A Technology Enabled Framework for Dynamic Allocation of the Radio Frequency Spectrum

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Abstract

This paper outlines a dynamic spectrum allocation framework that will mitigate the shortage of spectrum by enabling more efficient sharing of this critical resource. This approach involves coordinated activities on three fronts: technology, policy, and strategy. First, the approach capitalizes on emerging radio technologies to increase the utilization of each spectrum allocation. Applicable technologies include per-packet adaptable radios, software-defined radios (SDR), layered radio architectures, and spatial diversity through advanced antennas. Second, spectrum management policy will play an important role in motivating radio developers to create and field the requisite technologies. Such "technology-enabling" policy may significantly differ from the management policies in place today. Third, the authors believe that the long-term solution to the spectrum shortage can only be solved with a well planned, coordinated, strategic vision. Such a vision might best be captured in the form of a National Strategic Spectrum Roadmap. It is the authors' belief that together, technology, policy, and strategy can address the pressing spectrum shortage and "unblock" the spectrum.

I. Introduction

Growing interest in wireless communications has highlighted the fact that the usable radio spectrum is a finite resource in short supply. Given the urgency and magnitude of the problem, one might even argue, as FCC Chairman Kennard did, that we are clearly in the midst of a 'drought of RF spectrum. This problem is, in part, the result of the inefficient use of spectrum directly resulting from the "regulator's limited ability to plan future spectrum markets" (Kennard, 2000; Rosston, 2001). A complex, vigorous debate as to how to unblock current spectrum allocations to enable these new communication services centers largely on economic and political arguments. While there is little debate that radio spectrum is a national resource to be used in the "public interest", there is great debate regarding just what the public's interest really is and how it can best be served. The economic and policy proposals are interesting and vary widely in their approaches to the problem, but several overlook some key physical attributes of radio spectrum that differentiate it from other natural resources. This paper hopes to offer new insights and suggestions by describing the critical role a few fundamental parameters play in radio systems. As Hazlett points out, some believe that "magic" technologies such as spread spectrum CDMA and 'cognitive radios' can *create* spectrum abundance and turn the drought into a flood (Gilder, 2001; Hazlett, 2000) This isn't likely. We believe the use of a technology-neutral approach that exploits technology advances applied to the underlying physical attributes of the radio spectrum offers a better long-term management solution to this shortage. This technology-neutral approach is key to ensuring a lasting foundation for unblocking upon which future systems designers are free to innovate using the latest state-of-the-art techniques.

The *exponential* growth in microelectronic capabilities has enabled a new generation of communication systems and has been the catalyst for the tremendous pressures for more availability of spectrum. These same technologies also hold the key to unblocking the spectrum *if* they are made an integral part of future spectrum allocation policy. Technology must play a significant role as an enabler of new spectrum sharing mechanisms, yet a delicate balance must be struck with policy that enables technical innovation in the system design while also creating incentives for sharing between, not just within, systems. We will propose what we refer to as an (*s,v,t)* lease or allocation mechanism with the intent to initiate discussion of new spectrum management policy based on three basis functions of RF communication engineering: spectrum or frequency (*s*), volume or space (*v*) and time (*t*). Our intent is to propose the coupling of future spectrum allocation policy to the (*s,v,t)* vector space. We will highlight what we believe are the critical mechanisms enabling such policy, but we will not attempt to define the policy itself.

The FCC recognizes the need for change in the way spectrum allocation is approached. The three generally recognized models for assigning spectrum rights are: "Command and Control" in which frequency allocations are granted to limited categories of spectrum users with service restrictions; "Exclusive Use" in which a licensee has exclusive and transferable rights to the use of a specified portion of spectrum within a geographical area; and a "Commons" approach in which unlimited numbers of unlicensed users share frequencies with no right to protection from interference (FCC, 2002). The first model is by far the most prevalent today, the latter has spawned a plethora of innovate consumer products such as Bluetooth devices, home monitoring and wireless networking; the exclusive use model has perpetuated the ubiquity of portable telephony by providing competitive incentives to the cellular phone network providers in the form of market domination through geographical coverage (while also directing billions of dollars toward the U.S. treasury). The (*s,v,t)* framework we propose in this paper encompasses each of these models; they are subsets of our general approach. *How* the *s, v, or t* allocation is incentivized, negotiated, and enforced differentiates these approaches. Developing the technology to enable this framework then using policy in an appropriate manner to foster a more open use of the RF spectrum is a more general, scaleable, timeless approach.

