interference between mobile and unlicensed transmitting devices that share spectrum with existing telecommunication facilities.

Lack of Knowledge and Varying Perspectives about Spectrum May Further Constrain the Use of More Spectrum Efficient Technologies

The extent to which emerging and future technologies, such as those that would exploit white and gray spaces, could be utilized to increase spectrum efficiency is dependent on the degree of freedom these technologies would be provided to operate across the spectrum. While unconstrained operation may not be realistic—given the sensitivity of certain uses of spectrum—it may be possible to develop policy-based rules to maintain some constraints, such as blocking the use of certain frequency bands, while allowing greater freedom in other areas of spectrum. Defining such rules, however, requires a level of understanding of the spectrum environment—including how and how much spectrum is used—and spectrum efficient technologies that NTIA and FCC do not currently have. For example, in 2002, the FCC's Spectrum Policy Task Force noted that in order to define rules for the implementation of the interference temperature concept, additional knowledge—including the need to acquire data on the current ambient noise levels for different frequency bands and geographic regions—would be required.[23] To that end, the Task Force recommended a systematic study of the spectrum environment.

Currently, NTIA has the capability to capture knowledge needed to better understand the radio spectrum environment through a radio spectrum measurement program, which it established in 1973 to assess whether spectrum is being used in accordance with applicable regulations and to provide information to prevent or resolve interference problems involving federal government systems.[24] However, the measurement program is

[23] Under the proposed approach, an interference temperature metric would establish maximum permissible levels of interference, thus characterizing the "worst case" environment in which a receiver would be expected to operate. Different threshold levels would then be set for each band, geographic region or service based on an understanding of the radio frequency environment.

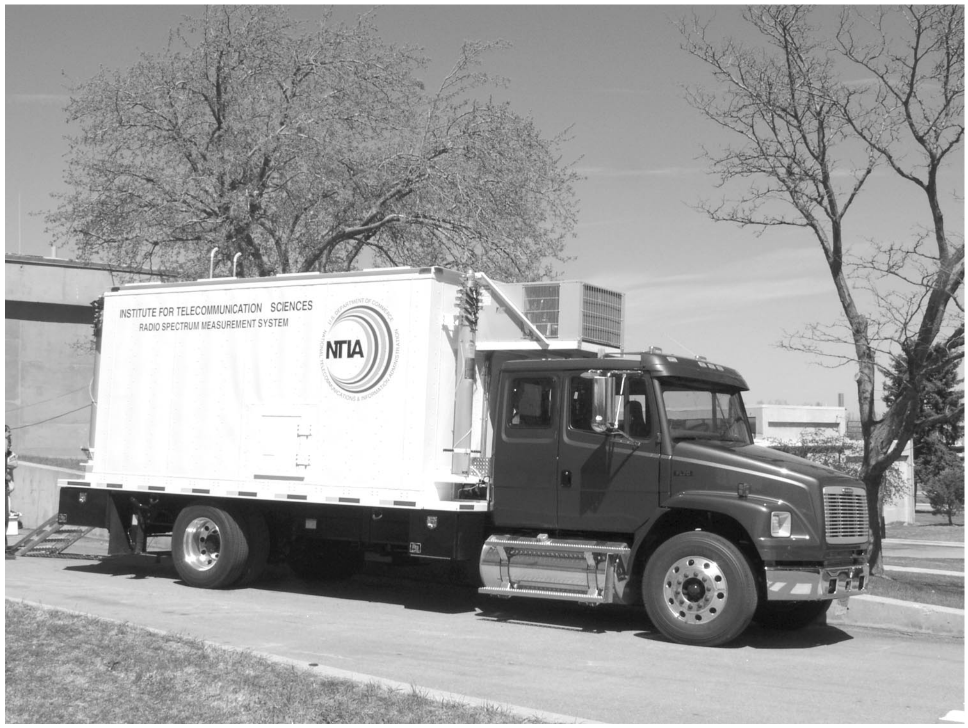
[24] FCC and FAA also have spectrum-monitoring capabilities.

