

Spectrum Buyouts

A Mechanism to Open Spectrum

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Abstract

The “shortage” of radio spectrum is usually attributed to the *scarcity* of spectrum, but it is due to the *inefficiency* of radio technologies and spectrum management. Regulatory reforms are being proposed to assign exclusive rights to spectrum, but such reforms would be harmful because the spectrum is not a property but a *protocol* by which information is carried. New packet radio technologies enable efficient communications by sharing a wide band without licenses. However, it is difficult to relocate spectrum by persuading incumbents to return their spectrum. Therefore we propose *reverse auctions* by which the government buys back spectrum from incumbents as an optional mechanism for spectrum relocation. The equilibrium price of this reverse auction will be much less expensive than that of ordinary spectrum auctions, because the former price will be close to the value of the band that is used *least efficiently* if the auction is competitive.

1. Introduction

The use of radio waves for communications dates back to the beginning of the last century. The Radio Act of the United States was enacted in 1912, after the tragedy of the Titanic, when airwaves failed to communicate SOS signals to ships nearby. Initially radio communications were limited to military and marine use, but the Radio Act was revised in 1927 to allow private companies to use radio waves as a result of heightened calls for the release for business use. Although industrial sectors sought full freedom, the federal government (particularly the Navy) opposed the release of bandwidth to civilian sectors. As a compromise between these interests, the current licensing system for electromagnetic spectrum was established under the Federal Radio Commission, predecessor of the Federal Communications Commission (FCC).

As the wireless technologies available at the time did not enable general users to hold two-way communications, radio stations broadcast signals, and the receiver, the *radio*, did nothing but convert airwaves into sound. Since the signals were broadcast at high power, licenses were awarded for entire regions. The FCC gives a broadcasting station a license for a specific frequency, power, area, and usage. This licensing system was extended to communications and has not changed in the past 75 years. This “socialistic” system worked fairly well when there were many vacancies in the spectrum, but growing demand for wireless communications, led by cellular telephone usage, has led to a serious “spectrum shortage”.

This “shortage” does not represent a deficiency of natural resources, but is instead the result of inefficient radio administration. In a market economy, government licensing is an exceptional mechanism. It is usually justified by the claim that spectrum is a “scarce resource,” but

economists have long argued, “the number of Rembrandts existing at a given time is limited; yet such paintings are commonly disposed of by auction.”¹ In accordance with such recommendations, spectrum auctions for cellular telephones (PCS) began in the United States in 1994. At first, FCC officials were skeptical because these were the first large-scale auctions--conducted for 99 licenses simultaneously across the United States--managed by complicated mechanisms designed by economists and implemented by nation-wide computer networks. As it turned out, the PCS auctions were a dramatic success. The U.S. government earned more than US\$20 billion in six PCS auctions through 1996, and the U.S. cellular-phone industry developed rapidly through the entrance of new operators and enhanced competition².

European countries, which had been leading the world in mobile communications, embraced auctions to promote competition and regional integration through the entry of international operators to many countries for third-generation (3-G) mobile telephones. When 3-G auctions were held in 2000, at the peak of the “wireless bubble,” license fees skyrocketed far beyond their true value, with fees amounting to more than 100 billion euro for all of Europe. After the bubble collapsed, the expected market for “mobile multimedia” proved almost nonexistent. Mobile operators in Europe fell into a business crisis due to huge liabilities. Deployment of 3-G services was delayed or even aborted due to technical problems and financial difficulties.

Economists argued that it was not the auction but the operators' extremely speculative behavior that was to blame. Through auctions, at least theoretically, spectrum can be allocated efficiently if operators behave rationally. This would serve better than traditional licensing by paper examinations, known as “beauty contests,” in promoting competition and in realizing the full value of spectrum³, yet it is undeniable that auctions induced the large-scale “winner’s curse.” An even more important problem is that spectrum auctions depend on the legacy systems of

telephone switching. This system is inefficient and expensive to operate in the Internet age, as has been evidenced by the tragedy of 3G.

A final problem is that very little spectrum is available for auction. Relocation of spectrum is conducted by governments after the removal of incumbent operators by negotiation, which takes a long time. Since spectrum is allotted by licenses for specific use, even if a band is idle, no one is allowed to use it and incumbents cannot convert it to a different use. As a result, it is estimated that, integrating space and time, more than 90 percent of the spectrum under 3 GHz in the metropolitan area of Tokyo is unused. Rural areas must be even less efficient. Obviously, spectrum auctions cannot cure the problem.

While 3G is stumbling, Wireless Local Area Networks (WLANs) have been growing rapidly, as they can realize much higher speeds than cellular telephones by sharing a wide band. This “second coming of the Internet” will change wireless communications as fundamentally as the wired Internet changed the telephone network. WLAN and other new digital wireless technologies are demanding a wholesale revision of radio administration to cope with these innovations. It is much more efficient to open the spectrum without licensing requirements than it is to divide it into small pieces of private property. Clearly, the regulatory framework inherited from an age when there were no transistors, radars, or televisions should be overhauled.

This article is organized as follows. In section 2, we will examine the primary assumption of spectrum auctions, namely, that spectrum is a scarce resource. It can be overcome by new wireless technologies such as packet radio, spread spectrum, and cognitive radio. In section 3, we will show that spectrum is not “commons” but “public goods” that can be used without congestion if terminals are intelligent and that it is harmful to “privatize” spectrum. In section 4, a mechanism named spectrum buyouts that encourages transition to a new regime of radio

administration system is proposed. According to this proposal, the government would take back spectrum from incumbents by reverse auctions and open it without a license. In the concluding section, we argue that this new regulatory framework will realize more efficient communication founded on facility-based competition between wired and wireless communications.

2. Packet Radio Technologies

Is Spectrum a Scarce Resource?

The auction was proposed as a mechanism for allocating spectrum efficiently, but it was based on the old assumption that the spectrum is a scarce resource that the government has the right to allocate. Almost ten years ago, Paul Baran, the inventor of packet radio, and George Gilder, a telecom guru, argued against PCS auctions, saying that it would make the implementation of packet radio technologies more difficult.