A strategic view of spectrum management might translate "public interest" to "national interest". It is certainly in the national interest to create spectrum allocation mechanisms that, in the least, do not penalize federal, state, and local government entities through the *ad-hoc* reallocation of spectrum currently under their use. Such reallocation directly impacts mission effectiveness, operational capability, technological advantage over our enemies, and incurs considerable expense to the taxpayer for system modification. The side effects of reallocations, therefore, are important considerations that have a direct, lasting impact on the public at large. During times of war or crisis, the public interest aspect of government spectrum use is apparent and generally supported by the public. The post 9/11 example of Verizon modifying their system to provide prioritization of government emergency mobile telephone calls and for high security for the 2002 Winter Olympics, underscores the point (Stern, 2001). This clearly outlines the level at which the arguments for, and the execution of, the "next steps" in spectrum management must take place. The Department of Defense and other Government agencies are currently allocated vast amounts of spectrum, presumably for good reason – that of National safety. The cost to modify any "legacy" equipment using the airwaves is ultimately passed on to the citizens – either directly through the users of a given service (e.g. a more expensive telephone handset) or indirectly through taxes to fund government modernization programs. Effective, efficient use of RF spectrum by the government must be preserved and harmonized with the commercial sector.

In order to avert future spectrum management crises, we recommend a three-pronged management approach based on strategy, policy, and technology. The strategy would create a National Strategic Roadmap for spectrum with a transitional plan from current allocation mechanisms. This would be constructed by a small collection of unbiased individuals with a firm knowledge of the underlying technologies and systems issues who will represent both public and private interests. The results of their work would need to be supported by an authority that transcends the FCC and the NTIA. With a strategic view in place, policy can be used to institute incentives for innovation and flexibility, to create and manage lease mechanisms, and to identify practical methods of compliance monitoring and lease revocation. The successful implementation of the resulting policy would rely heavily on advanced radio technologies that could facilitate better spectrum sharing.

II. Increasing Spectrum Utilization

It is instructive to consider the few ways in which more bandwidth can be "mined" from our current spectrum allocations and, of those, which may hold the most profitable yield. The four primary means of yielding more bandwidth are:

1. Better source compression. Optimal source compression uses the minimum possible information bandwidth necessary to still represent the message accurately at the

transmitter input. Current technology can compress voice, video, and data at very near the theoretical limits. *Very few additional gains can be realized here through technological advances; the anticipated yield is low.*

2. Transmit information using more efficient waveforms. Shannon showed that any communications channel has a maximum theoretical throughput (capacity) that cannot be exceeded (Shannon, 1948). The objective of spectrum efficient communication, therefore, is to always transmit information through the channel at a rate near the theoretical maximum. Current modulation and coding techniques allow us to approach these theoretical maximums with our current level of technologies. *Very little additional gain can be realized here through technological advances; the anticipated "mining" yield is low.*

3. Isolate users spatially and "reuse" the same spectrum. Many transmissions are intended for a specific set of users, so it's inefficient to "broadcast" radio energy where there are no intended receivers. If we could carefully craft the spatial distribution of the radio emission, we could reuse the same piece of spectrum for several communications channels. This form of spatial separation is widely used in cell phones, satellite spot beams, and wireless local area networks (LANs). Significant amounts of bandwidth can be "mined" through spatial reuse. In some applications such as "micro-LANs", unbounded capacity gains can be achieved across wide areas. *Extremely high yields are possible, but we are only now developing the requisite technologies to realize these gains.*

4. Penalize inefficient use of spectrum. To achieve this, one would create spectrum allocation and management policy based on strong incentives to share. While sharing in the form of spectrum reuse has naturally occurred *within* a licensee's system, with some minor exceptions in the unlicensed bands, disincentives to share *between* licensees are built into our current spectrum management policies. *We believe significant bandwidth can be "mined" through the application of sharing policies.*

Since spatial reuse and spectrum sharing policies offer the greatest gains, we will focus on those as areas most profitable for development of additional available spectrum. As will be seen shortly, spatial diversity, along with frequency and time diversity will form the basis for our proposed dynamic lease concept.

