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Populating the Vacant Channels
THE CASE FOR ALLOCATING UNUSED SPECTRUM IN THE DIGITAL TV BANDS TO UNLICENSED USE FOR BROADBAND AND WIRELESS INNOVATION

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Abstract

There are vacant channels between broadcast television stations in every media market. This spectrum can be used by unlicensed devices without interfering with television viewing.

An unlicensed allocation of these bands would be the most productive way to use this spectrum. Unlicensed spectrum is a proven way to generate technical and commercial innovation; promotes healthy diversity in markets and regulatory models; and complements the licensed allocation in the nearby 700 MHz band.

A broad cross-section of society would benefit, including rural and inner-city residents seeking affordable Internet access, entrepreneurs starting up digital communication businesses, cities and companies seeking to foster growth and productivity, and citizens who want to create home or community broadband networks.

Congress should press the FCC to act on its dormant Notice of Proposed Rulemaking by allocating this spectrum to unlicensed use.

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1 Introduction

There will be under-utilized wireless spectrum in the gaps between TV broadcasts when the transition from analog to digital television is complete. This spectrum is a valuable asset: TV uses frequencies with such desirable propagation characteristics that they are often referred to as "beachfront spectrum."

Congress and the FCC have an opportunity to improve Americans' lives and boost the economy by allowing consumers and entrepreneurs to use this fallow spectrum. They should act now to allow unlicensed use in the TV "white space."

Unlicensed spectrum encourages innovation, is an efficient way to experiment with new technologies and business ideas, and provides a regulatory complement to nearby licensed allocations. Reclaimed TV spectrum in the nearby 700 MHz band has already been reserved for flexible licensed use.

An unlicensed allocation would not take spectrum away from broadcasters, or inconvenience the television audience. Rules and technology will ensure that Americans who watch television using over-the-air broadcasts will continue to receive their signals free of harmful interference.

Many Americans would benefit from such an allocation:

- Rural residents and businesses who currently lack broadband Internet access
- Citizens in inner-city neighborhoods where Internet access is not affordable
- Entrepreneurs who want to start up businesses to serve these customers, but who can't afford the costs of obtaining spectrum licenses
- Cities and businesses that want to stimulate growth by creating wide-area networks in their downtowns or throughout their offices or campuses
- Citizens who want to improve their quality of life by creating community networks in their own neighborhoods

The argument below proceeds in three steps:

1. There will be vacant channels ("white spaces") in the DTV bands.
2. They are usable without harmful interference to TV reception.
3. An unlicensed allocation is the best way to use this resource.

The following action should be taken:

- Congress should require the FCC to allow unlicensed use in this band.
- The FCC should act on its stalled 2004 Notice of Proposed Rulemaking in this matter by issuing a rule that will allow manufacturers to begin designing devices.

1.1 Assumptions

Since a case is only as good as its assumptions, here are mine:

- Competitive markets are usually the optimal way to allocate resources.

- Economic efficiency should not be the only guide to policy. Fairness and prudence should also be taken into account.

- The predictions of economic models and policy scenarios are uncertain. A portfolio of diversified policy approaches is better than putting all one's eggs in one basket.

- Innovation and competition should be cultivated by ensuring that there are market entry opportunities.

1.2 Definitions

"Spectrum-title" licensed

A regulator such as the FCC can issue a license to an entity to operate in a spectrum band. This private entity has the right to control access to the spectrum, including extracting revenue from end-users in some cases. Licenses can be awarded by fiat, lottery, or bought at auction. Licenses can be restricted to a particular end use employing specified technology (e.g., broadcast licenses), or may be "flexible," that is, the choice of end use and technology is up to the licensee.

An exclusively assigned, flexible, and automatically renewable license is effectively an ownership interest similar to title in land. This is the regulatory approach most commonly contrasted with unlicensed allocations. I will use the term "spectrum-title (licenses)" to refer to such flexible, assignable, renewable licenses, even though the Communications Act of 1934 prohibits private ownership or other rights in spectrum beyond the limited term of a license (which most commonly are eight years).[1]

The terms "exclusive use"[2] and EAFUS[3] are also used to describe allocations where a licensee has exclusive, flexible, and transferable rights to use specified spectrum, and I consider them to be synonyms of "spectrum-title" as used in this paper.

Unlicensed

I use the term "unlicensed" to indicate spectrum uses in which any device that meets criteria set by a regulator may be operated without a license.[4] Some unlicensed rule provisions have few technical constraints except those related to interference to the primary users, while others specify more detailed restrictions that typically include power limits.

The terms "license-exempt," "commons," and "collective use" are also used to describe such allocations, and are effectively synonyms for "unlicensed" as used here. I consider an unlicensed band to be a "managed commons" owned and supervised by the government, rather than property owned in common by all users.

Unlicensed uses are typically "secondary," i.e., there are "primary" licensed users in the band with which unlicensed use may not interfere. Lehr (2004) has made a case for "dedicated unlicensed" allocations – bands in which unlicensed operation is primary. While I support such allocations, this paper advocates a "secondary use" unlicensed allocation in the broadcast bands. A "secondary" white spaces allocation is useful but does not substitute for allocations of dedicated unlicensed spectrum in the lower frequencies (below 1 GHz) that more easily penetrate obstacles.[5]

1.3 The story so far

There is broad consensus in the United States that the traditional method of allocating spectrum is outdated and inefficient. The FCC's Spectrum Policy Task Force (FCC 2002) concluded that current spectrum policies were in need of reform. It recommended a balance between three spectrum rights models:

- "Command and control," the traditional method of spectrum management in the US, in which allowable spectrum uses and users are determined by regulatory judgment;
- "Exclusive use," where a licensee has exclusive, flexible, and transferable rights to use specified spectrum ("spectrum-title," in the usage of this paper);
- "Commons," where unlimited numbers of unlicensed users share frequencies ("unlicensed," in this paper).

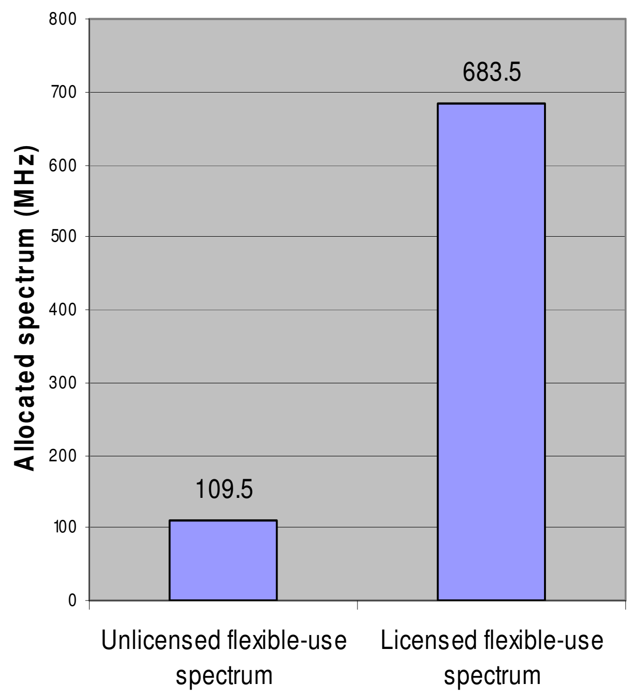
We are in the midst of a transition from "command and control" towards a mix of spectrum-title and unlicensed. The optimal mix of spectrum-title and unlicensed is still being debated. Both allocations have been successful. Cellular telephony and Wi-Fi networks each make intensive use of spectrum-title and unlicensed bands, respectively. Both industries have seen rapid growth and a great deal of innovation.

The most successful unlicensed bands have been the ISM bands at 900 MHz (used for cordless phones, telemetry, meter reading, etc.) and 2.4 GHz (Wi-Fi networks, Bluetooth headsets, etc.). New unlicensed allocations have been made at increasingly higher frequencies, such as the 5 GHz U-NII bands,[6] and bands above 60GHz.[7] These bands have not yet been intensively used, not least because signals don't penetrate obstacles such as walls and trees very well at such high frequencies. These frequencies are appropriate for point-to-point microwave links, but less helpful for building local area networks, which were the breakthrough application for unlicensed technology in the 2.4 GHz band. At very high frequencies such as 60 GHz, the severe attenuation with distance coupled with the small beam size of modest antennas makes licensing less relevant because it is, in fact, hard to cause interference.