limited to measuring and recording radio signals between 10 kHz and 20 GHz at selected sites through equipment housed in a single van (see fig. 1)[25] and in portable suitcases. As such, the van has been used primarily to help reach consensus on difficult or unusual interference and spectrum sharing problems having a high national importance. For example, such measurements have assisted in reaching some consensus on the use of ultra-wideband (UWB) devices, expanded 5 GHz unlicensed device operation, and broadband over power lines. According to NTIA, all of these activities directly support the Administration's goals related to facilitating emerging technologies. However, the last compliance-type measurements were conducted in the mid-1980s. According to NTIA, these measurements were discontinued because of a lack of resources and generally low benefits provided to national spectrum management. NTIA has also discontinued its broadband spectrum surveys—which covered the spectrum from about 100 MHz to 20 GHz.[26] The last broadband survey measurements were made in the San Francisco area in 1995 with results reported in 1999.

[25] In fiscal year 2002, NTIA received $2.1 million to replace the van. The replacement van was used for the first time in the summer of 2003.

[26] The term "broadband" used in this context refers to a survey of multiple radio frequency bands. The use of the term here does not refer to technologies that encompass all evolving high-speed digital technologies that provide consumers integrated access to voice, high-speed data, video-on-demand, and interactive delivery services.

Figure 1: NTIA's Spectrum Measurement Van



Source: NTIA.

In addition, NTIA lacks sufficient information to more accurately model and test the impact of emerging technologies to determine their likely operational characteristics. For example, NTIA must typically rely on federal agencies to provide information on the technical characteristics of their radio communication systems. According to NTIA officials, this information has been insufficient to perform detailed analyses of some technologies. Furthermore, since NTIA and FCC have different spectrum management responsibilities—federal and nonfederal, respectively—they have different perspectives on spectrum use. NTIA tends to focus on protecting the federal government's use of the spectrum from harmful interference—especially in areas critical to national security and safety—while FCC tends to focus on maximizing public access to and use of the spectrum. As a result, NTIA and FCC have different perspectives on the assumptions and operational scenarios that should be used to assess potential interference from new technologies. This divergence can lead to difficulties in establishing agreed-upon service rules and technical standards, resulting in delays in accommodating new technologies.

The effect of limited knowledge and varying perspectives on defining policy-based rules is demonstrated in the government's recent efforts to accommodate commercially developed low-power UWB devices,[27] which offer greater utilization of the spectrum in a shared environment. Potential uses include radar imaging of objects buried underground or behind walls and short-range, high-speed data transmissions. Because UWB devices transmit over large swaths of spectrum and emit into spectrum used by both federal and nonfederal users, NTIA and FCC have shared responsibilities in their use. However, there has been considerable debate over how much interference UWB devices would cause to other spectrum users—with particular concern for protecting the Global Positioning System and public safety systems. For example, NTIA was concerned that allowing UWB systems to emit intentionally into certain bands would cause potential interference to vital federal government services. To assess the potential impact of introducing UWB devices into the spectrum environment, NTIA had to make assumptions about the devices' characteristics and simulate their transmissions because commercial UWB devices were not available for testing.

In February 2002—after substantial debate among NTIA, FCC, and other interested parties—FCC established rules to allow the development and marketing of unlicensed, low-power UWB devices in a limited frequency range and with power limitations, based in large measure on standards recommended by NTIA.[28] However, FCC has expressed its intent to revisit the adopted standards eventually because of its concern that the standards may be overly stringent—reflecting technical analyses of "worst case" scenarios, not real-life operating conditions—and could unnecessarily constrain development of UWB technology.[29] Conversely, some federal agencies remain concerned that not enough is known about how UWB interacts with existing systems, including the aggregate effect of large numbers of UWB devices. According to FCC officials, UWB device manufacturers expressed concerns that their investments in components that comply with the adopted standards would be lost if a less restrictive order is adopted too soon. In February 2003, FCC made minor changes to

[27] UWB devices employ very narrow or short duration pulses to create wideband transmissions.

[28] NTIA has also established similar rules governing federal use of low-power UWB devices.

[29] The lack of technologies capable of providing users with real-time knowledge of spectrum environments has required an approach to spectrum management based on worst-case assumptions to minimize interference.

UWB regulations but opted not to make any significant changes to the existing UWB technical parameters, citing the lack of experience with UWB devices and concerns that any major changes to the rules for existing UWB product categories would be disruptive to current industry product development efforts.

