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Adaptive Spectrum Radio: A Feasibility Platform On The Path To Dynamic Spectrum Access

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Abstract

A new paradigm for managing and allocating the electromagnetic spectrum is now possible due to advances in technology and a receptive environment within regulatory agencies. New radiocommunication technology provides a key component to this possibility as it increases the flexibility for radio transmissions to dynamically adapt and access the spectrum. Such dynamic spectrum access, however, requires revised policies and regulations since traditional spectrum management allocates a band of frequencies to specific services and assigns a single frequency or group of frequencies to specific radios.

In order for the policy community to gain confidence in the possibilities of the new paradigms, the technology developers need to demonstrate the capabilities of the systems that enable dynamic spectrum access. The MITRE Corporation has developed a feasibility radio platform that demonstrates the principles for dynamically accessing the spectrum as it adapts its frequency and modulation to exploit spectrum gaps both in frequency and time. This paper discusses both a path to demonstrating the technology for the policy community as well as the MITRE developed Adaptive Spectrum Radio (ASR) testbed.

Introduction

The era for overhauling the framework and processes by which governments manage the radio frequency spectrum is upon us. Government policy initiatives, such as the United Kingdom's reorganization of its spectrum policies based on Martin Cave's report [1] and the United States Federal Communications Commission's (FCC) Spectrum Policy Task Force [2], along with private efforts at various "think tanks" indicate that regulatory agencies and the private sector are seriously reviewing options for spectrum management reform. While traditional economic arguments for reform have been around since Leo Herzel's proposal [3] and Ronald Coase's seminal paper [4] in the 1950s, the key factor impelling this current review is recent technological advances.

The ability to dynamically and adaptively access the spectrum is one of the most important emerging technologies that enable spectrum policy reform [5]. Advances in digital signal processing enabled by increasing capabilities of microprocessor and related components allow radios to dynamically change transmission parameters including data and coding rates, modulation, and even frequency. Digital signal processing-based radios, typically referred to as Software Defined Radios (SDR), provide the platform for these dynamic radio systems.

Forms of adaptive spectrum access have been implemented in the past including current and next generation mobile systems, but the key difference in the emerging adaptive spectrum radios is the increased flexibility, both in speed and variety of parameters, to alter transmissions that dramatically increase the ability to adapt to a changing radio frequency environment. A rudimentary form of adaptive spectrum access implemented in some systems operating in unlicensed bands is the selection of a frequency channel based on measurements of activity. More advanced implementations of adaptability include the various methods for changing data rate, code rate, and modulation order implemented by second (2G) and third generation (3G) mobile standards [6-7]. For example, Enhanced Data Rates for GSM Evolution (EDGE) adapts the transmission parameters modulation (GMSK or 8-PSK) and coding rate. This type of adaptability is well suited for packet data and in situations with slow variations in fading and distance loss over the cell coverage area.

The increased capability of emerging adaptive spectrum access systems requires changes to the methods for managing the spectrum since they enable new systems to opportunistically access the spectrum and to change their transmission characteristics, challenging notions of fixed frequency assignments and rigid certification–pillars of the current spectrum regime. Before changes can be implemented in spectrum management, the technology community needs to present demonstrations and associated studies showing the capabilities and possibilities. This paper reviews factors necessary to demonstrate the technical principles for dynamic spectrum access and the interrelationship between technical demonstrations and policy changes. One element of this review is the use of prototype systems to investigate options under consideration by the policy community. Demonstrations are not intended as final indicators of future applications or design, but they do provide a means to explore policy options.

To illustrate the use of prototype systems, this paper also presents the MITRE Adaptive Spectrum Radio (ASR) testbed [8]. The testbed architecture supports SDR development using Application-Specific Integrated Circuit (ASIC), Digital Signal Processor (DSP), and Field Programmable Gate Array (FPGA) components, but with MITRE developed software. Success thus far demonstrates not only the feasibility of dynamic spectrum access but also allows future exploration of policy considerations.

Dynamic & Adaptive Spectrum Access

Forms of dynamic spectrum access already exist, but the full concept for adaptive spectrum access whereby a system can adjust its transmissions in a cooperative or even an un-cooperative environment is only now becoming possible. The definition of a fully “dynamic” or “adaptive” system is not clearly delineated, but the capabilities of such a system would include:

- Sensing the radio frequency environment;
- Controlling its transmissions based on measurements and other a priori information in an autonomous, opportunistic, and real-time fashion;
- Adjusting multiple transmission parameters including, but not limited to, frequency, power, modulation, signal timing, data rate, coding rate, and antenna; and,
- Operating in cooperative networked systems and/or environments with non-cooperating systems (i.e., opportunistically accessing spectrum).