The untapped potential of spectrum sharing techniques can be illustrated by examining in detail the tremendous utilization factors enjoyed today by the cellular telephone industry in a relatively small collection of spectrum. Cellular systems today occupy a collective bandwidth of about 193 MHz, yet provide mobile communications services to well over 100 million total subscribers, a rough order spectrum utilization of better than 518,000 subscribers / MHz or 1 user for every 2 Hertz allocated. Naturally, the collective "system" makes statistical assumptions on call events and duration and hence cannot accommodate all 100 million calls simultaneously. Still, no other application of spectrum has come near that level of utilization for voice service or higher bandwidth uses. The licensees are able to "share" their spectrum allocations among their subscriber base and achieve such utilization factors largely through spatial diversity – the avoidance of interference through separation in space or cells. Diversity in the form of multiple access techniques such as CDMA and TDMA further increase subscriber density.

If spectrum sharing opened up access to over 100 million users in only 0.64 percent of the prime spectrum under 30 GHz, imagine the possibilities if all spectrum were shared among, or even within, licensee allocations.

We will now suggest a method of dynamic spectrum allocation on which new allocation policies can be constructed that significantly increases spectrum utilization.

III. A Dynamic Allocation Framework

Today, a radio frequency authorization is an assignment of *spectrum* over a *volume* of space for a duration of *time*, (*s*,*v*,*t*); Radio engineers have historically used each of these parameters in the design of multiple-access wireless communication systems. Usually, each of these parameters is fixed by the terms of the authorization and, hence, they determine much of the design of the resulting communication system. Frequency is generally allocated in fixed chunks, the volume (operating area) is generally quite large (often all of CONUS or global), and the duration of the allocation is generally quite long (years). Furthermore, the allocating authority rarely makes provisions for the sharing of this allocation although as pointed out above, the recipient of the allocation often does "share" or "reuse" the spectrum with their own users. As pointed out above, the cellular telephone industry has significantly increased the number of calls per megahertz of frequency; likewise the military was among the first to apply multiple access *en masse* due to its need for netted communications.

The parameters (*s,v,t)* are basis functions which, along with their derivatives, can be used to completely describe any use of spectrum. So sharing *among* various "licensees" can be enabled through a refined allocation process that recognizes and grants authorizations based on a candidate's system specific values of (*s,v,t).* Thus, two candidates can be authorized to use the same frequency if they differ in their operating "volumes" or their operating "times". In addition, modern radio technologies enable the *dynamic allocation* of (*s,v,t) "leases"* and enable much finer control over both the volume used and the operating time. Note we do not specify a central authority – the authority could be distributed and operating in near real time, even within the communication devices themselves. Likewise, we do not specify a period on the duration of the leases – they could span from seconds to years. For example, instead of one cellular telephone system having exclusive use of a block of spectrum, several cellular providers could share allocations with a simplified dynamic lease arrangement looking something like[†] (s = 1850.00-1850.25 MHz, v = cell size, t = call duration). This would certainly further increase the utilization of the spectrum simply by making it available in a controlled way to other providers. This increased utilization could be another mechanism for introducing secondary markets only in this example, directly with the allocating authority as opposed to the current exclusive rights licensee. This opens access up to smaller, often more innovative companies that do not have the capital or opportunity to acquire spectrum yet keeps their access free of conditions such as non-competition clauses that are likely to be associated with a spectrum sublease from a licensee.

Thus, our recommended approach to maximizing spectral utilization is not a given set of waveforms or access techniques but rather construction of the allocation process so the potential user of spectrum has a strong incentive to *minimize* one or more of the (*s,v,t)* parameters and thereby utilize the critical resource more efficiently. It is through these minimizations that access for other users are made possible. The lease management authority (even if that authority is geographically and bureaucratically distributed) dovetails the use of spectrum by the licensees resulting in higher utilization levels and new access for all. Specific frequency bands would no longer have to be tied to a specific use since spectrum could be allocated for other applications simultaneously while still allowing for the positive control of the spectrum. Even this positive control can be relegated to others if so desired; this approach is scaleable across all authority domains.