The gradual completion of the transition from analog to digital television is freeing up new spectrum at lower frequencies where signals propagate better. As broadcasters release their temporary duplicate channels in the 700MHz band, 108 MHz of spectrum is being re-allocated to public safety and spectrum-title commercial use.[8] At the completion of the digital television transition, TV broadcasts will be limited to channels 2-51, between 54 and 698 MHz. Channels 14-51 (470-698 MHz) are the sweet spot for the applications I describe in this paper.

Currently, more than six times as much spectrum is allocated to flexible licensed use as to unlicensed below 3 GHz (see Figure 1).[9] Reallocations of spectrum since the FCC Spectrum Task Force Report have been significantly biased against unlicensed. According to Snider (2005), licensed flexible-use spectrum below 3 GHz has increased by 489.5 MHz, while unlicensed spectrum allocations have decreased by 10 MHz.[10]

Figure 1 - Licensed vs. Unlicensed flexible spectrum under 3 GHz



The FCC issued a Notice of Proposed Rulemaking on May 13, 2004 proposing to allow a new generation of wireless devices to use vacant television frequencies (the "Vacant Channel

NPRM").[11] This followed a Notice of Inquiry seeking comment on the possibility of allowing unlicensed devices to operate in the TV broadcast bands at locations and times when the spectrum is not in use by authorized services.[12] In its 2004 NPRM, which remains pending, the Commission proposed the authorization of unlicensed access to vacant TV channels (below Channel 52) for certified low-power devices of two types:

- "Personal/portable" unlicensed devices — such as Wi-Fi cards in laptop computers, or wireless in-home LANs, which operate at very low power — with a maximum power output of 100 milliwatt (mW), and a permanently attached integral antenna with a maximum permissible gain of 6 dBi.[13]

- "Fixed/access" unlicensed devices that are generally operated from a fixed location and may be used to provide a commercial service such as wireless broadband Internet access. These devices can operate with a transmitter output power of up to one watt (the current Part 15 power limit for devices operating in the unlicensed 2.4 GHz and 900 MHz bands) and employ higher gain directional antennas, with requirements for transmitter output reductions for antennas with gains above 6 dBi.

These are very low power levels, even in the "higher power" fixed/access mode. The maximum permissible omni-directional power for unlicensed use in the 2.4 GHz band is one watt; unlicensed emissions in the TV bands will be no higher than this for fixed/access operation, and one-tenth of this power in the case of personal/portable uses.

The Vacant Channel rule-making is currently inactive.

2 Why there are white spaces

Vacant (or unassigned) TV channels result primarily from two circumstances that date to the original allocation of the TV band. First, cheap analog TV receivers had to be protected by "guard bands" since they suffer interference from signals transmitted in adjacent channels. To compensate, the FCC typically allocates a vacant channel on each side of a licensed channel (so-called "adjacent channel" guard bands); and, in addition, does not assign the same channel for use in neighboring markets (so-called "co-channel" guard bands). Digital receivers are far less susceptible to such interference. Second, the same amount of spectrum is allocated nation-wide, even though many fewer TV stations are licensed in rural than in urban areas. This by itself creates an 80 percent "vacancy rate" in the most rural markets.

"White spaces" thus exist — both in channels licensed to broadcasters, as well as vacant ones — as a result of obsolete guard channels, uneven population distribution, the fact that many licensees are low-power and serve only a portion of a market area, and uneven radio propagation loss over real terrain. A series of studies of spectrum occupancy have demonstrated that there will be unused spectrum in the digital television broadcast bands. I summarize the results here.

A 2005 study by Shared Spectrum Company for the National Science Foundation found average spectrum occupancy to be 23 percent for TV channels 14-51.[14] In other words, three-quarters of the band was empty. The project conducted spectrum-occupancy measurements at six locations from January 2004 to August 2005 using a high-dynamic-range spectrum-measurement system.

A study of 22 TV markets by Free Press and the New America Foundation found that an average of seven full-power stations operate in local TV markets.[15] The number of vacant channels after the DTV transition ranged from 15 (Trenton, NJ) to 41 (Fargo, ND) — equivalent to 30 to 82 percent of the available spectrum.[16] The analysis for each city included every licensed broadcast station (high-power, low-power, Class A, and translators) as well as out-of-market signals that might be available to local consumers, and low-power outlets that may not be broadcasting today but are licensed to do so. Every channel with FCC interference protection was excluded from the white space calculation. Channels allocated for public safety, medical telemetry, and radio astronomy were also excluded.

It is clear that there are ample vacant channels in both rural and urban areas.

While over-the-air television broadcasting will doubtless continue, distributing television from high-powered broadcast towers is becoming less important. Most households in the United States get their TV from other means, such as cable service and satellite broadcast. The FCC estimates that fewer than 15 percent of households rely primarily on over-the-air broadcast television (the rest subscribing to cable or satellite services), a number that it says has "fallen slowly but generally steadily in recent years."[17]

Local broadcasters' most important assets are increasingly their local newsgathering resources; their ability to sell advertising on channels that must be carried by multi-channel video operators such as cable systems; and/or their capacity to demand compensation from operators for their consent to retransmit these signals. As transmission becomes less important, an over-the-air license becomes a means to the end of extracting fees for programs delivered via other media, rather than an end in itself. It is reasonable to expect traditional broadcast transmission will continue to decline, freeing up even more spectrum for new uses and steadily increasing the opportunity cost to society if the spectrum remains fallow.

3 Why unlicensed won't cause interference

The broadcasting industry contends that unlicensed devices operating in the unused parts of the TV bands would cause harmful interference to television broadcasts and other uses of licensed TV channels.[18] In a recent paper, three experienced wireless engineers have provided a detailed rebuttal to these objections (Marcus, Kolodzy, and Lippman 2006). I summarize their arguments here.

In its Vacant Channel NPRM, the FCC proposed three technical methods by which broadband devices and other unlicensed users could avoid harmful interference to TV reception. One method — subsequently approved by the Department of Defense for unlicensed sharing with military radar in the upper 5 GHz band — is sensing combined with a "listen-before-talk" requirement. With this method, if a device hears another transmission on the frequency it is using, it automatically switches to another channel. Broadcasters nevertheless worry that unlicensed devices that are shielded from TV signals will incorrectly assume that a vacant channel is available and make transmissions that interfere with TV receivers. Marcus *et al.* point out that detectors optimized for TV signals can be orders of magnitude[19] more sensitive than a normal TV set.[20] Furthermore, unlicensed devices form networks with each other. As a result, cooperative sensing can ensure that all of them, even those that are shielded and can't detect a TV signal, are aware of broadcast stations. In either case, the so-called "hidden node" problem is solved.

A second method cited in the Vacant Channel NPRM is geolocation. The FCC proposed that devices that know their location can avoid broadcast channels in their vicinity by reference to a database. Broadcasters have raised concerns that geo-location systems such as GPS will not operate indoors. However, advanced GPS systems such as those used for Emergency 911 in cell phones *do* work indoors, to within an accuracy of a few hundred yards — perfectly adequate given the many-mile range of TV broadcasts. Such a system can also be engineered to be fail-safe. If no valid GPS signal is received, then no geo-location is deemed to have occurred, and unlicensed use is not permitted. Alternatively, systems using digital TV broadcasts to triangulate position could provide location information once the DTV transition is complete. Marcus *et al.* recognize the industry's concerns about the quality and timeliness of TV station databases, and believe that this should be addressed by improving the quality of FCC data. The completion of the DTV transition will in any event lead to a more stable roster of broadcasts.

The Vacant Channel NPRM offered the option of a local beacon to notify unlicensed receivers about the presence of available channels, but didn't specify its range. Broadcasters worry that a beacon might induce unlicensed devices to operate when they shouldn't, if the beacon's range didn't match that of broadcasts.

This problem can be addressed by ensuring that the footprint of a beacon is smaller than the broadcast area to which it relates, meaning that devices at the edge of the broadcast station's license area would not receive the signal allowing them to transmit on that frequency.