One key benefit for adaptive spectrum access is the potential to improve the efficiency in spectrum use. By adjusting transmissions, adaptive systems can utilize unused frequencies even if they vary over time. In addition, adaptive systems may maintain a quality of service in a changing environment while also adjusting emissions to reduce interference to other systems.

Numerous research organizations and companies are investigating adaptive spectrum access systems. One notable effort is the Defense Advanced Research Projects Agency (DARPA) neXt Generation (XG) program [9]. This program is developing an access technology to increase the ability of military systems to access spectrum adaptively and to ensure the operation of new systems, without the extensive, frequency by frequency, system by system, coordination now required in each nation where a system will operate.

Demonstrations Path to a New Spectrum Policy

The impact of adaptive systems to policy is extraordinary as it challenges the current basis for spectrum management. At present, mechanisms for accessing spectrum and limiting interference typically assume “fixed” or statically-assigned frequency assignments for a system within a band allocated to a defined radio service sharing characteristics of the system under consideration. Often, additional spectrum is set aside to provide a guard band or minimum frequency separation between neighboring spectra, and a set of technical or operational rules is defined for usage in cases where a common spectrum is shared or where neighboring systems require protection from interference. In addition, regulatory agencies require certification of systems that they operate in accordance with technical parameters governing frequency and emissions, both in-band and out-of-band.

Adaptive spectrum access systems do not operate in such a rigid manner, and, indeed, their primary benefits are derived from the flexibility afforded them by operating in a dynamic way. Since the current methods of assigning fixed frequencies inhibit the advantages of adaptive systems, spectrum management policies and procedures need updating to accommodate them.

The FCC recognizes this need in their Spectrum Policy Task Force Report [2]:

> “Because new, smart technologies can sense the spectrum environment and because they have the agility to dynamically adapt or adjust their operations, increasing access to the spectrum for smart technologies, such as software-defined radios, can improve utilization, through more efficient access, of the radio spectrum without detriment to existing spectrum users.” (p. 15)

The report goes on to recommend that “the Commission develop access models that take this new technological potential into account.” While the FCC report identifies these needs, it does not define specific rules or “rights” to accommodate these technologies nor does it present a specific path by which to delineate them.

One path that can assist the FCC and other regulatory bodies as they begin to define new spectrum access models is the use of demonstrations of technology. In order for the policy community to gain confidence in the possibilities of the new regulatory paradigms, technology developers need to show the capabilities of the systems that enable dynamic spectrum access. The two principal objectives for demonstrations are:

- Inform the policy and regulatory community of the feasibility for adaptive spectrum access; and,
- Identify and investigate considerations for policies using adaptive radio demonstration platforms.

By understanding the basic operations of adaptive radios, the policy and regulatory community can better revise and update rules and procedures. In addition, reviewing technology in its early development phases enables regulators to inform developers ways in which the technology may need to evolve to accommodate policy and regulatory concerns. This two-way process can mutually benefit all sides by identifying issues early and by preventing contentious proceedings as has been seen in recent regulatory deliberations involving emerging technologies like ultra-wideband (UWB).

A good example of a new technology awareness program is the DOD's Defense Information Systems Agency's (DISA) Emerging Spectrum Technology program, led by the Defense Spectrum Office (DSO). This project intends to proactively understand policy ramifications of new technology having military benefits to ensure that policies do not inhibit their introduction. Other organizations, including the FCC, are also enhancing technology awareness efforts.

The demonstration component for programs reviewing policies occur at different stages of both the technology's and the policy's development. Figure 1 illustrates the phases in which demonstrations are applied to support policy revisions. The key to this paradigm is the evolutionary nature where policy is prepared in conjunction with and influenced by technology development.