Federal Requirements to Invest in Spectrum Efficient Technologies Are Limited

NTIA is responsible for promoting the efficient and effective use of spectrum that has been assigned to federal users. However, the current regulatory framework and system certification process for federal spectrum use tend to focus on compliance with existing standards to avoid interference, not on spectrum efficiency. Furthermore, agency regulations do not systematically require the consideration of spectrum efficiency in the development and acquisition of systems.

While NTIA's certification process helps avoid interference, it does not directly consider whether the fielded system would use too much spectrum or could incorporate other technologies to improve spectrum efficiency. In general, NTIA's certification process focuses on maintaining the integrity of the current spectrum structure by ensuring that

- fielded systems operate in a frequency band allocated for the type of service they provide, such as maritime mobile radio;
- frequency assignments are available for systems to operate in their intended operational environment; and
- the technical characteristics of fielded systems are compatible with the operation of other systems, that is, they will not significantly interfere with others.

NTIA's ability to influence spectrum use is also somewhat limited because it only receives and reviews spectrum certifications for "major" federal systems that directly use the radio-frequency spectrum—that is, systems that could have significant impact on other users of the radio spectrum—with each agency determining which of its systems are major. In addition, systems that utilize spectrum, but are not direct transmitters or receivers of radio waves, such as network routing strategies, are not subject to the certification process and therefore not within NTIA's influence. Finally, NTIA officials told us that in general, individual agencies have not identified and reported their long-term requirements for spectrum. These officials also indicated that telecommunication investments are not easily identifiable because agency budget submissions do not break out or otherwise provide the ability to readily identify investments for systems that require spectrum. Although agencies must obtain spectrum certification prior to submitting budget proposals to OMB for approval, as required by OMB Circular A-11, NTIA officials told us that OMB does not routinely receive this information from NTIA nor systematically review and coordinate intended spectrum use during its review of agency budget submissions. Because agency investment in radio spectrum dependent systems cannot be readily identified, NTIA officials also stated that NTIA has generally had to react to spectrum demands as they become apparent through the certification process as opposed to planning for future spectrum use.

NTIA has generally relied on agencies to ensure that their systems are as spectrally efficient as possible.[30] However, the acquisition guidance and policies of the agencies we reviewed do not require the systematic consideration of spectrum efficiency in the design and development of systems. Similar to NTIA's certification process, these agencies' internal certification procedures tend to focus on avoiding significant interference among systems. For example, FAA's policy for the use of radio spectrum identifies spectrum efficiency as a broad objective, but its certification process focuses mainly on equipment characteristics and compliance with NTIA standards and national and international spectrum allocation rules. While DOD's acquisition policies and procedures require system developers and acquirers to consider spectrum supportability, they do not specifically require consideration of spectrum efficiency. Ensuring spectrum supportability could ultimately result in some spectrum efficiencies. However, we have previously reported that DOD's weapons programs often failed to obtain, consider, or act on spectrum supportability knowledge during the early stages of acquisition,[31] as required by DOD policy. Several weaknesses underlie this failure, including program managers' lack of awareness of spectrum certification

[30] A few NTIA policies and technical standards do specifically require federal agencies to improve efficiency in a few portions of the spectrum. For example, in 1992, the Congress directed NTIA to adopt and implement a plan for federal agencies with existing mobile radio systems to use more spectrum efficient technologies. In response, NTIA required all federal agencies to upgrade their land-based mobile systems through narrowbanding, a process for reducing the amount of spectrum needed to transmit a voice signal, by 2008. NTIA also established a trunking program for land mobile systems in certain areas of the country. The trunking technique allows systems to share a common set of voice radio channels to conserve spectrum. For more information on NTIA's efforts to promote efficiency through its narrowbanding and trunking policies for land mobile radios, see GAO-02-906.