Marcus *et al.* refute the experimental evidence cited by the broadcast industry because they believe the results were based on a worst-case scenario, representing uncharacteristic use of white spaces under unrealistic conditions. They find no evidence that interference will result, except under such conditions; and further, that the FCC can easily prevent this type of desensitization interference in its Final Order, and through its device authorization process. They also note that digital receivers are far more capable of rejecting interference than previous generations of analog equipment.[21] They note concerns about interference to wireless microphones and similar devices, but argue that users of such devices — such as theaters, churches and schools — typically control the venues in which the systems are used and, in any case, have no more right to priority access than other unlicensed users. In fact, since only broadcasters and a few closely related industries are allowed to use these devices in the TV band, other users of these devices in the TV band are generally operating illegally. They argue that interference with cable head-ends can be addressed by special rules for high-power Wireless Internet Service Providers (WISPs); these objections would not apply to the low-power uses which are the subject of this paper.

Smart engineers and lawyers will always be able to construct worst-case scenarios in which harmful interference is conceivable. However, policy makers and regulators need to make judgments about the reasonable likelihood of harmful interference. Wireless technology is an imprecise art. The Grade B contour, the bedrock of broadcast licenses, is itself probabilistic. The FCC's rules define this contour — often a circle drawn around the transmitter site of a television station with only a little attention to actual terrain — in such a way that 50 percent of the locations on that circle are statistically predicted to receive a signal of Grade B intensity at least 90 per cent of the time. Some viewers inside the predicted Grade B contour do not receive a signal of Grade B intensity because of, for example, topographic conditions; other viewers receive a Grade B signal, but their reception is impaired by interference conditions.[22]

A similar statistical standard should suffice for other services in this band. The FCC created its personal computer emission rules in 1979 with a goal of protecting TV sets 30 meters away from a PC, assuming that the PC noise-like emissions were of no value. The emissions in white-space case are of some real value, so a 10 meter or greater interference goal seems reasonable.[23]

It is worth recalling that the current generation of radios is intelligent, and software can be upgraded remotely.[24] The FCC can require that the software controlling white-space wireless device behavior should be upgraded at specified intervals, or disabled remotely should any unforeseen interference issues arise, although these additional requirements come with the price of deterring some innovation and market entry.

Advocates for the broadcast industry have suggested that unlicensed use of white spaces should be limited to professionally installed equipment.[25] This would, theoretically, reduce the risk of interference from unlicensed devices. However, personal/portable operation by non-professionals is already deemed to be safe by the FCC. It's safer, but unnecessary.

Another suggestion is to limit deployment to fixed uses. This, again, is unnecessary given the very low power transmission and anti-interference rules contemplated for personal/portable uses. Distributed ownership and innovation has been a key ingredient to the success of other unlicensed bands. Limiting the application to fixed, professional installation will limit the market to a small part of its potential.

It has been also suggested that unlicensed operation be limited to rural areas. There are many objections to this approach. First, there are low user-density areas in urban areas that would benefit in the same way rural areas would. Second, if something is engineered to avoid interference in rural areas, it'll work fine in urban areas. Third, there are fewer over-the-air television users in urban areas than rural areas, so there are even fewer potential sufferers of interference in urban areas than rural ones. Fourth, the only way to prevent "rural" devices from being used in urban areas is to require professional installation; see the objection to that approach above.

Finally, even if there were to be harmful interference — which I do not expect — regulators need to balance the harms of interference against the off-setting benefits to society of allowing innovative new services. As Ronald Coase put it in his landmark paper,[26] "It is sometimes implied that the aim of regulation in the radio industry should be to minimize interference. But this would be wrong. The aim should be to maximize output."

4 Wi-Fi Plus: Ways to use the white spaces

Unlicensed allocations in the 900 MHz, 2.4 GHz, and 5 GHz bands have led to many useful innovations, from cordless phones to wireless home networks to cheap point-to-point microwave links. No one can accurately predict the innovative services that could be built in the UHF-TV band, just as it was not possible to foresee the innovative services and products that developed in the current unlicensed bands. Past experience does suggest, however, that good signal propagation and low transaction costs will make this band another platform for innovation and a driver of economic growth.

Unlicensed spectrum in the white spaces will facilitate "Wi-Fi Plus" scenarios.[27] An unlicensed allocation will allow users and industry to extend the success of Wi-Fi in the 2.4 GHz bands. The core Wi-Fi standards are mature, and have proven to be a solid foundation for innovation. They could be cheaply transplanted to the vacant television channels by swapping in a radio frequency module to operate in the TV bands, and by repurposing the interference-detection technology already in place and approved by the Defense Department to sense and avoid military radar in the 5 GHz band.[28]

Wi-Fi Plus will enable WISPs to reach more customers in underserved rural and urban areas. Lower frequencies with better propagation characteristics are better suited for creating cost-effective, robust wireless broadband in areas with low customer density. An Intel study estimates that a rural wireless network transmitting on the 700 MHz TV band can cover four times the area, and at a higher quality of service, than a network transmitting at 2.5 GHz.[29] Indoor antennas would enable in-home deployment without expensive professional antenna installation.

WISPs could use either a tower talking to surrounding homes individually, or a mesh architecture, in which each home passes along traffic for its neighbors. Mesh technology has been proven in metropolitan networks. The placement of mesh nodes today has had to be carefully planned since 2.4 GHz and 5 GHz signals don't pass through obstructions very well; this constraint is relaxed in the TV bands, facilitating deployment, reducing cost, and improving quality of service.

The tower and mesh arrangements can complement each other. A WISP could serve customers close to its connection to the Internet backbone from a tower, and customers beyond the reach of the tower could be reached by hopping signals across a mesh from homes that *can* see the tower.

A mesh network can appear without the need for a system operator. Once there are a sufficient number of suitable devices in a neighborhood, they can be configured to automatically form a peer-to-peer network. This provides ubiquitous connectivity to enable applications such as video distribution from local schools, without incurring backhaul network costs. This mesh could eventually grow to form a cloud of basic connectivity that would be available wherever a user might go.

Since an operator is involved, transmissions from WISP towers can be at relatively high power (one watt), with ranges in the order of miles, without the risk of harmful interference to television broadcasts. The home-to-home mesh applications need much lower power levels (around 100 milliwatt) and have much shorter range (a few hundred feet through obstructions).[30]

With a range of hundreds of feet, Wi-Fi Plus hotspots would have a larger footprint than today. Customers will be able to find hotspots more easily since they will be "visible" from further away, though they will not be able to use the full speed afforded by 2.4 GHz and 5 GHz base stations until they are much closer.

Finally, there are likely to be many industrial applications. A mesh of devices using these frequencies could communicate with each other over mid-range distances. Applications might include connecting soil sensors on a farm, and data communications between machines in an industrial complex.

5 Why unlicensed is the best use

There are three options for making use of the white spaces between digital television broadcasts:

1. Allow unlicensed use
2. Auction for spectrum-title use
3. Do nothing, which amounts to ceding the entire band to the broadcast industry

This section will argue that an unlicensed allocation is the best option, since it encourages innovation, complements the spectrum-title allocation of the 700 MHz spectrum, and encourages regulatory and market diversity.

5.1 Unlicensed use would stimulate innovation and growth

5.1.1 Innovation flourishes in unlicensed bands

Experience in the 2.4 GHz ISM band — frequencies once known as the “junk bands” — proves the benefits of an unlicensed allocation.[31] Almost every laptop computer on sale today includes Wi-Fi technology that uses this band.

Technology innovation has been dramatic. Maximum network throughput speed has increased almost fivefold.[32] The 802.11e standard that facilitates multimedia applications has contributed to the rapid growth and positive outlook for networks that support voice and video streams. The draft 802.11n standard promises data throughput rates up to 540 Mbit/s, ten times faster than today’s best devices.[33] Products based on this specification are expected to make up about 15 percent of all the home wireless LAN routers shipped worldwide in 2006.[34]

This has all happened very quickly: the first 802.11 standards underlying Wi-Fi were ratified in 1999 and 2000.[35] The worldwide market for wireless local area networks had grown to $2.5 billion by 2005. By 2009, only a decade after its inception, overall Wi-Fi market revenues are forecast to reach $4.8 billion.[36]

Figure 2 - The Nabaztag Rabbit

Unlicensed allocations encourage new players to enter the market, leading to innovation and competition. Usage scenarios are decentralized, leading to rapid industry growth. Wi-Fi enabled devices now include cameras (Kodak, Canon, Nikon), freestanding ‘radios’ that tune to Internet stations over Wi-Fi (Kerbango, Roku) and even a rabbit: the Nabaztag[37] desktop toy provides weather forecasts and wake-up calls, and waggles its ears when your loved one moves the ears of their toy.