The principle objective for demonstrations during the conceptual phase is to show the notion of new technologies, like adaptive spectrum access. Demonstration testbeds used in later phases can identify and explore policy considerations and options. Three areas of policy that may require updating to accommodate adaptive spectrum access systems are: certification, spectrum access, and interference mitigation. Although adaptive radio platforms could be used to explore certification issues (e.g., integrity of the software), such issues are not unique to adaptive systems so they may be better explored using other SDR platforms. Because of the nature of adaptive systems, issues involving spectrum access and interference mitigation are inextricably linked. Consequently, the design and demonstration of feasibility platforms may be used to identify and explore spectrum access and interference mitigation policy considerations including:

- **Band/Channel Blocking**. Can adaptive systems operate with policies that prohibit the transmissions in specific channels, even non-contiguous ones? Can different emission levels be set for different channels?
- **Interference Temperature**. The FCC Spectrum Policy Task Force [2] introduced the concept of "interference temperature" as a means for defining the environment in which systems must operate. Specifically, the Task Force recommended that "the Commission shift its current paradigm for assessing interference–based on transmitter operations–toward operations using real-time adaptation based on the actual RF environment through interactions between transmitters and receivers." Consequently, adaptive systems may be an integral part of policy.

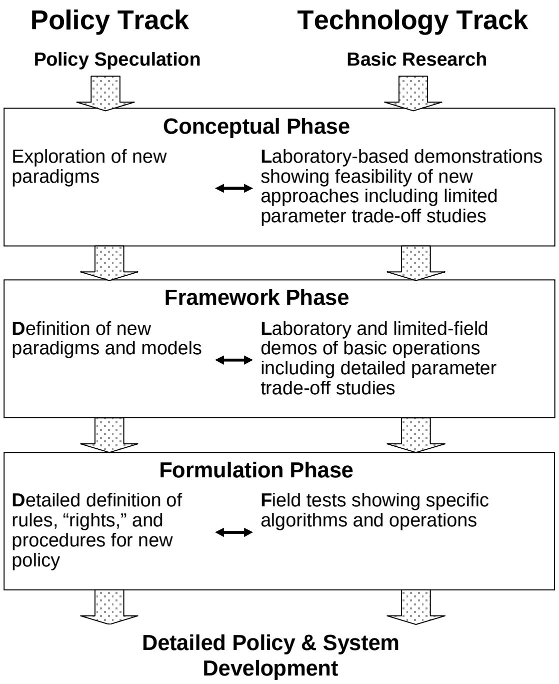

Figure 1. Policy/Technology Development Phases

  In such a regime, the defined "temperature" levels need to be defined. Should policies define permitted limits for transient interference to account for imperfections in the algorithms and protocols for accessing the spectrum? What are the achievable sensitivity levels for sensing the environment?

- **Technical Parameters**. Should policies define acceptable parameter values associated with the adaptive algorithms (e.g., time required to sense environment, latency between "acceptable" measurement and transmission, etc.)?
- **Databases of Existing Use**. Do policies need to be adopted that require the availability of databases to assist the operation of adaptive systems?
- **Environments**. In what environments can adaptive systems operate (e.g., dense voice traffic, radar, etc.)?
- **Refarming**. Can the introduction of adaptive systems improve the efficiency in certain bands so that legacy systems may continue operation rather than relocate?
- **Secondary Markets**. Can adaptive spectrum access systems enable secondary market trading?

The design and demonstration of feasibility testbeds can provide preliminary answers to the above questions. Although analysis and simulation can also assist in answering these questions, the design and demonstration of a feasibility platform provide additional assurance during the early phases of policy definition. Such a demonstration radio does not need to be complete or fully functional, since its basic operation can stimulate discussion and identify the policies that need to be considered. The next section discusses the MITRE Corporation's Adaptive Spectrum Radio testbed which can be used for these early explorations of policy changes.

MITRE's Adaptive Spectrum Radio: Overview

The MITRE Corporation, in partnership with its government sponsors, has studied adaptive spectrum utilization as a potential way to ease congested spectrum. The level of unused capacity in currently deployed communication systems gauged by previous work [8] indicates a potential for the adaptive spectrum utilization concept relying, in part, on technology identifying momentarily unused capacity within a channel and then adapting a waveform to make use of it. Gaining access by sensing the communication media before transmitting has been used effectively in local area networks, including Ethernet's CS-CDMA scheme. Like CS-CDMA, an adaptive spectrum radio senses channel (spectrum) occupancy before transmitting, but unlike CS-CDMA, the system adapts the transmit waveform to take advantage of unused spectrum.