[31] U.S. General Accounting Office, *Spectrum Management in Defense Acquisitions*, GAO-03-617R (Washington, D.C.: Apr. 30, 2003).

requirements, out-of-date and unclear spectrum management publications, competing demands of program mangers, and a lack of effective enforcement mechanisms for existing spectrum certification requirements.[32]

Creating Incentives to Encourage the Development and Use of Spectrum Efficient Technologies Is Challenging

The fact that spectrum is virtually cost free may influence whether agencies consider spectrum efficiency and invest in spectrum efficient technologies. Currently, agencies have little or no economic incentive to use the radio-frequency spectrum more efficiently because they pay only small administrative fees for its use. Once it is allocated and users gain access to the spectrum, there are generally no financial incentives for them to consider accommodating other users, or in many cases, even to move to more efficient technologies. Incentives—both governmentwide and agencywide—could theoretically go a long way in encouraging agencies to proactively develop and use spectrum efficient technologies. However, incentives may not be appropriate, desirable, or feasible in all circumstances.

In the private sector, the goals of maximizing profits can be a strong incentive to increase efficiency and utilization of the spectrum. For example, firms offering cell phone service may use various technologies, such as modulation techniques, to increase the number of cell phone users in a particular band. While market-based incentives promote efficiency, this model is not easy to apply to the federal sector—largely because government agencies need to balance their missions of providing public benefit with achieving economies and the difficulty of finding ways to apply these economies.

For more than a decade, NTIA and others have considered the use of market-based incentives to promote spectrum efficiency in the federal government. In its 1991 report *U.S. Spectrum Management Policy: Agenda for the Future*, NTIA suggests exploring with FCC various fee proposals that would invoke the forces of supply and demand to create market-based mechanisms for spectrum management. Following this report, NTIA imposed agency fees to cover its administrative costs, which amount to about $55 per assignment. In November 2002, FCC's Spectrum Policy Task Force Report also discussed the use of fees to improve

[32] In our April 30, 2003, report, we made several recommendations aimed at addressing these weaknesses.

spectrum efficiency in the public sector where market forces may be inadequate to spur efficiency. In October 2003, the Center for Strategic and International Studies reported that market approaches such as licenses that can be traded or sold would allow the market to determine the most efficient use of the spectrum.[33] The President's Spectrum Policy Initiative, chaired by the Secretary of Commerce, is currently examining issues of spectrum efficiency. Adopting market-based incentives to encourage spectrum efficiency is not limited to the United States. To varying degrees, Australia, Canada, and the United Kingdom have put in place mechanisms to reflect the opportunity costs associated with government spectrum use. These mechanisms include auctions and incentive-based fees, more flexible licenses, and secondary markets. The three countries have reported more flexibility in reassigning and allocating spectrum to its most efficient use.

However, creating viable economic incentives to achieve spectrum efficiency in the U.S. federal government may be difficult. As we have previously reported,[34] NTIA could face several challenges if it decides to use such incentives. First, implementing a market-based approach may be difficult for some agency functions that are critical and unique, such as public safety and national defense. Second, incentives that would require greater flexibility among license holders of spectrum may ultimately result in problems of interference. Although flexibilities have resulted in improved spectrum efficiency in other countries, these flexibilities may not apply to the United States because of the unique and worldwide missions of the U.S. military and the divided structure and missions of the U.S. spectrum management system. Third, it is unclear whether licensees would have the right to buy and sell spectrum, and what rights would be conferred and under what circumstances rights would be granted. Finally, while it may be possible to impose fees on federal agencies' use of assigned spectrum, it is far from obvious how such fees or other economic incentives could be applied to agencies' opportunistic use of white and gray spaces in the spectrum—as would be the case with software-defined cognitive radios, which adapt their use of the spectrum in real time. In its 2002 report, FCC also acknowledged that there are instances where

[33] Center for Strategic and International Studies, *Spectrum Management for the 21st Century: A Report of the CSIS Commission on Spectrum Management*, (Washington, D.C.: Oct. 2003).

[34] GA0-03-277.

regulation, as opposed to a market-oriented approach, is more appropriate.