New applications continue to emerge. Commercial networks of wireless hotspots emerged in 2003 (Boingo, Wayport, iPass, T-Mobile, and others), metro mesh[38] networks started to appear in large numbers in 2005, and Internet Voice services over wireless networks are now being created, particularly in enterprises.

There has also been dramatic business model innovation, from rural entrepreneurs offering broadband Internet access to their communities for the first time, to hotspot access packages from mobile telephone companies:

- Over the six years to 2005, annual sales of Wi-Fi chips have grown to more than 100 million units/year, with a 64 percent average yearly growth rate.[39] The Wi-Fi market is expected to grow to 430 million chipsets per year in 2009. Roughly 45 million wireless local area network chips were embedded in mobile PCs in 2005, and approximately 40 million chipsets for home/small-office wireless routers and residential gateway devices were shipped.[40]

- Broadband Internet access is available in 40,000 hotspots in the United States.[41]

- The number of hotspots worldwide has grown 87 percent between January 2005 and January 2006, from 53,779 in 93 countries to 100,355 in 115 countries.[42]

- There are 38 city and regional wireless broadband networks that provide public access in the US. There are also 28 citywide networks used for municipal purposes in the US, and 22 city hot zones.[43]

- There are thousands of Wireless Internet Service Providers (WISPs) providing broadband Internet access services using license-exempt bands.[44] These are generally entrepreneurial small businesses.

Few would argue that Wi-Fi networking and its benefits would have materialized had licenses to operate in this band been auctioned off. Unlicensed bands encourage experimentation and do-it-yourself ventures that rapidly lead to increases in social welfare.

5.1.2 Smart radio technology manages interference without dividing up and selling spectrum

In the past, exclusive licenses were used to manage interference between spectrum users. Each user was allocated a slice of frequencies. Wi-Fi, based on the 802.11 family of IEEE standards,[45] has demonstrated that technologies such as spread-spectrum modulation, power control and channel access protocols can enable many users to use the same band simultaneously, in the presence of microwave ovens and other types of low-power-density devices also authorized by the FCC's Part 15.247 rules.

Efficient sharing in the 2.4 GHz band occurred because 802.11 was designed with many independent, concurrent users in mind. If regulators are concerned that such a standard might not emerge through market forces in the vacant channels, they can create technology-neutral rules that encourage sharing. For example, devices could cluster their choice of operating frequency so that narrowband operations are separated from broadband operations; or they could search for and use open channels before using those in which other devices are already operating; or they could observe a common power spectral density limit (i.e., less time on the air would mean more power); or they could be limited to using the minimum necessary radiated power to complete a communications link; or they could employ listen-before-talk techniques; or the maximum time a station can transmit or otherwise occupy the medium could be limited.

Advocates of flexible and exclusive licensing have argued that investors need a license's guarantee of immunity from interference before they will be willing to make investments in infrastructure.[46] Spectrum-title allocations protect capital investments and encourage the upgrading of equipment. Since users of unlicensed allocations act independently, a coordinated organized upgrade — like the decade-long changeover from analog to digital cellular networks in the US — is impossible, these advocates argue.

It is true that large-scale centralized network investments have been the rule in cellular telephony, which operates in spectrum-title spectrum. However, the lack of interference guarantees has not prevented thousands of rural WISPs and scores of metro Wi-Fi meshes from being built. This undermines the claim that operators will not invest in wide-area infrastructure if they don't have protection against interference. The reason: unlicensed benefits — such as relatively inexpensive infrastructure and devices, a low likelihood of interference in low density areas, and the anticipation of a high social return — offset the risk of interference.

Unlicensed networks are "edge" networks. Investments are made by individuals at the periphery, rather than by a service operator at the core. The de facto 2.4 GHz technology standard changed from 802.11b to 802.11g between 2000 and 2006. The comparable changeover in the dominant cellular data standard from GPRS, which entered wide deployment at the same time as 801.11b, to EDGE is not yet complete. Licensed applications tend to have centralized network infrastructure, with long upgrade cycles; unlicensed ones are decentralized, and new generations of devices have rapidly supplanted old ones. Upgrade cycles for unlicensed technologies are as fast as, if not faster than those in spectrum-title networks.

Of course, technologies are nominally independent of regulatory models. Innovations such as decentralized interference management and smart radios can be used to good effect in both spectrum-title and unlicensed applications. The point here is that it is unnecessary to invoke spectrum licenses to solve all interference problems; technology and the network operator's incentive to improve customer satisfaction can suffice.

5.1.3 Unlicensed spectrum is not only for short range

Some argue that unlicensed spectrum makes sense only when it operates purely within physical property lines.[47] It is true that obtaining a license to operate a service purely within one's home or business would impose an unnecessary overhead on all concerned, and thus that unlicensed is a sensible allocation for such uses. The converse — that unlicensed should *only* be used within property lines — does not hold, however.

For a sufficiently large property, real-estate owners can evidently arbitrate spectrum interference issues since all devices are under their control. However, the large number of neighboring Wi-Fi networks that can be detected in any urban apartment demonstrate that unlicensed technology enables many users to coexist peacefully. With a sufficiently large number of users, congestion will of course reduce capacity. However, as with Mark Twain's obituary, reports of the congestion-induced death of the spectrum commons have been greatly exaggerated.[48]

Some argue that unlicensed allocations should be limited to short-range use, supposedly because unlicensed does not provide the coordination necessary to operate over large distances. This linkage between range of operation and regulatory model is misleading. There are useful and productive wide-area applications of unlicensed, including rural WISPs, business and university campuses, and metropolitan meshes. Unlicensed point-to-point systems in the 5.7 GHz band are now common and are often used by cellular companies to connect new cell sites initially, since no paperwork is required for operation. WISPs report using these point-to-point relays to backhaul data from local access points to fiber connections to the Internet over distances of up to 35 miles. The campus and mesh cases demonstrate that one can build long-range coverage by aggregating short-range services, and prove that interference issues are not insurmountable.[49]

5.1.4 Expansion bands with better range are needed to build on the benefits of Wi-Fi

The 2.4 GHz ISM band was the beachhead for Wi-Fi wireless local area networks. The technology developed at that frequency not because it has the best propagation for wireless networking, but simply because the then-called "junk band" was freely open for innovation without incurring the upfront cost of obtaining spectrum licenses or, alternatively, stitching together leasing agreements with hundreds of licensees in order to offer a nationwide service. The U-NII bands in 5 GHz have not been heavily used to date, although a standard (802.11a) and allocations have been available for some time.

Higher-frequency bands such as 5 GHz enable unlicensed applications to operate at higher networking speeds, since more bandwidth is available.[50] The more severe signal degradation at higher frequencies is not problematic if many adjacent base stations can be assembled, or if line-of-sight deployment can be arranged. Interest in 5 GHz has been growing over the past year.[51] It is likely to be used for enterprise networks, for example for campus-wide voice-over-IP service, and for line-of-sight trunk traffic on mesh networks. Use by consumers at home is unlikely, because the signals won't go as far as they do in the 2.4 GHz band. Indeed, some users will have trouble providing coverage for their whole house without careful planning.

However, higher speed is not the only objective; longer range is important for many applications. While range can be increased by radiating more power, more powerful transmitters can be dangerous close to users, and consume more electrical power. Portability and low power consumption are essential for ubiquitous computing.

The benefits of longer-range, low-power options for Wi-Fi include:

- Increased range for WISPs;
- Larger footprints for hotspots – one can get some connectivity from further away, though the highest speeds will still require close proximity to a base station;
- Reduced start-up costs for metro meshes, since fewer base stations are required;
- Increased reach for metro meshes – some users connecting to existing 2.4 GHz metro networks may need to install special antennas in their windows;
- The creation of neighborhood mesh networks.

It is therefore important to provide a range-enhanced outlet for Wi-Fi innovation by allowing unlicensed operation at frequencies below 2 GHz. A more diverse spectrum ecosystem could greatly enhance the cost-effectiveness and quality of wireless broadband deployments. At this time, the TV white spaces are the only available option for such an allocation.

5.1.5 The advantage of low power

Low-frequency signals go further at a given transmitter power than higher-frequency ones; this is why a 100 milliwatt Wi-Fi system in the TV white spaces will have a somewhat greater range than a similar system in 2.4 GHz. Conversely, one needs less power to cover a given distance at low frequency than high. Low power uses have many advantages: less battery usage, more precise coverage using a multitude of small cells rather than one big one, and improved security by limiting the interceptable range of any given transmission.