In general, an adaptive system must form its transmit waveform to exploit unused channels. The basic methods of separating channels are frequency division (FDM), time division, and code division. From a general perspective, an adaptive radio must be able to alter waveform characteristics pertaining to one or more of these separation techniques. For example, in the case of FDM, an adaptive system waveform must exploit momentarily unused frequency channels. Additional efficiencies accrue if an adaptive FDM waveform simultaneously exploits a discontiguous set of unoccupied frequency channels because it would, on average, support higher bandwidths and availability.

Viable communication using adaptive systems requires another important capability; namely, “opportunistic” media access control (MAC). The adaptive spectrum utilization concept requires that individual radios inform each other where idle channels exist and when to use them—without using fixed control channels. Since adaptive systems in different locations may identify different sets of unoccupied channels, there needs to be a means of selecting a mutually agreeable subset of channels, a “joint occupancy vector,” and when to use it. Thus, an adaptive system must conduct a control dialogue over an unoccupied channel without first knowing what, if any, unoccupied channels each radio senses. In the case of FDM, the adaptive system cannot rely upon a fixed frequency channel for control because unoccupied frequencies may change from one moment to the next and from one location to another.

Realizing all three of these key adaptive functions, sensing the spectrum for unoccupied channels, adapting the transmit waveform, and designing an opportunistic MAC, presents many engineering challenges, but MITRE research indicates that current technology makes such communications possible. Advances in micro-electronics has led to FPGA cores and DSPs that can compute correlations and Fast Fourier Transforms (FFTs) fast enough to support timely channel occupancy estimation. Expanding research into ad hoc networks is likely to overcome many challenges similar to those inherent in implementing an opportunistic MAC. As discussed below, digital signal processing makes adaptive waveform synthesis possible. To tie these three key functions together, Figure 2 depicts the overall spectrum utilization process for an FDM system; in the figure, two adaptive systems make estimates of spectral occupancy and then negotiate to use a common subset of unoccupied channels. Although it is not explicitly shown, the process in Figure 2 constitutes a single burst cycle and would repeat itself at a rate dictated by requirements to control interference.

MITRE developed an adaptive spectrum approach to operate in the midst of an FDM communication system such as advanced mobile phone service (AMPS). Figure 2 visualizes an adaptive waveform that transmits data over the unoccupied frequencies. Such a waveform requires non-contiguous modulated carriers with excellent roll-off characteristics outside its passbands. One method could sum a series of individually modulated and filtered carriers to fill each unoccupied gap in the spectrum, but a more integrated solution improves computational efficiency. The following section discusses work that successfully implemented an adaptive waveform synthesis using a signal similar to orthogonal frequency division multiplexing (OFDM). The core IFFT process provides a potential advantage since, as the spectrum occupancy estimator for an FDM system uses an FFT, it might be possible to integrate the sensing and demodulation processes—or at least reduce DSP loading.

MITRE ASR: Architecture & Design

MITRE developed a testbed to demonstrate feasibility of the adaptive spectrum radio concept with the intention of providing four basic capabilities: (1) periodic estimation of a channel's occupancy state, (2) periodic adaptation of a time-limited waveform in response to occupancy state estimates, (3) periodic "joint occupancy vector” negotiation with subsequent burst data transfer, and (4) measurement of impairments to primary users. The testbed architecture reflects the desire to support these capabilities as well as a

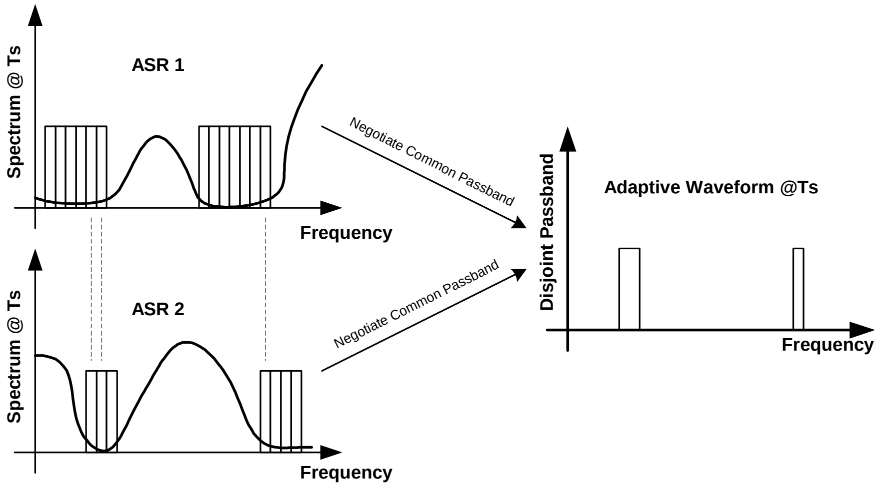

Figure 2. Adaptive Spectrum Approach

compromise between flexibility and performance. Flexible signal processing was important because experience with control schemes and algorithms could evolve to new code, favoring an architecture centered on programmable devices (DSP). Alternatively, a more realistic proof-of-concept demonstration would involve wideband signals, generally demanding application specific solutions. Figure 3 depicts an architecture that blends the speed of ASICs with the flexibility of DSPs.