The FCC is fostering a real estate paradigm for the spectrum. You buy or lease spectrum as you would a spread of land. Once you have your license, you can use it any way you want as long as you don't unduly disturb the neighbors. You rent a stretch of beach and build a wall. [The packet radio] system, by contrast, suggests a model not of a beach but of an ocean. You can no more lease electromagnetic waves than you can lease ocean waves⁴.

Eli Noam also questions "Could the state sell off the right to the color red? To the frequency high A-flat?"⁵ He cited the licensing of spectrum as a violation of freedom of the press. To understand this problem, it is necessary to distinguish *frequency* from *spectrum*. Frequency is not a resource but a *parameter* used to modulate original data (baseband) into radio waves, so it cannot be

scarce any more than amplitude and phase⁶. In radio communications, transmitters modulate basebands into airwaves by mixing them with carriers of a specific frequency and sending the wave in radial form. Receivers identify radio signals by tuning in to the desired frequency and filtering out other frequencies. Let the radio amplitude be A , the frequency q , the phase p , and the time t . Then, carrier c can be expressed by

$$c(t) = A \cos (qt+p).$$

The amplitude modulation (AM) system modulates basebands by A , and the frequency modulation (FM) system modulates them by the change in p . When basebands are modulated into radio waves, they are distinguished by the frequencies of their carriers. Sending multiple signals on the same carrier causes interference. Therefore interference is not a problem of scarcity but rather a result of *confusion* by receivers that cannot distinguish signals from noise. So a frequency can be used by multiple users if their receivers can identify signals.

On the other hand, spectrum has limited capacity. According to Shannon's Channel Capacity Formula, the channel capacity C (bits per second) is limited by the bandwidth, B (Hertz):

$$C = B \log_2 (1+S/N),$$

where S is the power of the signal (in watts), and N is the noise level (W/Hz). In analog radio, as it is impossible to distinguish signals of the same frequency, spectrum should be divided into small portions to avoid interference. And, since N is given physically, the only way to do this is to magnify S to discern signals from noise. Thus radio signals are sent in narrow bands and at high power to large areas. If B is divided into small portions of equal size, b_1, b_2, \dots, b_n and allocated to each licensee, each licensee can get at most C/n of capacity. The inefficiency of this *high power and narrow band* radio system did not matter when radio equipment was very expensive and a small part of the spectrum was utilized, but it is posing serious problems today.

Cellular phones depend on the circuit switching in which each user occupies a band exclusively even if no signals are transmitted. A digital wireless technology called *packet radio* extends B by sending different packets in a band. Packet switching was invented as a radio transmission system by Paul Baran in 1964, but it had not been deployed until TCP/IP (Transmission Protocol/Internet Protocol) was adopted in ARPANET, the predecessor of the Internet, in the 1970s. As packet switching encapsulates data into many packets that can be mixed into one line, many users can send their data in a single line. This is much cheaper than the circuit switching of telephone systems, in which every user occupies one line during communication.

However, we cannot exclude undesired signals by physical lines in wireless communications. So the traditional wireless technologies of mobile telephones were based on the frequency division of spectrum. Packet radio, in contrast, avoid the interference by identifying individual packets even if multiple signals are carried in the same frequency. Spectrum is used efficiently by *statistical multiplexing*, which levels traffic in a wide band. Since average traffic usually represents a very small portion (less than 10 per cent) of the maximum capacity, if 100 users share a bandwidth of 20 MHz, more than 2 MHz will be available for each user on average. This is obviously more efficient than allotting 200 kHz across 100 users.

If B is large, it is not necessary to magnify S to increase C . Lowering power makes it possible to multiply spectrum by establishing many stations. This *low power and wide band* system makes digital radio more efficient than traditional broadcasting systems. The problem is thus not the *scarcity* but the *efficiency* of spectrum usage. Therefore, bandwidth can be better shared by many WLAN terminals. If a wide band can be utilized by many users identifying signals packet by packet, this will be much more efficient than dividing spectrum into narrow bands and selling them to individual users.

A packet radio technology called *spread spectrum* has been widely adopted to send various packets in a band while avoiding interference. In the direct-sequence spread spectrum (DSSS) adopted in WLAN, transmitters multiply original signals (baseband) by *pseudo-noise* (encryption key) and spread the resulting signals into thin waves over a wide band using weak power (Figure 1). Receivers decode the airwaves by inverse spreading, in which the signals are multiplied by the inverse pseudo-noise. By multiplying and dividing the baseband by the same number, this process recovers the desired data but scatters the noise thinly to allow its elimination by filters⁷.

Thus it is not necessary to have a separate frequency for each station to prevent interference. A number of users can use full bandwidth by multiplexing and identifying individual packets by their spread codes. Spread-spectrum technology was invented during World War II to prevent interception and electromagnetic jamming of military communications. It was later adopted for communications in the unlicensed band (2.4 - 2.5 GHz) to prevent interference from other devices such as microwave ovens. This band is called the ISM (Industrial, Scientific, and Medical) band, because it was originally released for unlicensed use by hospitals, factories, and so on, rather than for communication purposes.

WLAN technology, standardized in the 802.11 Committee of the Institute of Electrical and Electronics Engineers (IEEE), initially attracted little attention because its speed was only 2 Mbps. But after the enhanced mode IEEE 802.11b (Wi-Fi) was standardized in 1999, WLAN exploded; within a few years the number of users worldwide grew to more than 30 million (2002 figure). This is because 802.11b realized up to 11 Mbps (3-4 Mbps on average) by sharing the wide ISM band (22 MHz per channel)⁸. In contrast, the speed of data communications in current 2-G mobile telephones is around 10 kbps due to bandwidth limitations. For example, the PDC adopted in Japan allocates only 25 kHz (12.5 KHz in “half-rate” mode) per user.