Conclusions

With the rapid advances in telecommunications technology and the increasing demand—both public and private—for radio-frequency spectrum, NTIA and FCC are faced with the daunting task of achieving greater spectrum efficiency while maintaining the level of services that users have come to expect. Further development and use of spectrum efficient technologies may provide an answer to this dilemma without negatively affecting the ability of agencies to carry out their missions; however, users have not actively pursued these technologies because there are few regulatory requirements or incentives to do so and because factors associated with the nation's current spectrum management system may not encourage the use of these technologies. To ensure the most efficient use of spectrum, it will be necessary to rethink the current environment in which spectrum is managed, define requirements, and examine the requirements and incentives needed to encourage agencies to promote new and emerging technologies for achieving spectrum efficiency. Efforts currently under way at the national level, such as the President's Spectrum Policy Initiative, provide an opportunity to establish appropriate policies and mechanisms, including incentives, to facilitate greater consideration of spectrum efficiency and create a more flexible, adaptable spectrum management environment that allows emerging technologies to fulfill their potential of spectrum efficiency. Without greater flexibility and incentives, efficiency may remain an unmet promise, and the growing demand for spectrum may soon threaten agencies' ability to meet their missions.

Recommendations for Executive Action

We are making six recommendations to help increase the development and adoption of spectrum efficient technologies. Specifically, we recommend that the NTIA Administrator and the FCC Chairman jointly

- assess and determine the feasibility of redefining the spectrum allocation system to build in greater flexibility where appropriate to facilitate emerging technologies;
- develop and implement plans to gain a more thorough and on-going understanding of the current spectrum environment; and
- strengthen efforts to develop jointly accepted models and methodologies to assess the impact of new technologies on overall spectrum use and increase opportunities to permit testing of those technologies.

To better ensure federal agencies consider and invest in spectrum efficient technologies, we further recommend that the NTIA Administrator

- establish guidance for agencies to determine and report their future spectrum requirements;
- strengthen NTIA's spectrum certification process to more directly address spectrum efficiency; and
- determine approaches, where appropriate, for providing incentives to agencies to use spectrum more efficiently and then pilot and measure the effectiveness of those approaches.

Agency Comments and Our Evaluation

We provided a draft of this report to the agencies that we reviewed. The Department of Commerce, FCC, and DHS provided written comments (reprinted as appendixes I, II, and III, respectively), and DOD, DOT, NASA, and NSF provided oral comments. DOJ did not have comments.

FCC in commenting on the draft report supported our recommendations and indicated it would work with NTIA to incorporate the report's findings and recommendations in future work. FCC also emphasized a number of actions it has taken to encourage and facilitate new technologies that might improve spectrum efficiency. The Department of Commerce did not comment on our recommendations but noted that NTIA and FCC "have met regularly to explore areas of common focus in spectrum management." While we agree that meeting regularly is an important step toward building a more cohesive spectrum management process, it is not clear that these discussions have addressed or will address our recommendations to improve spectrum efficiency. Continued difficulty in reaching consensus between NTIA and FCC will hinder opportunities to accommodate new technologies and users and improve spectrum efficiency.

Several of the agencies' comments indicated their commitment to promoting greater flexibility and more efficient use of radio spectrum. Overall, the comments from agencies, other than NTIA and FCC, were generally technical in nature and were incorporated where appropriate. In addition, the agencies provided a few comments relating to our findings and recommendations. Most notably as follows:

- NSF observed that future use of spectrum through software-defined cognitive radios could adversely affect the operation of sensitive radio telescopes that NSF supports. We agree that this is a valid concern because these systems are "passive"—or receive only—and their use of spectrum could go unnoticed. As noted in this report, when seeking to increase spectrum sharing, spectrum leaders will need to carefully consider incumbent users operations and define appropriate rules to obviate those impacts.

- NSF, as well as DHS, also commented on our recommendations directed to the NTIA Administrator. Specifically, NSF noted that incorporating spectrum efficiency measures into the certification process of major systems could prove difficult and suggested either deleting or modifying the recommendation to focus on incentives. However, our recommendation does not call for the creation of measures but rather emphasizes the need for NTIA to focus on efficiency when considering certification. But in doing so, NTIA may determine that measures are an appropriate means to help increase spectrum efficiency and may be applicable in some cases. Further, we have recommended that NTIA take action to determine appropriate incentives for agencies to use spectrum more efficiently. Therefore, we did not modify our recommendations. Contrary to NSF, DHS stated that incentives do not apply to the government. While we recognized that incentives may not be applicable or desirable in all circumstances, we believe that there may be opportunities to use incentives to promote consideration of spectrum efficiency, and therefore recommended that such opportunities be explored.