The MITRE testbed uses commercial-off-the-shelf (COTS) signal processing hardware that implements the balanced approach shown in Figure 3 with a significant portion of its processing occurring within the DSP element. Thus, the testbed is a software defined radio platform. However, it is important to realize that high-speed processing within the ASICs allow the testbed to demonstrate the adaptive spectrum concept over a much wider bandwidth than would be possible without them.

Figure 4 shows the high-level hardware setup that constitutes the testbed. Two small VME chassis and a host computer make up most of the hardware, excluding test equipment like signal generators. Comparing it with Figure 3, the mezzanine boards contain the ASIC and FPGA elements while the quad-DSP carrier board provides programmability. Development within the testbed involves understanding the strengths and weaknesses of the architecture shown in Figure 3 and then mapping the required signal processing into the appropriate element. As noted earlier, promoting flexibility was prudent so most design activity focused on creating real-time code for the DSPs. COTS software running on the host computer (refer to Figure 4) provides a typical integrated environment for writing, running, and testing embedded code.

MITRE has demonstrated capabilities (1) and (2) listed above by implementing the Adaptive FDM Burst Modulator. Figure 5 shows how the signal processing maps into the hardware. As the diagram shows, the system implemented three principle functions: test signal generation, channel occupancy estimation, and adaptive FDM burst modulation.

The **Test Signal Generator** cycles through 15 different “spectrum occupancy” scenarios to create a test signal for the Adaptive FDM Burst Modulator. Each scenario has a different spectrum occupancy state defined by the on/off state of 256 modulated carriers. The AMPS forward control channel (FOCC) RF specification served as the basis for synthesizing each of the 256 modulated carriers that make up the test signal. AMPS specifies a 30 kHz carrier spacing, so if all the carriers were on, the test signal would spread across 7.68 MHz.

Two separate processes make up test signal generation. First, communication systems analysis software creates a pre-processed sample sequence for each spectrum occupancy scenario by simulating FOCC modulation on 256 carriers. In each simulation, unique sets of frequency-shifted carriers sum to form one of the spectrum occupancy scenarios. Each of the 15 complex sequences merges to form a sample-indexed file. The second process performs arbitrary waveform generation using the pre-processed file as input. Key functions include high-speed interrupt-driven data buffering, digital upsampling, and digital-to-analog conversion.

The **Channel Occupancy Estimator** periodically produces an “occupancy vector” (OV) that tells the Adaptive FDM Burst Modulator what waveform to synthesize. The OV tracks the test signal so that the burst modulator avoids using spectrum occupied by the simulated primary user.