5.1.6 Unlicensed as regulatory insurance

In addition to its intrinsic advantages outlined above, an unlicensed allocation also offers hedges against non-scarcity of spectrum, and government greed (Lehr 2004).

If it turns out that spectrum becomes relatively more abundant due to, say, advances in technology, license holders acting in concert would be able to charge customers excess fees based on the initial presumed scarcity that motivated a market in licenses. There are anti-trust remedies for such behavior, but they take a long time to catch up with the market. The availability of unlicensed allocations provides an immediate outlet for entrepreneurs that is unencumbered by licensee control.

On the other hand, if spectrum becomes very scarce, say because usage scenarios and demand outstrip spectrum utilization technologies, then unlicensed will become congested and spectrum-title will be an outlet for entrepreneurs who initially built their business in unlicensed bands.

There is no agreed upon way to determine the degree of scarcity of the spectrum resource even at a single moment in time, let alone in a dynamic situation where technology and usage are racing each other. Hence, one cannot make an *a priori* determination of which scenario is the most suitable. As long as both regulatory models exist, each provides a market test, and a check on potential inefficiencies, for the other.[52]

Modern regulatory theory tends to presume that the least regulated option — such as exclusive and flexible licensing to a single enterprise — is the optimal starting point, because it offers the most economic options/opportunities. However, it would be difficult to recover unlicensed allocations once one has devoted all spectrum to flexible licenses. Faulhaber and Farber (2002) might counter that a band manager (e.g., a device or wireless chip manufacturer) could choose to institute the equivalent of unlicensed in a market system, or the government might buy spectrum back from licensees and re-allocate it to unlicensed. However, there has been no interest in a band manager model, due to the difficulty of excluding non-payers; and the notion of government buying spectrum is based on the debatable premise that the public doesn’t “own” the airwaves already, as the Communications Act literally states.

Second, there isn’t much to choose between the degree of regulation of spectrum-title and unlicensed. It may be somewhat counter-intuitive, since it’s clear that the government has to do quite a lot of work in defining unlicensed usage rules. However, defining the goods to be traded is so tricky for spectrum, particularly this vacant channel spectrum, that a lot of government activity will be required to make the market work. Because of the desire to protect television reception in neighboring channels and markets from interference,the FCC’s need to define power limits and certify compliant equipment may be only slightly less meddlesome.

As for greed, there’s a moral hazard for government in extracting scarcity rents in spectrum. In order to get the highest possible price, government may be tempted to auction off as little spectrum as possible, perpetuating the current inefficient “command and control” allocation regime. Unlicensed provides a hedge against government delay in auctioning spectrum; if the price of spectrum licenses rises too high due to artificial scarcity, entrepreneurs willing to trade off the cost of spectrum against the cost of dealing with interference from other users will move to unlicensed.

5.2 There are risks and problems with spectrum-title allocations

An unlicensed allocation would ensure diversity in the regulatory portfolio at a time when there is great uncertainty about the relative merits of spectrum-title vs. unlicensed.

Scholars like David Farber, Gerald Faulhaber, Thomas Hazlett, Evan Kwerel, and John Williams have argued that the best way to optimize the value of a scarce spectrum resource is through markets in transferable, flexible, perpetual spectrum licenses.[53]

The case for spectrum-title allocation of the TV bands goes back at least a decade. In May 1996, Senator Larry Pressler (R-SD) introduced a measure drafted by Prof. Hazlett to allocate all spectrum in the 402 MHz TV band to overlay licenses, to be assigned via auction. High bidders would have won the right to use one of five nation-wide 80.4 MHz bands to provide any service that would not interfere with existing broadcasters.[54]

The arguments made by spectrum-title proponents have been questioned by Yochai Benkler, William Lehr, J.H. Snider, and Kevin Werbach among others.[55] I will analyze the following assumptions underlying the case for spectrum-title licensed allocations:

1. Spectrum is scarce
2. Transaction and coordination costs are low
3. A market in spectrum licenses is efficient

Even if the argument for market allocation of scarce spectrum was valid, it is worth recalling that not every scarce good is allocated by tradable property rights. The trading of licenses is not used to allocate access to public resources like roads, parks, navigable waterways, and art collections, nor even to private but licensed professional services.[56]

5.2.1 Spectrum may not be scarce enough to justify the overheads of creating a market to allocate it

It is difficult to say whether wireless spectrum is scarce or not. Some bands are relatively intensively used, but studies measuring actual use have shown that most are deserted (McHenry 2005). The prices of spectrum at auction seem to be declining, which argues against a critical scarcity.[57] It's probably just too early to tell. The transition out of a "command and control" spectrum regime has only just begun, and the market of flexible-use licensed spectrum is still in its infancy.

Spectrum scarcity is also a moving target. The carrying capacity of a given band is a function of the technology that is used by transmitters and receivers. As modulation schemes and end-device processing capacity have improved, the amount of information that can be carried in a given channel has increased.[58] One can also increase the carrying capacity by dividing up a region served by one frequency (e.g., by directional antennas) or by replacing a few high-power transceivers with many low-power ones. The spectral efficiency of wireless systems has risen steadily, from 0.1 to more than 3 Mbits/second of throughput per Hertz of bandwidth per square kilometer.[59]

5.2.2 Transaction and coordination costs cannot be ignored

Some arguments for a market in spectrum licenses are based on the Coase Theorem.[60] Coase showed that, under certain conditions, the initial distribution of entitlements (e.g., property rights or liability rules) has no effect on the ultimate allocation of resources. If the players are left to bargain among themselves, an efficient outcome will be arrived at regardless of how initial property rights are assigned.

The result holds provided that (1) the costs of transactions is zero; and (2) the parties to a dispute are able to negotiate, to strike bargains, and to be confident that their bargains are enforceable.

Transaction costs in this case include finding suitable spectrum, negotiating for access, and policing and enforcement with respect to interference. These costs cannot be neglected, particularly in socially important applications with low user density such as rural or disadvantaged urban areas. Finding providers will be difficult for people with poor access to information; negotiation will be expensive since it is an occasional activity; and enforcement will be tricky since there are few players in a large area. If spectrum is spread over many owners, simply establishing who owns what will be costly. Obtaining permission to operate, once owners are known, may also be expensive. If there is low or intermittent interest from buyers, providers are unlikely to set up a streamlined process for obtaining sub-licenses. For example, it is quite possible that a large telecommunications firm will be unwilling to engage in micro-transactions for spectrum access with start-up WISPs, individuals or neighborhood nonprofits. The transaction costs may well swamp the benefits, at least for the license-holder.

The application of the Coase Theorem should also be tempered by non-economic considerations. Assuming all the assumptions hold, the outcome after negotiations will be efficient only in technical economic terms. However, an "efficient" allocation may not meet other social criteria. For example, if the global efficiency of the system is achieved by a transfer of $100 from A to B, economics doesn't care whether A is a pauper and B is a plutocrat, or vice versa; society at large may have a different opinion.

5.2.3 It is difficult to define property rights in the white spaces

Neoclassical economic theory predicts that once a property right is clearly defined, it will in time be put to its most valued use through negotiation in a market. Defining bundles of spectrum rights has proved to be complex, though, both in terms of leasing policies[61] and arguments about the statutory basis for sub-leasing.[62] Property rights are likely to be ambiguous since they will depend on notions like avoiding harmful interference — and interference is a question of statistical models of propagation. [63]

It will be particularly tricky to define rights in the white spaces, since operating parameters will be different everywhere. TV band white space has been called "spectrum Swiss cheese," since the licensed incumbents occupy a different pattern of channels in each of the 210 television markets. A channel that is available in Baltimore, for example, may not be useable in nearby Washington, D.C. The Pressler/Hazlett proposal of five nationwide overlay channels would avoid this difficulty, since operation in a given band is not limited geographically. However, the most likely auction will divide assignments geographically in order to meet the needs of rural political interests and limit market concentration. Interference-avoiding frequencies will vary from place to place, particularly in the borderlands between broadcast towers. Thus, someone seeking to license spectrum access will need to petition a variety of providers.

Markets will probably be inefficient since spectrum scarcity will vary so much depending on locale that it will be difficult to support a liquid market to trade in the appropriate rights.

All in all, many of the assumptions on which theoretical arguments for market allocations of flexible licenses are based are questionable. This is not decisive, of course; the fact that a market is not perfect doesn't mean that it doesn't work. However, there is enough uncertainty to justify caution about a market allocation of all spectrum through licenses, and to warrant diversity in regulatory models.