We are sending copies of this report to the Acting Assistant Secretary of Commerce for Communications and Information and Administrator of the NTIA, the Chairman of the Federal Communications Commission, the other agencies we reviewed, and interested congressional committees. We will also make copies available to others upon request. In addition, the report will be available at no charge on the GAO Web site at http://www.gao.gov.

If you or your staffs have any questions about this report, please contact me at (202) 512-4841 or John Oppenheim at (202) 512-3111. Other individuals making key contributions to this report are Bruce Thomas, Jay Tallon, Gary Middleton, Karen Sloan, and Allison Bawden.

Katherine V. Schinasi
Managing Director
Acquisition and Sourcing Management

Appendix I: Comments from the Department of Commerce

THE SECRETARY OF COMMERCE
Washington, D.C. 20230

May 18, 2004

Ms. Katherine V. Schinasi
Managing Director, Acquisition and Sourcing Management
United States General Accounting Office
Washington, DC 20548

Dear Ms. Schinasi:

Thank you for providing the Department of Commerce with an opportunity to comment on the General Accounting Office's (GAO) draft report entitled *"Spectrum Management: Better Knowledge Needed to Take Advantage of Technologies That May Improve Spectrum Efficiency."*

I commend GAO for its efforts to examine the complex public policy issues surrounding our Nation's spectrum management procedures. As you are aware, the Department of Commerce is also addressing spectrum efficiency at the direction of President Bush as part of his Spectrum Policy Initiative. The President's initiative defines two courses of action: first, the establishment of a Federal Government Spectrum Task Force to focus on improving spectrum management policies to stimulate more efficient use of Federal Government spectrum; and second, to conduct broad outreach to encourage the public to express its views on improvements to our spectrum management policies. These initiatives are complete, and I will soon be forwarding to the President two reports outlining recommendations for improving the management of both Federal Government and non-Federal Government spectrum.

With respect to the draft GAO report, I note that it is recommended that the NTIA Administrator and the FCC Chairman "jointly" work to improve spectrum management procedures. It should be noted that the NTIA Administrator and the FCC Chairman are directed by statute to meet biannually to conduct joint spectrum planning with respect to, among other things, "actions necessary to promote the efficient use of the spectrum, including spectrum management techniques to promote increased shared use of the spectrum that does not cause harmful interference as a means of increasing commercial access."[1] During this Administration, the NTIA Administrator and the FCC Chairman have met regularly to explore areas of common focus in spectrum management, particularly spectrum efficiency. NTIA and the FCC, as co-managers of the radio frequency spectrum, will continue to work together on important spectrum management issues.

I hope this information is helpful. If you have any additional questions concerning the Department of Commerce's comments on the report or any issue involving spectrum management, please contact Acting Assistant Secretary for Communications and Information Michael D. Gallagher at (202) 482-1830.

Sincerely,

Donald L. Evans

[1] *See* 47 U.S.C § 922.

Appendix II: Comments from the Federal Communications Commission

Federal Communications Commission
Washington, D.C. 20554

May 21, 2004

Ms. Katherine V. Schinasi
Managing Director, Acquisition and
Sourcing Management
U.S. General Accounting Office
Washington, DC 20548

Dear Ms. Schinasi:

Thank you for sharing the General Accounting Office's ("GAO's") draft report, entitled "Spectrum Management: Better Knowledge Needed to Take Advantage of Technologies That May Improve Spectrum Efficiency." Chairman Powell has asked me to provide comments on the draft report. I will focus on your recommendations in response to the second of the two requests GAO received to explore possible steps to facilitate consideration and investment by federal agencies as well as others in spectrum-efficient technologies. In particular, GAO's draft report sets out three recommendations for joint action by the Administrator of the Department of Commerce's National Telecommunications and Information Administration ("NTIA") and the Chairman of the Federal Communications Commission ("FCC"). We value GAO's analysis as a way to build upon our existing work and cooperative efforts already underway with the NTIA.