(Figure 1 here)

Multiplexing by Space, Time, and Power

The method of multiplexing airwaves for many users is not limited to frequency. Shannon's Formula represents the limit of capacity in a given place, but it can be extended by multiplying stations because different users can use the same band repeatedly in separate places. This is the cellular technology by which mobile telephones enhanced bandwidth over traditional usage. The WLAN band is separated into a number of channels, which are allocated to each low-power station. As shown in Figure 2, channel A can be used repeatedly by dividing an area into many *microcells* in which each user can utilize full capacity without interference from other terminals. If the band is wide enough to allow division into many channels, theoretically, the capacity can be multiplied infinitely by dividing an area into an infinite number of cells⁹.

Of course, the overhead cost of connection between base stations will limit the number of cells in reality. But if they can be connected by wireless networks, this cost could be reduced. For WLAN terminals to be used as base stations in *ad hoc* mode, completely distributed multi-hop networks called *wireless mesh*, which link terminals to each other directly, can be built by WLAN terminals. If the price of WLAN chips falls to several dollars – as is likely in a few years – they will be incorporated into a wide range of devices that can communicate with each other.

(Figure 2 here)

In this regard, WLAN is even more revolutionary than wired Internet. TCP/IP is characterized by an architecture referred to as End-to-End (E2E), which means that the communication is controlled only by senders and receivers. In the wired Internet, however, routing and addressing are mostly performed by Internet Service Providers (ISP) because networks are built on the telephone-type topology. WLAN has deconstructed the centralized architecture and enabled completely decentralized E2E structures. Such *ad hoc networks* have been built throughout the world by volunteer organizations.

Public networks can be built by linking local wireless networks called *hot spots* in restaurants, hotels, airports, and so on. But the quality of the 2.4-GHz band is unsatisfactory. Industrial dryers, medical equipment, and different types of communication terminals such as Bluetooth interfere with WLAN. And the bandwidth (less than 100 MHz for 4 channels simultaneously) would not be sufficient if many operators built base stations in the same place. The quality of the 5-GHz band is higher than that of the 2.4-GHz band, although the higher the frequency (i.e., the shorter the wavelength), the heavier the attenuation, and the more vulnerable communication becomes to obstacles.

In the United States, 300 MHz is available within the Unlicensed National Information Infrastructure (U-NII) band at 5-GHz band. The European Union is planning to open 580 MHz for HiperLAN without a licensing requirement, which can be divided into more than 25 channels in which up to 54 Mbps can be transmitted in each channel with IEEE 802.11a¹⁰. In Japan, however, there is no unlicensed outdoor band at 5-GHz band; only 160 MHz is available by license and 100 MHz is available indoors without a license.

There is another dimension by which we can utilize spectrum efficiently: time. According to FCC Chairman Michael Powell,

Since the beginning of spectrum policy, the government has “parceled” this resource in frequency and in space. We permitted use in a particular band over a particular geographic region often with an expectation of perpetual use. Like Einstein who dramatically theorized on the importance of the time dimension almost 90 years ago, the Commission now should also look at time as an additional dimension for spectrum policy¹¹.

For example, meteorological radars occupy 5.25-35 GHz, but they use the band for only a few minutes per hour. If other terminals can sense the radar waves and stop using the channel while the radar is working, they can work together in a channel. Such adaptive technologies, known as cognitive radio, have been standardized and implemented into some 802.11a chipsets¹². Dividing bandwidth by time, these technologies enables the WLAN base stations to coexist with other terminals in a band and realize much more efficient use of idle spectrum. For example, 300 MHz of the UHF band is allotted to TV stations, but less than a half of it is used in Japan. So if WLAN terminals equipped with *cognitive radio* technologies can detect vacant channels and use them, more than 100 MHz of spectrum can be “created.” If such *overlay* usage is allowed in all bands, available bandwidth will be so large that its allocation would not be necessary.

Software-Defined Radio (SDR)¹³ will make such adaptation even easier by changing physical layers by software, just like applications for PCs. And *smart antennas*, combining various antenna elements with a single processor, can change the transmission/reception mode in response to the communication environment. If a channel is occupied by 802.11a, other terminals can change its modulation to 802.11a by SDR. To deploy SDR, however, regulatory reforms will be necessary: the present Radio Act bans non-standardized communication devices by certification of equipment, but if communication is performed by software, it would make no

sense to certify the equipment.

There is yet another dimension of multiplexing: power. Part 15 of the Code of Federal Regulations defines the admitted noise level for unlicensed devices. Ultra-Wide Band (UWB) is the technology that uses such very weak signals that cannot be distinguished from the radio noise generated by TVs, computers, and hair dryers. In contrast to the conventional radio technology that modulates baseband with a carrier (sine curve), UWB modulates the baseband with very short pulses (less than a nanosecond). This technology realizes high-speed transmission (up to 500 Mbps) by emitting pulses in a wide band, over a frequency range of several GHz. Since their waveforms are completely different from those of conventional radio waves and are emitted at very low power levels, advocates of UWB claim, the system will make overlay use possible over all bands without interference. In fact, however, interference was found in experiments conducted by the FCC. In February 2002, the FCC authorized UWB with very conservative restrictions for its band (above 3.1GHz) and with weak power. Therefore, for the time being, use of UWB will be limited to indoor use.

3. The Spectrum as Protocol

Regulatory Reforms

In November 2002, the FCC published a report written by the Spectrum Policy Task Force (SPTF). Summarizing a half year of extensive research and discussion, the report is indeed impressive in its deep understanding of digital wireless technologies and its call for bold reforms. Particularly noteworthy is the FCC's commitment to depart from the *command and control* approach that regulates usage by licensing. It is also remarkable that the FCC recognized the

efficiency of the *commons* approach.

However, the SPTF's conclusion is a half-hearted compromise between the commons model and the *exclusive rights* model, according to which incumbents can sell and buy their spectrum on secondary markets. SPTF insists that this “market-oriented” approach is more efficient than the commons approach for the band in which “scarcity is relatively high and transaction costs associated with market-based negotiation of access rights are relatively low”¹⁴. According to them, the spectrum is scarce below 5 GHz because of its propagation characteristics and “high level of incumbent use.” If they are not excluded as private property, they claim, “The Tragedy of the Commons” would take place.