5.3 Doing nothing isn't an option

It is likely that if nothing is done to allocate vacant channels, broadcast-related uses of the white spaces will continue to grow: more translators, more external broadcasts, more special licenses for equipment supplied by broadcast vendors, increased power for existing stations, and exemptions for broadcasters' data applications using more spectrum than they already have.

The broadcast industry has obtained licenses to operate in specific channels in the UHF bands and for the limited purpose of serving local communities; it has not been assigned the entire swath of spectrum for its perpetual, gratis use. The New America Foundation estimates that since 1997 broadcasters have acquired $6 billion worth of TV band white space by expanding outside their original grade B contour. After the DTV transition, when more bandwidth becomes available, more requests for expanded contours are expected.[64] If the broadcast industry would like to use spectrum to establish a return channel from their customers, or for any other ancillary use, then it should seek access to the spectrum on an equal footing with everyone else.

It actually would be in the broadcast industry's own interest for the white spaces to be affirmatively designated for unlicensed use. Technology is advancing so rapidly that one already can buy a software-defined FM radio based on Open Source for $550.[65] If demand for operation in these bands is not met through legitimate equipment that protects broadcasts from interference in a well-regulated way, less benign do-it-yourself solutions will appear. Broadcasters would surely not want to emulate the entertainment industry's experience of playing catch-up with home-grown peer-to-peer file sharing software.

5.4 The best overall solution is a mix of spectrum-title and unlicensed

The Spectrum Policy Task Force (FCC 2002) concluded that current "command and control" spectrum policies were in need of reform and recommended a mix of spectrum rights models that includes an expansion of both flexible use spectrum-title and unlicensed. This is true for spectrum allocation overall, and for the TV bands specifically. Part of the spectrum freed up in the DTV transition will be auctioned; the rest should be made available for unlicensed use.

5.4.1 Spectrum-title and unlicensed compared

Spectrum-title and unlicensed allocations have complementary strengths and weaknesses:

Spectrum-title	Unlicensed
Licensee controls behavior of all transmitters in the band	Control is decentralized, and users have to co-exist with transmitters they do not control
Statutory protections from interference from other users	Unlicensed users have to accept interference from other users, and (in the case of a secondary use) may not interfere with primary users
Spectrum use coordinated by the licensee	Spectrum use coordinated through regulation and *de facto* standards
Relatively high transaction costs for 3rd party access to spectrum	Relatively low transaction costs in obtaining spectrum access
High cost of entry for service providers and equipment manufacturers	Low cost of entry for service providers and equipment manufacturers
Market in spectrum licenses and devices	Market in certified devices

To date, capital expenditure in licensed bands has focused on substantial, centralized network infrastructure investments by the licensee. Bands which support unlicensed use have necessarily seen a more decentralized investment model where equipment is purchased by end users.

Both regulatory models have transaction and administrative costs (Benkler 2002):

	Property-based spectrum-title allocation	Unlicensed allocation
Transaction costs	Need to negotiate permission to transmit in a specified band	Overhead in equipment cost and spectrum usage in coordinating communications
Administrative costs	Definition and adjudication of property rights	Setting standards for devices and enforcing equipment compliance

Administrative costs in the spectrum-title model are borne by government: the costs of defining property rights, running auctions by the regulator,[66] and resolving disputes regarding interference. The transaction cost of spectrum coordination is borne by licensees and sub-licensees, since the owner of a chunk of spectrum manages it.

The costs for unlicensed arise both in the administrative process of defining and enforcing technical standards to manage congestion and harmful interference, and in the "cost" of bandwidth devoted to negotiating access among receivers rather than to transferring data. The transaction costs are embedded in the cost of equipment, and reduced efficiency of communications. Administrative costs are borne by government in the regulatory process, and by industry in the standard-setting process. There is an opportunity cost if the spectrum use entailed by regulation is not the most efficient one. If there is little spectrum scarcity, and thus limited congestion, transaction costs diminish; administrative costs remain, but may be reduced since standard-setting and compliance may be less onerous.

Spectrum-title users will probably suffer higher technical and marketing overhead costs in the white spaces than unlicensed ones. In both cases, technical rules will have to be developed to determine how white space users will operate without interfering with broadcast users. However, license owners and regulators will additionally have to figure out how to make a market in spectrum rights.

5.4.2 Economics can't pick between flexible-use spectrum-title and unlicensed

The spectrum-title and unlicensed models are sufficiently different that economic analysis is of little help in picking between them. Licensed spectrum has few operators and well-defined prices; unlicensed has huge numbers of operators and no market prices for spectrum services.

The well-defined service prices in the spectrum-title model enable economists to assess its social value by estimating consumer surplus.[67] Hazlett (2005) estimates the annual consumer surplus for the Commercial Mobile Radio Services (CMRS) cellular bands in 2003 in excess of $81 billion, leading to a capitalized social value of CMRS bandwidth in excess of $800 billion. This is an annual value of at least $450 million/MHz.[68]

The work to calculate a consumer surplus for unlicensed uses has not yet been done. One could derive proxy prices for unlicensed spectrum using hedonic regression.[69] Until such work is done for unlicensed, an apples-to-apples economic comparison can't be made.[70]

A rough-and-ready calculation suggests that the social value of unlicensed spectrum is significant. There are about 47 million Americans working for firms with 500 or more employees. Let's assume that 4 million workers save one hour in eight as a result of this technology.[71] Based on an annual wage of $35,000, that's a time value of about $4,000/year each, or $16 billion/year in all. (Recall that the global market in Wi-Fi equipment, and thus its cost, was $2.5 billion/year in 2005.) If we take the value to consumers as being of a similar magnitude, the annual value of Wi-Fi uses of unlicensed spectrum is of the order of $30 billion, or $360 million/MHz.[72] This number, which excludes the value of other uses such as Bluetooth and cordless phones, places a lower bound on the social value of the unlicensed bands which is in the same ballpark as Hazlett's figures.

A choice between flexible-use spectrum-title and unlicensed allocation is a choice between regulatory models. Any regime choice will bias outcomes. In a spectrum-title regime, the pace of innovation and development will be dictated by license holders rather than end-users or equipment suppliers. In an unlicensed regime, on the other hand, end-users and device manufacturers drive innovation. Neither model is intrinsically better than the other; in the absence of a clear choice, diversity in regulatory models is the best bet.

5.4.3 A combination of spectrum-title and unlicensed is better than either on its own

I have so far argued that both spectrum-title and unlicensed have advantages, and that the economic data does not exist to choose between them. I believe that any choice would be inadvisable. The two regulatory models complement each other, and a combination would be more valuable than each individually.

Markets facilitate the interaction of diverse groups, and such diversity is essential to efficient operation. Markets are remarkably efficient at solving all sorts of problems, provided diversity, interaction and incentives are in place.[73] It is important not only to have diversity of participants within a given market structure, but also to have different kinds of markets. Anti-trust legislation and rules on auction participation seek to avoid unhealthy concentration and to increase diversity of operators in markets for spectrum licenses. However, licenses are just one kind of spectrum-related market; an unlicensed allocation creates a market in device technologies in which manufacturers compete with each other to provide affordable innovation directly to end-users.

In many spheres, society maintains a mix of public and private goods. Parks and private property are the paradigmatic example. A recent survey for the National Recreation and Park Association found that open spaces have substantial positive impacts on surrounding property values.[74] Between one and three percent of the value of properties within 1,500 feet of a park could be attributed to park proximity. The closer, the better: in Dallas, homes facing one of 14 parks were found to be worth 22 percent more than homes more than one-half mile from such an amenity. Conversely — but more difficult to prove, since parks don't trade on the open market — the proximity of housing increases the value of a park; without people to use a park, its value declines.

I believe a combination of spectrum-title and unlicensed spectrum allocations will result in a greater social benefit than each individually, in the same way that a public park enhances the market value of surrounding properties, and the use by surrounding residents increases the utility of the park. A combined allocation nurtures new deployments. Unlicensed bands allow entrepreneurs to enter a market without incurring the cash drain of obtaining a license. If a business is so successful that it attracts competitors that increase interference, it would have the option of relocating to a nearby spectrum-title band where it can buy the right to avoid interference. The spectrum-title allocation gains value because unlicensed acts as a demand generator.