Under Titles I and III of the Communications Act, the FCC is charged, among other things, with adopting policies for non-federal spectrum use that make wireless communication services available to all Americans, that provide for national defense, and that promote the safety of life and property. In fulfilling these responsibilities, the FCC has been undertaking various groundbreaking steps to encourage the use of new, more spectrum-efficient technologies. As the GAO draft report recognizes, in 2002 FCC Chairman Powell established a Spectrum Policy Task Force ("SPTF") staffed by senior agency personnel to identify outmoded procedures and policies, and evaluate changes in spectrum policy, that could increase the public benefits derived from the use of the radio spectrum. The SPTF's work resulted in a report published in November of that year setting out many new recommendations for spectrum policy reform.

GAO's draft report specifically notes the SPTF's recommendation that the Commission should adopt, where feasible, a more quantitative approach to interference management based on the concept of the "interference temperature." Under this approach, a "cognitive" or "smart" radio would sense the use of a given frequency band in a particular location. The radio then would utilize the band only to the extent possible without exceeding the "interference temperature" limit prescribed for that band. In that way, a radio could use spectrum that would otherwise have to lie fallow before the advent of such technologies. The SPTF Report recognized that the FCC required better information about actual use of different bands before it could set "interference temperature" limits for specific bands and, as a result, recommended that the Commission undertake a systematic study of the radiofrequency ("RF") noise floor. Since the issuance of that SPTF Report, the Commission has adopted a Notice of Proposed Rulemaking that seeks further comment on the "interference temperature" concept, on how best to obtain more systematic data on the RF noise floor, and on two proposals for rule changes that would facilitate deployment of such technologies in two satellite bands.

As the draft report recognizes, we also have worked closely with the NTIA in the FCC's consideration and reform of its rules to allow the use of ultra-wideband ("UWB") unlicensed devices. UWB devices are able to use sophisticated processing capabilities to provide communications at very low power across wide swaths of spectrum without causing interference to current spectrum licensees – federal and non-federal – that are authorized to use those spectrum bands at much higher power levels. UWB technology is another example of new cutting-edge technologies that allow use of spectrum for communications.

I wanted to note as well that the FCC has been aggressively adopting and considering other changes to its rules to facilitate the use of the latest technologies to encourage more efficient spectrum use. The use of "software-defined radios" and "cognitive radios," for instance, is not limited to situations in which the "interference temperature" metric can be employed. As one example, the FCC late last year adopted rules that allow the more efficient use of spectrum in the 5 GHz band by unlicensed devices with cognitive features. These devices do not have to comply with an "interference temperature" limit, but only have to avoid using a frequency in real time whenever a licensee is using that frequency. Similarly, the FCC is seeking comment on other proposals that do not require setting specific "interference temperature" limits, but would allow radios with certain cognitive features to use currently unutilized or underutilized spectrum: (1) in rural areas, (2) in the 3650-3700 MHz band, and (3) in the "white spaces" in the TV bands. As yet another example, the FCC has sought comment on possible reforms of its rules that would facilitate the use of "smart radio" features by licensees to enable more opportunities for part-time leasing of spectrum. The goal of all these proposals is to facilitate the use of more spectrum-efficient technologies while we are continuing to pursue the "interference temperature" construct. Finally, we are working with our Technological Advisory Committee and in other forums to explore other approaches for assessing and increasing the deployment of spectrum-efficient technologies.

As the draft reports rightly notes, these and other new technologies potentially enable new approaches for the sharing of spectrum between federal and non-federal users. For instance, new technologies now allow the use of "millimeter wave" spectrum at 70/80/90 GHz. In close consultation with NTIA, the FCC has adopted an innovative regulatory approach providing for the registration of individual links in federal and non-federal databases. This approach should permit a speedier and more efficient sharing of spectrum by both federal and non-federal users than would otherwise be possible.

There undoubtedly is other spectrum not being used today, or being underutilized, that could be more efficiently used if new spectrum-efficient technologies were deployed

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and if more flexible approaches to spectrum allocations were used. I would note, however, that the Communications Act of 1934, as amended, specifically provides that the FCC licenses non-federal radio stations. In contrast, radio stations owned or operated by the Federal Government obtain their frequency designations from the President, or his designate. Therefore, in response to your first recommendation for joint NTIA-FCC collaboration, the FCC will be happy to work with NTIA within those statutory limits to explore approaches for facilitating the use of new technologies to permit non-federal users to use spectrum formally allocated to federal users, as well as federal users to use spectrum formally allocated to non-federal use. And we will continue our recent policy of generally adopting flexible allocations for non-federal spectrum to help facilitate the use of spectrum-efficient technologies.