The (*s,v,t)* concept is illustrated graphically in figure 1 for a range of lease durations. Figure 1 depicts the blocking approach to spectrum where a license to operate is granted over some frequency block in a large geographical region for a long duration of time; figures 2-5 depict four new systems that could co-exist within that same spectrum using the (*s,v,t)* unblocking concept. Figure 2 is an example of a mobile voice communication system such as a phone call or a land-mobile radio system. The time and bandwidth of the lease are small and, in this case, the licensee was also able (or willing) to limit the spatial characteristics of the session. Figure 3 depicts a similar mobile system in which only high-speed data is being exchanged rather than voice hence the spectrum requirement increases over a similar duration. Figure 4 depicts a spatially contained broadcast system that operates 24 hours per day (otherwise the allocation could be on an hourly basis) over a small bandwidth. Figure 5 illustrates a wideband burst wireless LAN system utilizing very large bandwidths over a duration of microseconds localized in a very small volume such as a room. All of the unblocked systems could coexist within the original block allocation through frequency, time, and spatial diversity techniques.

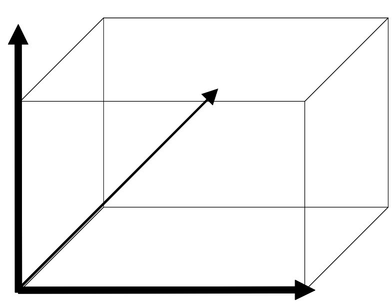

Figure 1. Block Spectrum Allocations of Today

[†] It would actually include spectral, geographical, and time envelope; spectral and geographical envelopes would be "maps" that specify diversity parameters

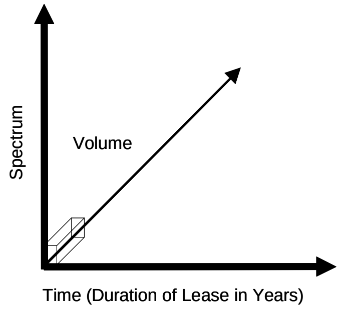

Figure 2. Notional Unblocked (s,v,t) Allocation for an Mobile Voice Application

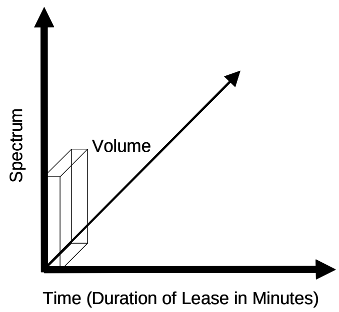

Figure 3. Notional Unblocked (s,v,t) Allocation for a Mobile Data Application

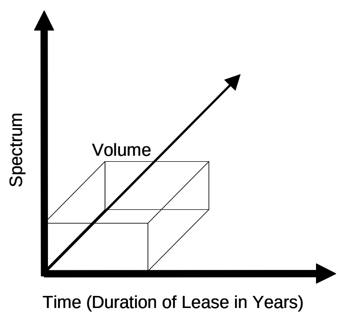

Figure 4, Notional Unblocked (s,v,t) Allocation for a Localized Broadcast (e.g. low power FM)

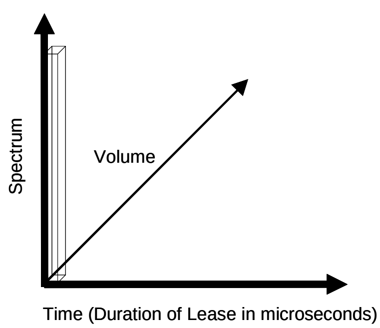

Figure 5. Notional Unblocked (s,v,t) Allocation for a Burst Wideband Wireless LAN

The communications channel is always an integral part of the system design due to the effects that it has on the RF propagation of electromagnetic waves. This results in certain types of applications being most applicable in certain bands. For instance water-vapor absorption frequency windows make some bands particularly attractive to satellite communications or radars. Creating (*s,v,t)* lease parameters with a universal language but band-specific applications is a natural way to address these issues.