This justification is incorrect because scarcity is not related to private ownership; roads and parks, for example, are supplied as commons even though they are scarce. In standard economics, a resource is efficiently allocated as private property if its consumption is *rival*, i.e., the marginal cost of joint consumption is large, and its supply is *excludable*, i.e., the transaction (excluding) cost is small. If a resource is rival but non-excludable, it is efficient to supply it as a common pool resource (CPR)¹⁵. Examples of CPR are fisheries, roads, and streetlights. Non-rival and non-excludable resources are best supplied as (pure) *public goods*. Examples of public goods are mathematical theorems and communication protocols¹⁶.

In other words, resources can be allocated efficiently in market mechanisms if the externalities of supply and consumption are small. In principle, such externalities can be internalized by an institutional arrangement to divide resources and assign property rights to the parts, but common resources are often too complicated to divide. Furthermore, such “privatization” is inefficient for information, because privatization makes it impossible to share the externalities of innovation, whose social value is usually larger than the private benefit of the innovator. This seems to be a

classical trade-off between incentives and efficiency of information, but it is not the case for spectrum. Exclusion is necessary only in so far as the spectrum is separated by frequency. If terminals are intelligent, they can allocate spectrum dynamically by identifying each other's signals without exclusion.

Thus the analogy of spectrum as “commons” is misleading because the spectrum is not CPR but public goods. Too many people quote the “tragedy” that has nothing to do with the spectrum whose marginal consumption cost is zero if it is used efficiently¹⁷. Rivalry among multiple users of spectrum can be eliminated using packet radio technologies that increase the network capacity by adding stations and terminals. Since they can be shared and used without limits, it does not make sense to allocate them by market mechanisms. Therefore, to avoid semantic confusion, we compare spectrum to *protocol*¹⁸ with which information is carried.

Open Spectrum Management

Radically new technologies such as WLAN, SDR, and UWB are demanding a “new spectrum policy paradigm” in Chairman Powell's words. Noam proposed a reform named *open access*¹⁹. If you allocate bandwidth dynamically, this will be far more efficient than the current system of static allocation. If demand is lower than capacity, everybody can access bandwidth freely. If demand exceeds capacity, a “clearing house” charges fees for wireless traffic, acting as a tollbooth. It is much harder to charge for airwaves than for cars because the former do not pass through specific gates, so this proposal has been regarded as unrealistic. However, digital technologies such as spread spectrum have now rendered this idea feasible.

If bandwidth were to be supplied to an extent greatly exceeding demand, so as to become free goods, open access would become possible without fees. Even if bandwidth did not exceed

demand, however, the allocation of packets by spread spectrum would be more efficient than charging for packets. Packets in the wired Internet are stored and forwarded by routers without charge. Congestion leads to waiting, but this is not a very serious problem in data communications and can be overcome by widening the bandwidth. Already we can reach up to 108 Mbps by using two channels of 802.11a together. UWB has realized 500 Mbps and its capacity will easily extend to more than 1 Gbps.

In the long run, the spectrum should be maintained by public administration that makes rules and enforces them by monitoring abuses. However, “Public” does not necessarily mean “governmental.” Today the Internet is preserved by hundreds of millions of users worldwide without any government control. Standardization of radio equipment by the government has ended with the failure of 3G. Today, such non-profit organizations (NPO) as IEEE and the Internet Engineering Task Force (IETF) have taken over the role of the ITU. Of course, this does not mean that government regulation is unnecessary. Even if there is sufficient bandwidth, interference will occur between different physical layers. One way to prevent such interference is to fix a physical layer (modulation) for each band; for example, 802.11b for 2-3 GHz and 802.11a for 3-6 GHz. Some argue against unlicensed usage because such physical regulation will impede innovation²⁰, but regulation is not necessary for this purpose. For example, if a channel is occupied by Bluetooth, WLAN can use another channel by sensing the carrier. If there is sufficient bandwidth and flexible technologies such as cognitive radio are deployed, various physical layers can coexist in different channels.

To coordinate various kinds of terminals to work cooperatively, regulating channels, powers, frequencies, and the modulations of different terminals will be the important task of radio administration. Traditional regulation has focused on transmitters, but it is also necessary to

regulate receivers to control interference among different types of terminals. Since digital receivers are much more tolerant of interference than analog, there should be a more flexible criterion *interference temperature*, according to the FCC's term, to enable different systems to coexist in a band. Such regulation should be enforced, not for operators but for manufacturers because communication terminals will exist as ordinary electronic appliances independent of operators and service providers. The standardization can be left to the NPO, but the certification of equipment and monitoring of abuse should be carried out by the government.

It is a challenge for regulators to coordinate different modulation systems in a band. Even if cognitive radio terminals can allocate channels dynamically, some priority might have to be placed in order to guarantee the bandwidth for moving terminals. It would be better to secure *device rights* that define the priority to use a channel rather than to allocate fixed spectrum, according to David P. Reed. For example, the government can reserve some channels for mobile IP phones. Mobile phones can use all channels in a band and preempt the "mobile channel" even if other modulation systems use the channel; other data transmission can use the mobile channels only if they are not occupied by mobile phones. The government can charge mobile terminals extra fees, which can be priced by auctions. Although it is most important to supply sufficient capacity to render abuse unnecessary and harmless, surveillance and enforcement might have to be intensified, at least transitionally.

4. Reverse Auctions

Strategy for Transition

During the transition period, licensed and unlicensed bands will coexist, but the criteria by which

the spectrum rights are specified should be determined not by the so-called scarcity but by the excludability (efficiency of exclusion) of a band. Above 3 GHz, it is pointless to exclude spectrum because there is no new technology that depends on frequency division in that band. Exclusion might be justified in the extremely lower band (probably below 30 MHz) where high-power propagation is economical and no digital radio technology is likely to be implemented. In the intermediate band, the *easement* of overlay usage should be enforced.