We also are supportive of your second recommendation for joint FCC-NTIA activity – developing and implementing plans to gain a more thorough understanding of the current spectrum environment. A greater understanding of spectrum use holds the potential of allowing even more efficient use of spectrum than is possible with greater use of new spectrum-efficient technologies alone.

Finally, we will continue ongoing efforts with the NTIA to develop jointly accepted models and methodologies to assess and test the impact of new technologies. Successful development of such models and methodologies can only expedite the consideration and approval of new spectrum-efficient technologies.

I commend you and your staff for your hard work in helping to develop ideas for improving U.S. spectrum management policies in a manner that ensures that the radio resource will be effectively and efficiently employed for the benefit of the American people. We support any effort to continue to improve our policies in this area, and will work with our colleagues at NTIA to assess how best to incorporate the report's findings and recommendations in our future work.

Sincerely,

Edmond J. Thomas
Chief
Office of Engineering and Technology

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Appendix III: Comments from the Department of Homeland Security

U.S. Department of Homeland Security
Washington, DC 20528

Homeland Security

May 18, 2004

Ms. Katherine V. Schinasi
Managing Director, Acquisition and
Sourcing Management
U.S. General Accounting Office
Washington, DC 20548

Re: SPECTRUM MANAGEMENT - Better Knowledge Needed to Take Advantage of Technologies That May Improve Spectrum Efficiency," GAO-04-666, May 2004; GAO Case 120254

Dear Ms. Schinasi:

The Department of Homeland Security (DHS) appreciates the opportunity to review and comment on the General Accounting Office (GAO) draft report to the Honorable Tom Davis and the Honorable Adam H. Putnam, Committee on Government Reform, House of Representatives, entitled "SPECTRUM MANAGEMENT - Better Knowledge Needed to Take Advantage of Technologies That May Improve Spectrum Efficiency," GAO-04-666, May 2004.

The draft report does not include any specific recommendations regarding DHS. However, we submit the following comments for your consideration:

- The Department applauds the ongoing and continuing research into advanced technologies that will expand the better utilization of scarce spectrum allocations and recommends an active role by both the National Telecommunications and Information Agency (NTIA) and the Federal Communications Commission (FCC) in encouraging migration to spectrum efficient technologies, particularly research being conducted by the Department of Defense. We furthermore consider such actions as positive in respect to the goals of the President's Spectrum Policy Initiative.
- We recommend that the NTIA and FCC proceed with caution and closely monitor the development of the Software-Defined Cognitive Radio (SDCR) and the determination of spectrum utilizations by licensees within the spectrum. Furthermore, we recommend that the FCC conduct an in-depth study into the interference temperature concept that is considered controversial and will be used as a potential baseline in the establishment of a noise floor. Protection must be in place for incumbent users. The terms "white spaces" and "gray spaces" as they pertain to SDCR technologies must be well defined. We also recommend that all spectrum assigned to public safety first responders be restricted and protected from SDCR devices by use of spectrum lockout capabilities or other suitable solution.

- In regard to the current structure and management of spectrum used within the United States, we recommend that both the NTIA and FCC identify spectrum that can be set aside and protected for future technology testing and evaluation.
- With the ongoing interference temperature initiative within the FCC, we recommend that the enforcement avenues within the FCC be expanded to allow for the identification of sources of interference and the enforcement aspect of protecting incumbent licensees or users.
- The use of incentives to encourage agencies to develop and use spectrum more efficiently does not apply at the federal government level. The use of incentives may have some functionality in other environments, but does not apply to the government. A more appropriate means for governmental spectrum efficiency is a mandated migration process similar to the ongoing wide-band to narrow-band transition in the VHF and UHF federal bands.
- We recommend that the FCC and the NTIA work more closely and proactively in all issues surrounding spectrum management.

Thank you again for the opportunity to comment on this draft report. If you have questions or need clarification regarding our comments, please contact Mr. Thomas Krones, (202) 401-5861, or e-mail: Thomas.krones@dhs.gov.

Sincerely,

Anna F. Dixon
Director, Bankcard Programs
and GAO/OIG Liaison

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