Short lease durations (hours – days) will be enabled within systems by the application of technology (e.g. layered radios, software-defined radios, per-packet adaptable radios, digitally encoded active radars, etc.). For example, real-time spectral reuse of deployed systems can be enabled through designs that support the ability to shape antenna patterns or dynamically allocate frequency as in our cell phone example above. Such approaches can be used to ameliorate the host-nation spectrum issues that hamper the deployment of some military communications systems.

Longer time frame *(s,v,t)* allocations also offer advantages. Motivated by policy incentives, system developers can be encouraged to field systems in ways that tolerate a loss of exclusive right to use over a long period of time. For such allocations, the method of relocation would be entirely up to the licensee: it could be through the replacement of all fielded equipment; it could be through flexible systems that can be upgraded if possible; it could be a risk for which the licensee's company has no apparent solution but is willing to take in exchange for reduced current operating costs. As an example, a developer may be able to prototype low-cost, special-purpose disposable devices at a fixed operating frequency. The associated lease may be encumbered with a "sunset" clause that requires the developer to disable all transmitters before a certain date. This type of allocation is advantageous for limited-lifetime low-cost disposable devices such as medical monitors or remote sensors or even "fad" devices such as citizen band radios.

IV. Incentives

Policy incentives should thus be constructed to strongly encourage the short-term, real-time sharing of spectrum through minimization of at least one (s,v,t) parameter or an "(s,v,t) figure of merit". Incentives should also exist for those systems that are willing to provide long term reallocation requests.

The largest incentives should be reserved for those systems that do both – sharing spectrum today while standing ready to adapt in some manner for tomorrow. Likewise, the strongest disincentives should be reserved for those that insist on fielding systems that can do neither but want large allocations over large volumes of space for a long duration of time – in essence, to discourage potential licensees from creating blocks of their own. Incentives that support flexibility yet enable individual innovation are critically important. The government's investment in spectrum-dependent equipment alone is in excess of $80 billion (NTIA, 2000). It is probably even higher for industry although the costs of that infrastructure are distributed at the consumer level and are often cited as reasons why the terms of an allocation can't change. This is a direct artifact of the deeded-land model we have effectively created through exclusive use. These situations can be reduced through the application of incentives to tolerate long-term lease dynamics.

The Strategic Spectrum Roadmap should identify various classes of incentives. Potential classes include:

1. Monetary
2. Fast-track approvals to field *(s,v,t)* enabled equipment
3. "Pioneering Opportunities" in which the opportunity to define the specifics of real-time *(s,v,t)* leasing parameters for a given band are extended to the licensee

Again, incentives would be tied to the minimization of a defined *(s,v,t)* figure-of-merit as well as the long-term willingness of the licensee to adapt or even relocate entirely. With the cooperation of both the FCC and NTIA, we should strive to make these incentives applicable to both public and private sector users. Because money is ultimately the market instrument that most effectively regulates a limited resource, financial incentives in the form of real-time lease payments could apply to both of these sectors. Open access would still effectively be made available through the rate structure.

In an application where government systems have relatively low utilization during defined timeframes but high utilization over others (e.g. peacetime versus war or crisis or increased protection for major events such as Olympics, sports events, etc.), long-term incentives can be applied. For example, incentives can be created that encourage next generation wireless providers to grant the national system priority, precedence, or even exclusive use if that use is the most pressing public interest at the time.

V. Advantages of Dynamic Allocation

The idea of allocating spectrum based on *(s,v,t)* is not radical – in fact we do it today with very coarse resolution. We propose that *(s,v,t)* "leasing" should be an integral part of the spectrum roadmap. Major benefits include:

- **Enables dynamic spectrum allocations**. In many communication systems, dynamic allocation has proven far more efficient than provisioning or reservation. A simple analogy is the highway system; we don't reserve additional lanes just for emergency vehicle use. Instead, signaling mechanisms are used to dynamically allocate the traffic lanes when needed for emergencies. Likewise in data and circuit switched networks, priority and precedence schemes are preferred over provisioning when overall capacity is low. For RF spectrum however, there is an additional advantage in that it allows for the adaptation of allocations to changing spectrum needs – changes which simply cannot be foreseen and that traditionally require many years and dollars to "clear the band".