Thus a strategy of transition to more efficient technologies is necessary. As SPTF insists, spectrum policy must “provide incentives for users to migrate to more technologically innovative and economically efficient uses of spectrum”²¹. To achieve the goal, however, it seems that the FCC is going to give spectrum away to incumbents as their private property and let them use it efficiently. At the same time when the SPTF report was published, economists at the Office of Plans and Policy of the FCC published a working paper prescribing the “Big Bang auction” that would enable incumbents to sell and buy all spectrum.²²

Indeed this type of system would be politically easy to accomplish because incumbents will love it. However, a danger would exist that exclusive rights would authorize incumbents to exclude other parties from more efficient usage. If spectrum were sold at a high price, the “owner” of spectrum would maximize its value by differentiating it with proprietary protocols. This is rational behavior for individual users, but it would lead to socially inefficient outcomes. Even worse, such a policy is irreversible; once spectrum is given away to incumbents, it would be lost forever because the incumbents would never open it. Easement would be harder to enforce because incumbents would protect their private property by resisting such “regulatory taking”, as the local carriers did to the unbundling regulation for digital subscriber lines.

Legally, of course, governments can reclaim the spectrum as licenses expire. The Ministry of

Public Management, Home Affairs, Posts and Telecommunications (MPHPT) of Japan announced a plan for such a ruling in November 2002. MPHPT is going to rule that, if licenses expire, licensees must return their spectrum with compensation for the remaining book value of their equipment. As the term of license is five years and the term of amortization is six years, the average licensee's remaining value is very small. This is legitimate but difficult to enforce. If incumbents resist, it will take a long time to evict them by negotiation; MPHPT estimates that it would take 10 years to clear the 4-GHz band. Worse, many incumbents would refuse the "taking" of spectrum on which their businesses depend and a regulatory nightmare would result.

Such a problem can be resolved by breaking it down into two parts: it is important to motivate incumbents to exit by compensation, but it is harmful to give them exclusive rights for the spectrum. So it is advisable for the government to reclaim its spectrum through *reverse auctions* and then open the acquired spectrum without a license requirement²³. This mechanism can be implemented as an ordinary procurement process by which the lowest bidder sells products to the government.

Auction Design

The government should "clear" a band by reclaiming all the stations in the band nationwide, but it is not necessary to open all spectrum because, for example, 1 GHz might be enough to supply the bandwidth for WLAN in current use. As it is difficult to evaluate too many different bands, the government should focus on some specific bands.²⁴ However, if the government announces in advance that it will buy all spectrum for a specific band, as in the usual case of eminent domain, the "squatters" who resist it will get huge windfalls. Thus it would be better to have (groups of) incumbents competing to offer the low prices.

To simplify the analysis, let's assume that there are n firms in the market, each possessing one license with a particular "frequency".²⁵ (For example, a firm having a license with "frequency" 4.1 GHz means that this firm possesses frequencies ranging from 4.10 GHz to 4.19 GHz.) The auction design depends on the goals set by the government. To start with, let's assume that the government's objective is to buy back the K least efficiently used frequencies (*efficient buyouts*).

In this case the government can conduct a uniform-price auction. The rule is as follows: each firm bids a price for its own license (frequency). Based on the bids, the K firms with the K lowest bids become the "winners" (to sell their frequencies). The government pays each winner a uniform price which is equal to the $(K+1)$ st lowest bid. Under such an auction, all firms will bid their own (privately estimated) valuation of their licenses truthfully ("incentive compatible"), and the government will indeed procure the K licenses with the least efficient uses. The mechanism underlying this auction design is called the VCG (Vickrey-Clarke-Groves) mechanism.²⁶ As is well known, the VCG mechanism is efficient and induces truthful reporting as dominant strategies.

Since simple maximization of bandwidth may result in fragmentation of the band into many small pieces, there should be requirements on bands; for example, the band should contain frequencies that are continuous for at least 50 MHz. Since this kind of requirement is more relevant in practice, in what follows we propose a modified VCG mechanism to achieve efficient spectrum buyouts with a minimal bandwidth requirement.

We start with a description of the model. We assume that n firms possess a set of spectrum licenses with frequencies ranging from f_1 to f_n "continuously" ($f_1 < f_2 \dots < f_n$).²⁷ We assume that each firm possesses exactly one license, i.e., firm i possesses license i with frequency f_i , $i = 1, 2, \dots, n$. The government wants to procure licenses from these firms. There is minimal

bandwidth requirement, e.g., the band should be “continuous” for more than 50 MHz. In our case, we assume that this requirement is equivalent to procuring K licenses with consecutive frequencies ranging from low to high where K is much smaller than n . The government’s goal is to procure K consecutive licenses we call a “band group” with minimal budget. We assume that each firm (i) has a private valuation for the license it owns. Let this private valuation be θ_i . θ_i is only observed by firm i . Ex ante, $\theta_i \in [\underline{\theta}, \bar{\theta}]$, and θ_i ’s are distributed according to a joint density function $f(\theta) = f(\theta_1, \dots, \theta_n) > 0$.²⁸

In the event that the government procures license i at price t_i , firm i ’s profit from selling the license is as follows:

$$\pi_i(t_i; \theta_i) = t_i - \theta_i \quad (1)$$

We now consider a procurement mechanism conducted by the government. The government first asks the n firms to report their private valuations (their “types”). Given a report profile $\theta = (\theta_1, \dots, \theta_n)$, the mechanism is characterized by the procurement decision $x(\theta) = (x_1(\theta), \dots, x_n(\theta))$ and the payment or transfer $t(\theta) = (t_1(\theta), \dots, t_n(\theta))$, where $x_i(\theta)$ takes the value of either 1 or 0, and $t_i(\theta)$ is the payment made from government to firm i . When $x_i = 1$, license i is procured by the government; when $x_i = 0$, license i remains at firm i ’s hands. Due to the minimal band requirement, for any given θ , $x(\theta) \in X$ where $X = \{(1, \dots, 1, 0, \dots, 0), (0, 1, \dots, 1, 0, \dots, 0), \dots, (0, \dots, 0, 1, \dots, 1)\}$ which means that only K licenses with K consecutive frequencies can be procured (so each feasible $x(\theta)$ contains K consecutive 1’s and all the other decision variables are zeros). In particular, we have