Conversely, because unlicensed bands are open to all, licensed operators can also enhance their services, or increase their spectrum capacity, by routing certain traffic over unlicensed frequencies. For example, cellular operators are combining unlicensed hotspot data service with wide-area service in spectrum-title bands.[75] When customers access a cellular company's data network from a hotspot they do not burden the spectrum-title band, enabling the network to support more customers without buying more spectrum. Devices that combine spectrum-title and Wi-Fi operation are emerging, and will soon be common.[76] Licensees have also benefited from other unlicensed technologies like Bluetooth headsets and other mobile phone add-ons.

6 Conclusion

There are vacant channels between broadcast television stations. This spectrum can be used by unlicensed devices without harming television viewing.

An unlicensed allocation of these bands would be the most productive way to use this spectrum because unlicensed spectrum:

- is a proven way to generate technical and commercial innovation;
- promotes healthy diversity in markets and regulatory models; and
- complements the spectrum-title allocation in the nearby 700 MHz band.

A broad cross-section of society would benefit, including rural and inner-city residents seeking affordable Internet access, entrepreneurs starting up digital communication businesses, cities and companies seeking to foster growth and productivity, and citizens who want to create community networks.

The spectrum-title and unlicensed regulatory models complement each other, and a combination would be more valuable than each individually. Licenses are just one kind of spectrum-related market; an unlicensed allocation creates a market in device technologies in which manufacturers compete with each other to provide affordable innovation directly to end-users.

Congress should press the FCC to act on its dormant Notice of Proposed Rulemaking by allowing unlicensed operation in this spectrum.

Endnotes

[1] *See* 47 U.S.C. Sections 301, 304.
[2] FCC 2002.
[3] "Exclusively-Assigned, Flexible-Use Spectrum rights," Hazlett 2005.
[4] *See* Marcus *et al.* 2006, at page 3, for a description of the FCC's equipment testing and certification process required for all devices authorized to operate on unlicensed frequencies.
[5] *See* J.H. Snider, "Myth vs. Fact: The Rhetoric and Reality of Progress in Allocating More Spectrum for Unlicensed Use," New America Foundation, February 2006. Available at: http://www.newamerica.net/Download_Docs/pdfs/Doc_File_2897_1.pdf.
[6] FCC U-NII (Unlicensed National Information Infrastructure) *Report and Order*, ET 03-122, 18 FCC Rcd 24484 (2003).
[7] In 2001, FCC set aside a continuous block of 7 gigahertz (GHz) of spectrum between 57 and 64 GHz for wireless communications; 70/80 GHz Band WT Docket No. 02-146.
[8] *See* e.g., "Information Paper On The Reallocation Of The 698-806 MHz Frequency Band In The United States," International Telecommunication Union, Document 6E/XXX-E, August 2005 (http://www.ieee802.org/18/Meeting_documents/2005_Sept/18-05-0034-00-0000-Information_Paper_on_the_use_of_the_698-806_MHz%20Frequency_Band_in_United_States.doc), "700MHz spectrum worth $28 billion," United Press International, May 27, 2006 (http://washingtontimes.com/upi-breaking/20050525-121125-6725r.htm).
[9] Snider, *supra* note 5 and Snider, 2005, figure 5 and footnote 31. The ratio remains roughly the same (6.8) if one weights spectrum according to frequency, as done by the British regulator, Ofcom. If one adds the 300MHz currently available to unlicensed in the 5 GHz U-NII band, the weighted ratio is 3.6.
[10] Snider 2005, figure 7 and footnote 46.
[11] FCC 2004.
[12] FCC, *Notice of Inquiry* in ET Docket No. 02-380, 17 FCC Rcd 25632 (2002).
[13] "dBi" is the ratio, measured in decibels, of the effective gain of an antenna compared to an isotropic antenna. The greater the dBi value, the higher the gain and, as such, the more acute the angle of coverage. *See* e.g., http://www.wirelesstelcorp.com/glossary_of_terms.htm.
[14] McHenry 2005.
[15] "Measuring the TV 'White Space' Available for Unlicensed Wireless Broadband," Free Press and the New America Foundation, January 5, 2006. Available at: http://www.newamerica.net/index.cfm?pg=article&DocID=2713 (live on 5/23/2006).
[16] MSTV's David Donovan argued, at a debate hosted by the New America Foundation on Capitol Hill in November 2005, that there is no white space in the Philadelphia and New York City markets. Donovan contended that if a viewer using a high-gain antenna can receive signals from neighboring media markets (e.g., redundant network affiliate stations), then that channel should not be considered vacant. This ignores two salient points. First, a broadcaster's license rights are explicitly limited to providing services within the Grade B contour of the local market where the signal originates, and a viewer cannot have any reasonable expectation of watching channels from distant cities. Second, such a viewer will be receiving signals from redundant network affiliate stations, and the increase in consumer welfare from protecting this activity is negligible.
[17] "Media Bureau Staff Report Concerning Over-The-Air Broadcast Television Viewers," Federal Communications Commission, MB Docket No. 04-210, February 28, 2005, para II. A. 7. Available at: http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-257073A1.pdf.
[18] *See* e.g., FCC 2004, para 11, 12.
[19] 30-45 dB, Mike Marcus, personal communication, June 29, 2006.
[20] Unlike a DTV set, smart radio devices do not need to receive a DTV signal strong enough to display a video transmission; they only need to detect that there is a transmission on the channel. This is made even easier by the fact that TV stations broadcast continuously at high power.
[21] Concerns raised over the desensitization of DTV receivers (*See* e.g., http://www.mstv.org/static.html) can be addressed by adjusting the FCC's draft rules to regulate both average and peak power output by unlicensed devices. *See* Marcus, *et al.* 2006.
[22] Kennard, William E., FCC Chairman, letter to U.S. Rep. Rick Boucher, November 5, 1998. Available at: http://www.fcc.gov/Speeches/Kennard/Statements/stwek888.html.

[23] *See* Marcus, *et al*. 2006, page 4, for further discussion.
[24] For example, Qualcomm announced advanced firmware over-the-air updates on BREW®-enabled handsets in October 2004 (http://www.qualcomm.com/press/releases/2004/041025_foto_capabilities.html). In February 2005, the company announced that that Qualcomm and Bitfone would provide software update capabilities for Qualcomm's MSM6250™ chipset using Bitfone's mProve™ technology (http://www.qualcomm.com/press/releases/2005/050214_qct_bitfone.html).
[25] Anecdotal reports of comments to Congressional staff, June 2006.
[26] Coase, R. H., "The Federal Communications Commission," *Journal of Law and Economics*, Vol. 2 (October 1959), pp. 1-40.
[27] While I use the term "Wi-Fi Plus", I recognize that the rules for this band will be technology-neutral. Any technology that complies with the eventual FCC rules should be encouraged, and not just those in the 802.11 family. Wi-Fi is a trademark of the Wi-Fi Alliance.
[28] Detecting military radar is a much harder technical problem than detecting and avoiding a TV broadcast. Unlicensed devices in the 5 GHz band have to detect radars on their first pulse; pulses appear intermittently as a radar sweeps across its field of operation.
[29] Kibria, Masud and Chris Knudsen, "Capital Expenditure Implications of Spectrum Assets in Semi-Rural Environments," Intel Corporation Report, 4 August 2005, cited in Snider 2005. *See also* Lehr 2004 at footnote 44.
[30] For comparison: omni-directional transmitter power is limited to 1 watt in the 2.4 GHz unlicensed band; some antenna gain is allowed, *see* http://www.qsl.net/kb9mwr/projects/wireless/pwr.html for details. The Wi-Fi cards in most computers emit 100-200 milliwatt.
[31] In addition to Wi-Fi, the primary unlicensed band, at 2.4 GHz, is shared by more than 300 million FCC-certified consumer devices, including cordless phones, baby monitors, microwave ovens and toys. *See* Carter, Kenneth R., Ahmed Lahjouji and Neal McNeil, "Unlicensed and Unshackled: A Joint OSP-OET White Paper on Unlicensed Devices and Their Regulatory Issues," Federal Communication Commission, OSP Working Paper #39, May 2003.
[32] From a maximum of 11 Mbps for 802.11b to 54 Mbps for 802.11g and 80.2.11a
[33] "Faster Wi-Fi Standard Moves Forward," *PCWorld*, January 19, 2006. Available at: http://www.pcworld.com/news/article/0,aid,124413,00.asp.
[34] Dell'Oro Group, cited in "Faster Gear to Drive Wi-Fi Market" *PCWorld* January 24, 2006. Available at: http://www.pcworld.com/news/article/0,aid,124478,00.asp.
[35] *The Economist* (2004): The basic 802.11 standard was published in 1997. 802.11b was ratified in December 1999, and 802.11a in January 2000. Apple introduced Wi-Fi as an option on its new iBook computers in July 1999.
[36] Dell'Oro Group Inc, reported in "Dell'Oro: faster gear to drive Wi-Fi market," *Infoworld*, January 24, 2006. Figures do not include Wi-Fi capabilities embedded in DSL and cable modems. Available at: http://www.infoworld.com/article/06/01/24/74752_HNdellorowifi_1.html?WIRELESS%20LANS%20-%20WLAN.
[37] http://www.nabaztag.com/.
[38] A mesh network has two or more paths to any node; nodes act as traffic relays for each other. Information can move between two nodes that are not directly connected by "hopping" across intermediate nodes. A mesh can be contrasted with the point-to-multipoint networks used in cellular systems, where all nodes communicate directly with one central node, usually on a tower.
[39] Data released by In-Stat and the Wi-Fi Alliance, http://www.wi-fi.org/news/pressrelease-112805-120millionchipsets/.
[40] In-Stat Report IN0501813NT, December 2005, summary at: http://www.instat.com/catalog/IN0501813NT.
[41] JiWire Wi-Fi HotStats™ as of May 22, 2006 listed 39.951 hotspots in the US, http://www.jiwire.com/search-hotspot-locations.htm. JiWire reports that the number of worldwide hotspots grew 87%, from 53,779 in 93 countries in January 2005, to 100,355 hotspots in 115 countries in January 2006. Available at: http://www.jiwire.com/press-100k-hotspots.htm.
[42] Dell'Oro Group, 2006, loc. cit.
[43] "Second anniversary Report," MuniWireless.com, July 2005. Available at: http://muniwireless.com/reports/docs/July2005report.pdf.