- **Retains positive spectrum control**. *(s,v,t)* allocations allow maximum flexibility between systems yet, through management functions, allow positive control to be maintained should problems arise or when (not if) the overall use for a given band needs to change. Unlicensed bands play an important role in spurring innovation and creativity and have created markets where none were previously anticipated. Evidence of this can be seen by the quantity and popularity of commercially available communications devices operating in the license-free ISM bands. However, depending on the type of unlicensed band, they are only permitted with the understanding that existing systems must tolerate any interference they encounter or even be liable for interference caused to other users – the only hint of positive control being maintained is enough oversight to prevent exclusive use.

- **Scales to authority's management domain.** The geographical span of potential authority over spectrum allocation ranges from a few inches[††] to the entire globe.

- **Supports variable allocation resolutions (e.g., time allocations of seconds, minutes, hours, days, or years).** While fine-grain allocations will promote more efficient sharing for some applications, the approach does not preclude the course grain allocations of today.

- **Encourages innovation in system design.** Unhindered by overburdening spectrum policies, wireless technologies have the potential to change the face of future communications in unimaginable ways, both for federal users as well as commercial private users. If constructed, implemented, and managed correctly, *(s,v,t)* allocations will enable systems designers and their owners to make engineering and business model trades as they see fit – enabling them to take on risk with innovative technology while still sharing a band with other users.

- **Effective means to access secondary markets.** When used as a mechanism to unblock spectrum, (*s*,*v*,*t*) leases effectively provide a secondary market creation mechanism yet provide a means for the primary holder of the market to be either a primary licensee, band manager, geographic authority, property owner, or government. This range of implementation options also enable an orderly transition from fully blocked to a partially or fully shared band.

VI. Technologies that Enable Dynamic Allocation

The state-of-the-art of communications has grown tremendously since Marconi's first transmission. Communication systems are slowly evolving in some ways such as software-defined radios and undergoing a potential revolution in others such as ultra wideband communications. Yet underlying these system level advances are a myriad of technologies that both enable new communications techniques as well as dynamic allocation and sharing of spectrum. We can now digitally tune receivers across wide bandwidths with single Hertz accuracy. Consumer-grade analog-to-digital converters can operate over wide bandwidths with large dynamic range, which enables operation in strong interference environments. GPS receivers, micro-electro-mechanical systems (MEMS), and high accuracy oscillators can be combined to provide globally available time and position information with microsecond time and one meter distance accuracy. Antenna technologies can adaptively create high-gain, directional beams or nulls while also reducing the effects of multi-path interference, an efficiency-robbing artifact of high frequency communications channels, particularly in the PCS and short wavelength bands. Each of these can be applied to the implementation of an (*s*,*v*,*t*) allocation mechanism. Yet technology alone won't solve the spectrum shortage.

VII. The Role of Flexible Radio Architectures

Hazlett correctly points out that spread spectrum or other revolutionary digital technologies are not the panaceas that will create abundance of spectrum (Hazlett, 2001). There are no such panaceas and we likely won't see another era of abundance in RF spectrum. Rather, our goal should be to develop a spectrum allocation policy that increases spectral utilization by several orders of magnitude from what we currently have. For this to be accomplished, it is clear that flexible communication radio *architectures* are a key enabling technological foundation.