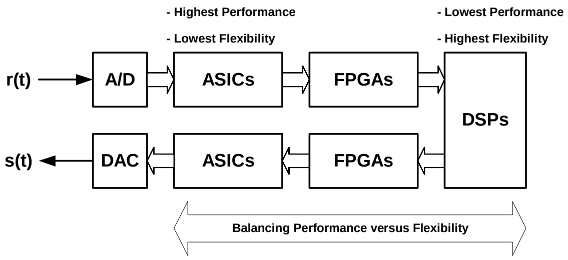

Figure 3. Adaptive Spectrum Radio Architecture

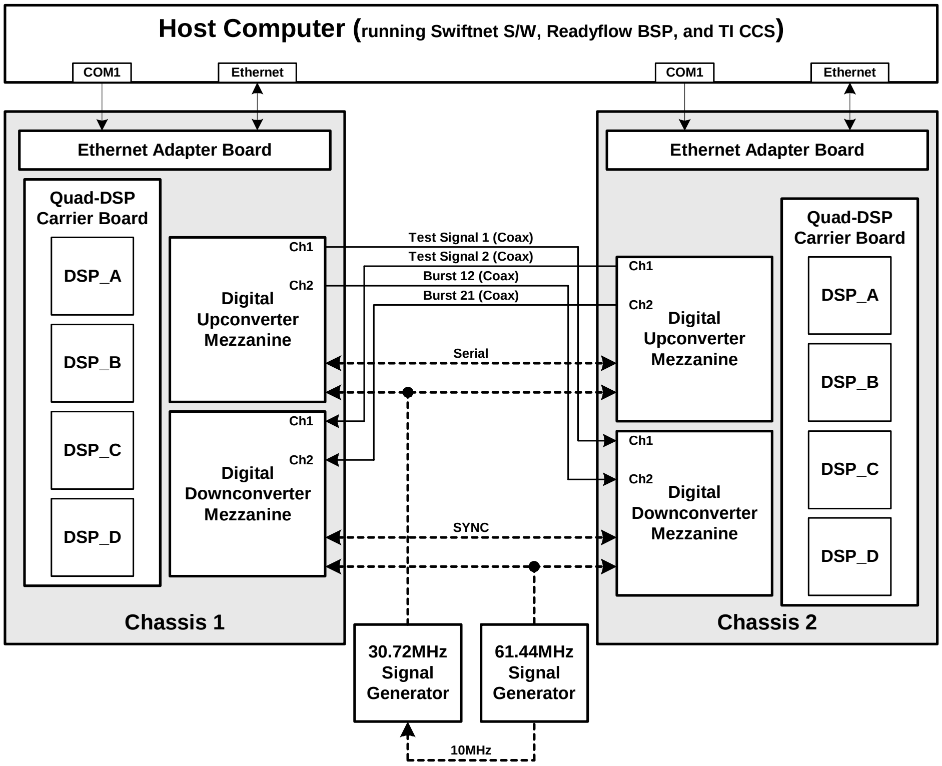

Figure 4. High-Level Testbed Architecture

Six functions make up channel occupancy estimation: analog-to-digital conversion (ADC), channelized digital downsampling, power spectrum estimation, occupancy determination, data fusion, and guard band insertion. ADC periodically captures a block of wideband samples. Hardware constraints make it necessary to channelize the digital downsampling process, so each block of samples passes through 8 digital downconverters that output downsampled blocks of data. After downsampling, the processing used an FFT to transform the time domain data into data representing estimates of power spectral density (PSD). To discriminate between relatively high-power and low-power signals, a threshold test converts the PSD data into binary variables representing the results of occupancy/no occupancy decisions. Data fusion merges the channelized data into an OV containing 256 binary decision variables; one variable for each of the carriers within the test signal. Finally, the Adaptive FDM Burst Modulator has frequency roll-off limitations between its populated and unpopulated carriers, so certain unoccupied channels are treated as if they were occupied to prevent their use. In essence, the Channel Occupancy Estimator alters the OV to avoid primary user interference by accommodating filtering limitations within the burst modulator.