[44] The FCC estimates that there are between 4,000 and 8,000 WISPs. It reports that the Wireless Internet Service Providers Association (WISPA) estimates that there are currently 4,000 WISPs, and that Part-15.org estimates that the number is closer to 8,000 WISPs. *Connected on the Go: Broadband Goes Wireless*, February 2005, Report by the Wireless Broadband Access Task Force. Available at: http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-257247A1.pdf.
[45] http://grouper.ieee.org/groups/802/11/, http://en.wikipedia.org/wiki/802.11.
[46] *See* e.g., Hazlett 2005; for a counter-point, see Lehr 2004.
[47] *See* e.g., Chartier 2004.
[48] In a study for the British Regulator Ofcom in Feb 2003, the consultants MASS found widespread usage of Wi-Fi in the 2.4 GHz band, but observed no cases of congestion due to traffic density. Biggs, M, A Henley and T Clarkson, "Occupancy analysis of the 2.4 GHz ISM band," *IEE Proceedings – Communications*, October 2004, Volume 151, Issue 5, p. 481-488; summary at http://www.ofcom.org.uk/static/archive/ra/topics/research/rrac/2-mikebiggs.ppt.
[49] Chartier (2004) cites a policy at Carnegie-Mellon University where the system administrator "will seek out the user of a specific device if we find that it is actually causing interference and disrupting the campus network [and] restrict the use of all 2.4 GHz radio devices in university-owned buildings and all outdoor spaces." Enquiries to CMU in May 2006 indicated that the University currently doesn't monitor air-space, and has not had occasion to shut down any devices.
[50] Speed is proportional to the amount of spectrum bandwidth available, everything else being equal.
[51] Wi-Fi Net News http://wifinetnews.com/archives/006298.html.
[52] Lehr 2004.
[53] *See* e.g., Faulhaber and Farber 2002, Kwerel and Williams 2002, Hazlett 2005.
[54] Hazlett 2005, 142 CONG. REC. 10672, 10672-76 (1996); Tom Hazlett, in conversation, June 15, 2006.
[55] *See* e.g., Benkler 2002, Lehr 2004, Snider 2005, Werbach 2004.
[56] The supply and quality of professional services is often managed through licenses (e.g., in health care, law, and accounting) but these licenses are not tradable.
[57] Lemay-Yates 2003, "Evolution of Spectrum Valuation for Mobile Services in Other Countries," March 2003 finds declining price as more licenses issued in US and other countries. Available at: http://strategis.ic.gc.ca/epic/internet/insmt-gst.nsf/vwapj/microcellsch_c.pdf/$FILE/microcellsch_c.pdf.
[58] Throughput is limited ultimately by the Shannon-Hartley theorem. Turbo codes and LDPC codes are approaching the Shannon limit.
[59] *See* e.g., data from Arraycom available at: http://commerce.senate.gov/hearings/073101Chart.pdf.
[60] Coase, Ronald H. "The Problem of Social Cost," *Journal of Law & Economics* 3, p. 1 (1960). Available at: http://www.sfu.ca/~allen/CoaseJLE1960.pdf.
[61] FCC, *Report and Order*, WT Docket 00-230, Adopted May 15, 2003.
[62] *Ibid*., Dissenting statement of Commissioner Michael J. Copps.
[63] Hatfield and Weiser (2005): "[A]ny workable system of property rights will need to rely on (at least to some degree) the predictive models - i.e., statistical predictions as to how often interference is likely to occur - that generally govern how spectrum is used today. Notably, any such reliance begs the question of how such models will be integrated into an enforcement system and with the reality of whether interference is actually present."
[64] Snider 2006.
[65] The USRP is available from http://www.ettus.com/. It works with GNU Radio, a free software toolkit for learning about, building, and deploying software-defined radios. For a profile of the entrepreneurs, *see* Wired News, "GNU Radio Opens an Unseen World," June 5, 2006, http://www.wired.com/news/technology/1,70933-0.html.
[66] These costs are set off against the (hopefully larger) revenue gained through auctions.
[67] "Consumer surplus" is the net economic value from consumption or use of a good or service. It is the difference between the maximum that a person is willing to pay, and what he/she actually spends. *See* e.g., Preston McAfee's text "Introduction to Economic Analysis," http://www.introecon.com/. Neoclassical analysis can only get traction when there are prices; that's why virtually all the economists that study spectrum focus on licensed allocations where auctions and spectrum services provide price information.
[68] CMRS utilizes about 175 MHz of bandwidth in the 800 MHz, 900 MHz, and 1.9 GHz bands (Hazlett 2005).

[69] Hedonic pricing: a procedure in which an item is decomposed into constituent characteristics, and values are estimated for each characteristic using statistical methods. This approach has been used in real estate and environmental studies, e.g., in deriving the value of clean air from house prices in different cities, but its results are usually hotly debated. *See* e.g., http://core.ecu.edu/econ/whiteheadj/5000/ch10b/hpm.htm, and http://www.sscnet.ucla.edu/ssc/labs/cameron/nrs98/hedoninv.htm.
[70] Hazlett's comparison of licensed and unlicensed by comparing industry metrics is debatable (Hazlett 2005, Table 2). He compares industries at very different stages of maturity; service revenue is not a proxy for consumer surplus; and investment in network equipment is an expense, not a proxy for social value.
[71] The 2003 "Wireless LAN Benefits Study," conducted by NOP World Technology for Cisco, reports that the value of time saved through the use of wireless local area networks is almost $14,000 per employee per year in mid-size and large organizations. Time savings of almost 90 minutes per employee per workday were reported Available at: http://newsroom.cisco.com/dlls/prod_111203.html.
[72] The 2.4 GHz band is 84 MHz wide. In 2003 there was little Wi-Fi operation in other bands.
[73] *See* e.g., James Surowiecki 2004, "The Wisdom of Crowds: Why the Many Are Smarter Than the Few and How Collective Wisdom Shapes Business, Economies, Societies and Nations."
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[75] T-Mobile's Total Internet plans offer unlimited GPRS, EDGE, and HotSpot Internet connectivity in a single bundle.
[76] *See* e.g., CNET News.com, "New chipsets to support cellular, Wi-Fi," Feb 10, 2006, http://news.zdnet.com/2110-1035_22-6037802.html. The Unlicensed Mobile Access (UMA) standards process is developing technology to provide access to GSM and GPRS mobile services over unlicensed spectrum technologies, *see* http://www.umatechnology.org/.

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