Historically, radio implementations have been monolithic blocks that encompass a wide variety of system functions from tuning to the appropriate frequency to presenting the output information to the user. While often cost-effective for a single purpose device even a minor design change can be incredibly expensive due to the interdependencies between components. (Imagine the difficulty of modifying complex pieces of software if object-oriented programming or even software modularity in the form of simple subroutines were not used.) These architectures also make it extremely difficult to reuse subsystems of one radio in the design of others. This drawback drove many radio manufacturers to an architecture that encapsulated functions that could be used in other designs resulting in lower production cost. The attraction of the apparent ease of software modifications through programmability led to the concept of a "software defined radio" (SDR) in which waveforms are defined by software and

[††] Compelling arguments can be made for the true "ownership" of spectrum for the most local cases – a few inches to a few meters – when tied to a specific location such as a home or office for which no authority would be required.

cognitive radios which utilize "radio-domain based cognitive reasoning as an adaptation mechanism" (Mitola, 1999). While this creates the potential for flexibility in the function and operation of the radio, we believe the superset of SDR, "layered radio" architectures will stand the test of time through which technology moves so quickly (Butler, 1998). The layered radio architecture is technology neutral and is based on encapsulation (layering) of key radio functions. Technology neutrality is key in this application as higher performance can always be achieved through a more aggressive use of specialized components. Size, weight, and power costs are incurred by generalization whether the device uses application specific integrated circuits (ASIC), field programmable gate arrays (FPGA), digital signal processors (DSP), or a general purpose CPU. This is illustrated in figure 6. The appropriate level of specialization is very much decided by the application, production volume, and customer needs. A "one size fits all" approach to design ignores the realities of competition in an open market place. *This underscores the importance in crafting policy that is technology neutral and that leaves the system implementers free to innovate*. The Department of Defense has the opportunity today to build *(s,v,t)* mechanisms into the next generation of military communications radios through the Joint Tactical Radio System (JTRS), an SDR architecture slated to guide nearly every military radio product operating from low-frequency to well beyond 2 GHz.

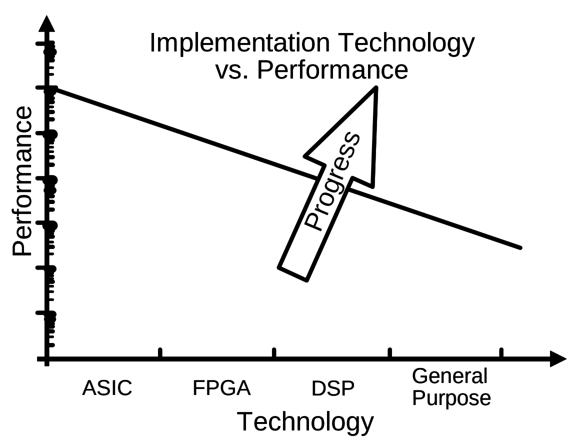

Figure 6. Specialization Offers Efficiency (Butler, 1998)

While SDRs will likely play a major role in the future of communications for some applications, policymakers shouldn't craft policy with the assumption SDR or any other technology will be the catalyst behind the creation of spectrum abundance any more than CDMA will be. They can however bet on an architecture that embraces the certain changes in technology and assume those changes will be the catalyst for changes in how spectrum is used.

VIII. Internet Analogies

A direct analogy to the Internet is to examine the equivalent of getting assigned a frequency: the widely reported pending shortage of Internet Protocol (IP) addresses in 1996. At the time, experts stated that with only roughly 160 million usable unique IP addresses available with IPv4 and the predicted exponential growth of devices to be connected to the Internet, we would run out of addresses within two years if we didn't hastily adopt IP version 6 (IPv6). Six years later, an estimated 600 million users were connected to the Internet utilizing approximately 69 million unique IP addresses within the original address space. The shortage was the result of liberally distributing huge address blocks to universities and companies when it seemed as though addresses would never be in short supply and precluding spatial reuse by allocating only globally unique IP addresses. The answer was sharing through dynamic allocation of addresses. This dynamic allocation now occurs routinely in numerous places throughout the Internet. Internet Service Providers dynamically assign IP addresses when dial-up users connect. Similarly, enterprise networks enable address reuse through the use of masquerading firewalls that hide internal IP addresses from the Internet at large. Likewise in spectrum management, sharing is the solution to the spectrum problem. Dynamic allocation, while unheard of today between licensees, could bring about a significant advancement in our utilization of RF spectrum.