$$\sum_{i=1}^n x_i(\theta) = K$$

We call the above problem the constrained procurement problem faced by the government (constrained by the minimal band requirement, or equivalently, constrained by the set X). We define efficient procurement in this context as procurement in which the government procures a set of licenses with the lowest total value while maintaining the minimal bandwidth requirement. It turns out that we can use a modified version of the VCG mechanism to achieve efficient procurement in this context. For notational convenience, we write

$$v_j(x, \theta_j) = x_j \cdot \theta_j \quad (2)$$

Then given a report profile $\hat{\theta} = (\hat{\theta}_i, \hat{\theta}_{-i})$, the efficient procurement decision rule is given by

$$x^*(\hat{\theta}) \in \arg \min_{x \in X} \sum_{j=1}^n v_j(x, \hat{\theta}_j) \quad (3)$$

Choose the following payment rule (the Groves' payment rule):

$$t_i(\hat{\theta}) = - \sum_{j \neq i} v_j(x^*(\hat{\theta}), \hat{\theta}_j) + h_i(\hat{\theta}_{-i}) \quad (4)$$

where $h_i(\hat{\theta}_{-i})$ is some function not depending on $\hat{\theta}_i$. In words, set the payment to firm i equal to the “externality” that i 's report imposes on other firms.

Proposition 1: *Truthful reporting is a dominant strategy in the mechanism with an efficient procurement rule given by (3) and payment rule given by (4).*

Proof: Given any report profile by other firms $\hat{\theta}_{-i}$, firm i solves the following problem:

$$\max_{\hat{\theta}_i} t_i(\hat{\theta}_i, \hat{\theta}_{-i}) - v_i(x^*(\hat{\theta}_i, \hat{\theta}_{-i}), \theta_i) \quad (5)$$

Substituting (4) into (5), we obtain firm i 's equivalent problem:

$$\min_{\hat{\theta}_i} \sum_{j \neq i} v_j(x^*(\hat{\theta}_i, \hat{\theta}_{-i}), \hat{\theta}_j) + v_i(x^*(\hat{\theta}_i, \hat{\theta}_{-i}), \theta_i) \quad (6)$$

Note that $h_i(\hat{\theta}_{-i})$ does not affect i 's choice and hence is left out in the above minimization objective function. Note also that firm i 's report $\hat{\theta}_i$ only matters through its effect on the decision $x^*(\hat{\theta}_i, \hat{\theta}_{-i})$. So alternatively we can ask which decision the firm wants to implement:

$$\min_{x \in X} \sum_{j \neq i} v_j(x, \hat{\theta}_j) + v_i(x, \theta_i) \quad (7)$$

By (3), the optimal decision is $x^* = x^*(\theta_i, \hat{\theta}_{-i})$. Note that this can be achieved by choosing $\hat{\theta}_i = \theta_i$ in the original problem (6), which implies that truthful reporting is a dominant strategy for the firms. *Q.E.D.*

Remark: Note that in the above proof we do not make use of the knowledge about the distribution of θ_i 's. In other words the modified VCG mechanism characterized above is prior-free. So truthful reporting is an equilibrium strategy for the firms regardless of the priors; this is true even when the firms' beliefs are inconsistent, or even when the firms do not have prior beliefs about other firms' valuations. Since the VCG mechanism is prior-free, it also greatly reduces the information burden on the seller's side.

As in Clarke's formulation, we can choose the following functional form for $h_i(\cdot)$:

$$h_i(\hat{\theta}_{-i}) = \sum_{j \neq i} v_j(x_{-i}^*(\hat{\theta}_{-i}), \hat{\theta}_j) \quad (8)$$

where $x_{-i}^*(\hat{\theta}_{-i})$ means the efficient decision rule when the frequency f_i (thus the band group that contains it) is not sold. It can be verified that when $h_i(\cdot)$ is given by (8), then the payments given

by (4) are always nonnegative. Specifically, only those firms who sell their licenses get positive payments, while those who don't sell end up with zero payments.

Some have argued that such an auction would be extremely costly, referencing the prices of PCS auctions, but this is not the case. In an ordinary spectrum auction, the equilibrium price will be equal to the net present value (NPV) of the *most efficient* use of spectrum. On the contrary, in our reverse auction, the price will be approximately equal to the opportunity cost of the *least efficient* use of spectrum. To see this, we consider some simple examples and see how the mechanism characterized above works. Suppose there are 20 firms, holding licenses with frequencies of 10 MHz ranging from 4.00 GHz to 4.19 GHz. Suppose the licensees, the bands, and their private valuations for their licenses are listed below:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20 th licensee	
4.00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	GHz
.5	.6	.2	.4	.3	.2	.3	.2	.8	.4	.9	.5	.5	.8	.5	.2	.4	.1	.3	.4	Million \$

Suppose the government conducts a modified VCG mechanism as described above to procure K licenses. Since this mechanism induces truthful reporting as dominant strategies, in equilibrium all firms will truthfully report their private valuations as shown in the table above. Given this report profile, the payments are determined by

$$t_i(\theta) = \sum_{j \neq i} v_j(x_{-i}^*(\theta_{-i}), \theta_j) - \sum_{j \neq i} v_j(x^*(\theta), \theta_j) \quad (9)$$

First we consider the case in which $K = 5$. According to the (constrained) efficient rule, the following decision is an efficient procurement outcome:

$$x_i^* = \begin{cases} 1 & \text{for } i = 3, 4, 5, 6, 7 \\ 0 & \text{otherwise} \end{cases}$$

Let's compute the equilibrium payments (or the prices) according to (9). The first term of the right hand side of (9) is the minimal total value of licenses among all firms but $i \in \{3, 4, 5, 6, 7\}$, which is given by the band group $\{16, 17, 18, 19, 20\}$, $.2 + .4 + .1 + .3 + .4 = 1.4$, therefore,

$$\begin{aligned} t_3 &= 1.4 - 1.2 = .2 \\ t_4 &= 1.4 - 1.0 = .4 \\ t_5 &= 1.4 - 1.1 = .3 \\ t_6 &= 1.4 - 1.2 = .2 \\ t_7 &= 1.4 - 1.1 = .3 \\ t_i &= 1.4 - 1.4 = 0 \text{ for } i \neq 3, 4, 5, 6, 7 \end{aligned}$$

Note that for those who sell their licenses, they sell exactly at their private valuations exactly. In other words, they make zero profit out of this reverse auction. This is not surprising, given the competition from the equally (least) efficient group $\{16, 17, 18, 19, 20\}$.