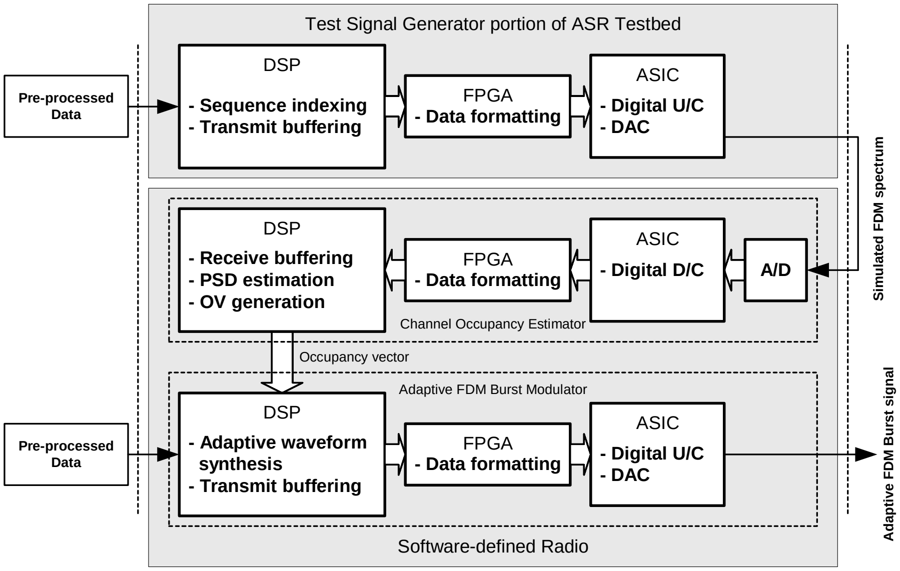

Figure 5. Adaptive Spectrum Radio Transmit Functional Allocation

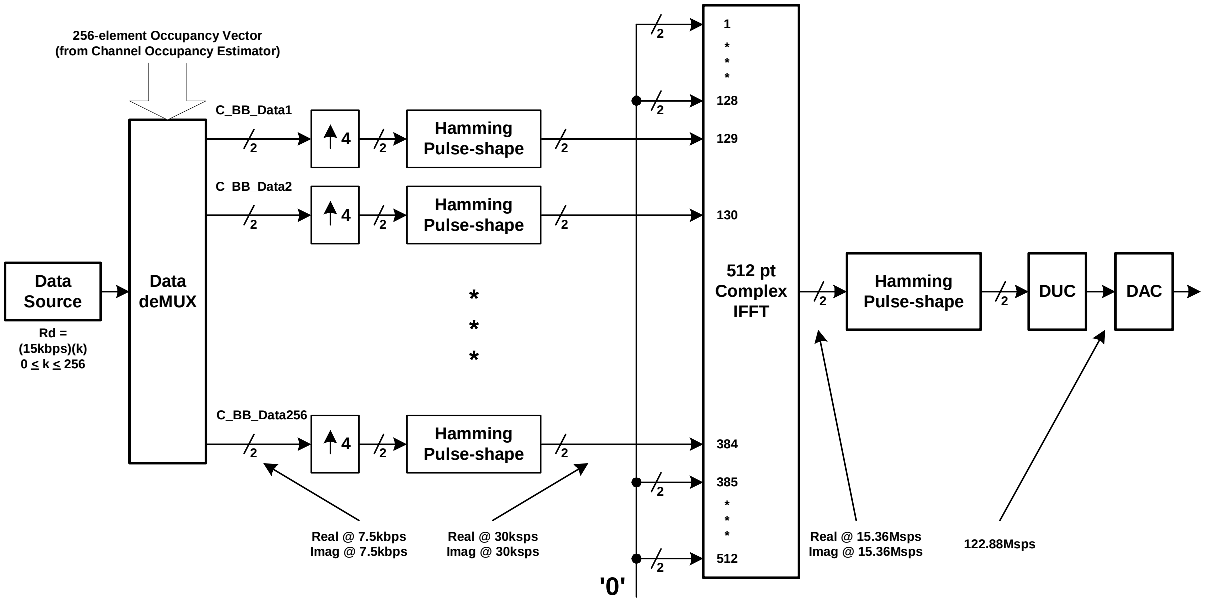

Figure 6. Burst Modulator Signal Processing

The Channel Occupancy Estimator periodically interrupts the **Adaptive FDM Burst Modulator** with an updated OV. After each OV-update interrupt, the burst modulator responds by synthesizing a waveform tailored to the OV. Figure 6 depicts the high-level signal processing carried out by the burst modulator. Variable-rate data enters on the left of the block diagram and a low-IF signal with a maximum bandwidth of 7.68 MHz exits on the right. The data de-MUX uses OV updates to determine which of the 256 frequency bins should receive data during the current burst cycle. All operations are complex, so every unoccupied channel should receive 2 bits from the de-MUX—assuming there is enough data in the transmit buffer. An upsampler allows Hamming pulse-shaping using 4 samples per real and 4 samples per imaginary data bit. Prior to performing a complex IFFT, pulse-shaped data fills the central 256 frequency bins of the IFFT. Null data fills 128 outlying frequency bins on each side of the IFFT input vector. After the IFFT transforms data samples from the frequency domain to the time domain, Hamming pulse-shaping forms the block of complex samples. Finally, upsampling with quadrature upconversion, followed by digital-to-analog conversion (DAC), completes a single burst cycle within burst modulator processing.

MITRE intends to add additional capabilities in future work. While the MITRE testbed provides a feasibility platform, it is not intended as the only architecture or waveform for future adaptive radio systems.

Summary

As the policy and regulatory community considers dramatic changes in the methods and processes used to manage the spectrum, technology demonstrations will prove useful. Platforms, like the MITRE Adaptive Spectrum Radio testbed, provide an opportunity to not only indicate the feasibility of adaptive spectrum access techniques but to also explore policy options involving this emerging technology.

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