In *The Wireless Craze*, Hazlett, referring to Larry Lessig's *Code: And Other Laws of Cyberspace*, draws an analogy between spectrum commons – open access to all- and the Internet:

> "No one allocates a particular channel to your machine; your machine shares the Net with every other machine on the Net. But the Net has a protocol about sharing the commons. Once this protocol is agreed on, no further regulation is required. The spectrum commons idea is motivated by analogy to the Internet. Yet the architecture of the Internet – a network of networks-seriously misallocates scarce bandwidth"

He goes on to point out solutions in which network privatization and infrastructure improvements made by network access providers "provides bypass around the commons" an act necessary to get the desired performance from the network because it couldn't be purchased at any price.

Although we're not endorsing a "commons" approach to spectrum, there are some points worth discussing relating these other Internet analogies with unblocked spectrum allocation. While true that our machines are all interconnected, our "sharing" of the Net is done through crude forms of diversity. Our Ethernet segments are switched so our ports aren't bothered with touching every packet from local machines on the same subnet. IP addressing itself provides segregation of the network much like spatial diversity in a cellular system. Congestion problems caused by junk email are effectively broadcasts that subvert this diversity mechanism. "Once a protocol is agreed on" implies a set of static protocols yet there have been significant, steady increases in the number of modifications and new proposals for protocols, many of them dealing with issues such as prioritization and dynamic allocation of bandwidth to directly address the "misallocation of bandwidth". It is widely recognized that poor Internet performance in terms of latency, throughput and reliability are the result of an overall shortage of bandwidth capacity in the network, much of it at switches, access points, and the last mile. As long as capacity is scarce, there are only two ways to address the problem: prioritization of the traffic that gets to flow, or provisioning of bandwidth through reservation. The latter is akin to a block spectrum allocation; the former is fine – if you happen to like the definition of "high priority" that gets chosen. But the "bypassing of the commons" through privatization of portions of the network and infrastructure upgrades cited isn't either of these – it's *adding* capacity which can be as easy in the networking world as laying a new fiber or adding another branch to the network graph. Unfortunately, the slope of the rate of technology to utilize comparable bandwidths at higher frequencies is quite linear while its more like exponential for networking. The only alternative left is unblocking.

IX. Summary and Recommendations

While the commercial communications industry migrates through and beyond 3G and 4G wireless, last mile connectivity, and other new PCS services, and the DoD migrates toward its major new initiatives such as the Future Combat System, Global Information Grid, Transformational Communications, space-based sensors, etc., our reliance on wireless capacity will continue to increase dramatically. Both industry and government's insatiable demand for bandwidth will outstrip any capacity gains that may be realized through highly efficient waveforms, source compression techniques, CDMA or any one "revolutionary" digital technology. The key to spectrum utilization lies in spatial diversity and a sharing policy based on dynamic allocation.

Historically, the financial markets have favored companies with exclusive use of a spectrum allocation. Wall Street's reluctance to back share-use ventures is most likely tied to the uncertainty caused by the potential of interference, a concern that is addressed by the positive control aspect of (*s,v,t)*. When implemented correctly, sharing can significantly increase spectrum utilization and offer market entry to all including many small companies that may not have the resources to acquire allocations today.

Demonstration and transition to such a system can be gradual for example, through the demonstration of dynamic sharing mechanisms within a licensee's system, or within a government system. It could also be introduced as a pilot in an experimental or unlicensed band.

The technology to build communication, radar, and other RF systems that share bands and drastically increase the efficiency of spectrum utilization exists now or is within reach. Policy must be crafted to create incentives for this increased system flexibility while allowing the implementers to innovate in their system designs and their application of technology. We have proposed a technology-neutral dynamic allocation framework constructed around the three physical properties of RF propagation: spectrum, volume, and time. Coupled with the proper incentive-based—as opposed to rule-based—policy, unprecedented spectrum utilization levels can be achieved. Furthermore, the technique allows gradual unblocking of currently allocated spectrum and also scales with domain authority from within a room to across the world.

A National Strategic Roadmap recognizing the value of a sharing approach like that based on (*s,v,t)* leasing mechanisms is an important step. Given the major impact the shortage of spectrum certainly has on the national interest, we cannot hesitate to advance the "state of the art" of spectrum management within our own borders. Once we accept new spectrum sharing allocation mechanisms as a nation, we will be better positioned to extend our ideas with our experiences to the international community.

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