Next we consider the case in which $K = 6$. Repeating the same arguments above, we have

$$x_i^* = \begin{cases} 1 & \text{for } i = 3, 4, 5, 6, 7, 8 \\ 0 & \text{otherwise} \end{cases}$$

Since $\sum_{j \neq i} v_j(x_{-i}^*(\theta_{-i}), \theta_j)$ is now 1.9 (given by the band group $\{15, 16, 17, 18, 19, 20\}$), the

equilibrium prices are:

$$\begin{aligned} t_3 &= 1.9 - 1.4 = .5 \\ t_4 &= 1.9 - 1.2 = .7 \\ t_5 &= 1.9 - 1.3 = .6 \\ t_6 &= 1.9 - 1.4 = .5 \\ t_7 &= 1.9 - 1.3 = .6 \\ t_8 &= 1.9 - 1.4 = .5 \\ t_i &= 1.9 - 1.9 = 0 \text{ for } i \neq 3, 4, 5, 6, 7, 8 \end{aligned}$$

The profits for the winning firms in this case are as follows:

$$\begin{aligned} \pi_3 &= .5 - .2 = .3 \\ \pi_4 &= .7 - .4 = .3 \\ \pi_5 &= .6 - .3 = .3 \\ \pi_6 &= .5 - .2 = .3 \\ \pi_7 &= .6 - .3 = .3 \\ \pi_8 &= .5 - .2 = .3 \\ \pi_i &= 0 \text{ for } i \neq 3, 4, 5, 6, 7, 8 \end{aligned}$$

So in this case, even though the prices for different procurements are not the same, the profits for each winning firm are the same. However, this is not always the case, as can be illustrated by the following example:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20 th licensee	
4.00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	GHz
.5	.6	.2	.4	.3	.2	.3	.2	.5	.1	.9	.5	.5	.8	.5	.2	.4	.1	.3	.4	Million \$

(This example is taken from the previous table, with modifications only of the private valuations for license 9 and 10.)

In this case, if $K = 6$, then again

$$x_i^* = \begin{cases} 1 & \text{for } i = 3, 4, 5, 6, 7, 8 \\ 0 & \text{otherwise} \end{cases}$$

and the equilibrium prices and the firms' profits are given by

$$\begin{aligned} t_3 &= 1.9 - 1.4 = .5 & \pi_3 &= .5 - .2 = .3 \\ t_4 &= 1.6 - 1.2 = .4 & \pi_4 &= .4 - .4 = 0 \\ t_5 &= 1.9 - 1.3 = .6 & \pi_5 &= .6 - .3 = .3 \\ & \dots & & \end{aligned}$$

So in this case, not only the prices but the profits are different. When the number of the firms holding different licenses is large (relative to K), there will be sufficiently many competing K -band groups. In that case the government may in general achieve efficient spectrum buyouts at a lower price. The first example above suggests that at the limit, the buyout price approaches the total value of the least efficient K -band group. In order to show this result more formally, for technical convenience we make the following two assumptions about the distributions of the valuations:

Assumption (I): *The firms' valuations θ_i 's are independently and identically distributed according to CDF $F(\cdot)$.*

Assumption (F): *The distribution of the valuation θ has full support. That is, the density function $f(\theta) > 0$ for any $\theta \in [\underline{\theta}, \bar{\theta}]$.*

We are now ready to state the limiting result:

Proposition 2: *Given Assumptions (I) and (F), as $M = n/K$ becomes sufficiently large, the buyout price will be arbitrarily close to the total value of the least efficient K -band group, which approaches $K\underline{\theta}$.*

The proof is straightforward, so it is relegated to the Appendix.

Remark: Though both Assumption (I) and Assumption (F) were used in the proof, we conjecture that the conditions for this limiting result would be much weaker. While the full support assumption seems to be a necessary requirement, we conjecture that Proposition 2 also holds for environments with correlated valuations.

The modified VCG mechanism as described above can work in more general settings. For example, if there are many licensees that have the same frequency in different regions, the government needs to buy the band nationwide. In such cases, the feasible set X can be defined as a matrix reflecting requirements for both the frequencies and locations of the firms. Or the government can require licensees to consolidate as one bidder for one “unit band” as a condition for applying the reverse auction.

One limitation of the VCG mechanism is that it can only guarantee efficiency when every firm’s valuation is private and not affected by others’ valuations.²⁹ If there are common value components among firms’ valuations, VCG mechanism may not be necessarily efficient

One other problem with the modified VCG mechanism is that it is hard to implement with conventional auction formats. Although the underlying equilibrium property is helpful, the rules in a modified VCG mechanism are actually quite complicated.

However, if the government can require licensees to consolidate as one bidder for one “unit band” as a condition for participating in the reverse auction, then dynamic mechanisms such as “simultaneous descending auctions,” a reverse version of the mechanism adopted for PCS auctions, can be implemented for spectrum buyouts. Such mechanisms are particularly effective if bidders’ (band groups’) valuations are interdependent, as they can adjust their value estimates by observing others’ drop-out bids.

Analysis of “simultaneous descending auctions” is conceivably much more complicated as we must analyze the formation of the band groups. All we have proved in this article is that there exists an efficient “market-oriented” mechanism with which the government can open spectrum and it can be very inexpensive (as competition increases). Implementation of the large-scale reverse auction that can be held by the government in practice is a very complicated task which will be left to another article.

Discussion

The value of the least efficiently used spectrum includes the NPV of the profit that would be gained by its user, the asset value of equipment, and the transaction costs that arise when the firm exits (or renews the equipment). The NPV is usually determined by future cash flow, terms of licenses, interest rates, taxes, and so on. In this case, however, even if an incumbent returns the spectrum, it can do the same business over wireless Internet when the spectrum is opened, but the profit will be lower because the market for the same services will be more competitive. So the NPV is the discounted value of monopolistic rent that will be smaller than the usual NPV.

Even if incumbents refuse to join reverse auctions, their monopolistic rents will deteriorate when entrants do the same business over wireless Internet using the opened band. Therefore, if sufficient bandwidth is opened and incumbents are rational, we can suppose that the equilibrium price will approach the asset value of equipment plus transaction costs. This result coincides with the plan of MPHPT, which reclaims spectrum while compensating for the remaining book value. The only difference is that the idle spectrum can be reclaimed immediately in our mechanism. Thus we recommend the reverse auction as an *optional* mechanism together with a strong

commitment that, after the government acquires the spectrum, it will open enough of it to wipe out monopolistic rents.

On the other hand, once the spectrum becomes a private property, as is planned by the FCC, its value will increase and the reverse auction will be more expensive. Faulhaber and Farber claims, on the contrary, that privatization will suppress the price and make spectrum a “commons” in the end by supplying more spectrum than its demand³⁰. If this were true, only irrational firms would buy spectrum that would eventually be worthless. Or, more realistically, they would make every effort to prevent the asset value of spectrum from depreciating by monopolizing it. Strengthening their claims for property rights would make relocation hopelessly difficult, as evidenced in the case of NextWave³¹.

Public users cannot be bidders, but they should be compensated for the cost of converting equipment or of exiting. Their bands should be evaluated as the average of the nearby bidders. Another problem is posed by whether or not a public band should be sold; for example, the band used by air traffic control should not be sold using the market mechanism. Such usage should be replaced more efficiently; for example, radars and Global Positioning Systems (GPS) can be replaced by UWB.

This reform might be criticized as an unfair income transfer for incumbents who are underutilizing allocated bands. We argue that, following the Coase Theorem, it is much more efficient to “bribe” incumbents to return their idle spectrum than to negotiate with them over a long time. The opportunity cost of wasting bandwidth and time would be much more expensive than the cost of buying the band back. In our scheme, the government does not have to negotiate with incumbents and politicians but only has to announce a reverse auction. Incumbents will bid and reveal their valuation of spectrum, and winners will return their bands even if they are using

them, as they would be reimbursed for the cost of replacing their old stations and terminals with WLAN.

Some may argue that there would be no need for spectrum relocation if overlay use were possible with cognitive radio technology in all bands. While this is theoretically true, cognitive radio is so complicated that it has not yet been implemented in portable terminals; because terminals have to store the detailed data of other equipment such as power, direction, and radar timetables. Moreover, if there is old analog equipment vulnerable to interference, new equipment must suppress the radiation very conservatively. Incumbents usually resist easement by overstating the risk of interference³². For example, UWB was at last authorized for a very limited power and bands by the FCC in 2002, after 20 years of negotiation mainly because GPS is vulnerable to interference with a weak emission below the admitted level. In such cases, governments can have “overlay auctions” to compensate incumbents for allowing easement. In the long run, this would be equivalent to the reverse auctions because incumbents will renew their equipment that can be used as overlay. So rational incumbents would be willing to sell their spectrum and change their stations and terminals with the auction fees.

The reverse auction is, as stated above, not a substitute for overlay use but a complementary strategy to facilitate transition in the band required for WLAN. Opening a clean band is obviously better than easement, so the problem is: which is faster and cheaper method for opening spectrum. This will depend on various factors such as progress in radio technology, the political power of incumbents, and so forth. Our guess is that, at least in the band above 3 GHz over the next 10 years, buyouts will prove to be the faster way. It would not be less expensive, but it could buy precious time by “bribing” incumbents. This might work as a middle-of-the-road solution of the commons approach, which is economically efficient but politically difficult, and

the exclusive rights approach, which is inefficient but easy. Both incumbents and entrants can benefit from this buyout, and we can open spectrum through a market mechanism.

Financing might be the most difficult part of reverse auctions, because this mechanism is not budget-balancing and the auction fee will be much larger than in usual procurement cases. A simple solution would be to finance the auction through general government accounts, in view of the fact that governments have made a great deal of money by auctioning off spectrum to private parties. This would cure the problem of spectrum auctions raised by Noam: auctions “tax” the communications industry and suppress investment. Through such repayment the government could revitalize wireless operators, which lost a great deal of money in the collapse of the bubble. It is, in effect, a collective auction by millions of WLAN users, so its cost is equivalent to that of an ordinary spectrum auction, in which the winner will pass on its costs to the consumer.

Another solution, probably better suited to Japan, would be to compensate the government’s cost of reverse auctions through *spectrum usage fees*. This would be more neutral to public finance, and raising the fee would press incumbents to use bandwidth more efficiently or to sell out. If the government had auctions of device rights, as we proposed above, the revenue could be used to finance reverse auctions. The present tariff of spectrum usage fees in Japan, however, is a disincentive for efficient use of bandwidth: because the fees are charged in proportion to the number of radio stations, more efficient users are charged more. If the fee is charged for bandwidth instead, this would offer incentives for efficient bandwidth use³³. Some parts of the spectrum can be sold by ordinary spectrum auctions; for example, fragmented bands between the bands for mobile phones in the UHF band can be auctioned to mobile operators, which will generate much higher revenues than the purchasing prices. As these financing methods are complementary, governments could use them in combination.

It might be risky to have governments conduct such large auctions because it could induce irrational behavior such as that seen in the 3-G auctions. If sellers rushed to sell their bands as soon as possible, the resulting price would be near zero, but such mistakes would not harm the government. If sellers were to collude to keep the bidding high, the government should have the option to quit. So it is necessary to perform preliminary experiments in the laboratory and small experimental reverse auctions before full-scale buyouts. Anyway our mechanism is safer than the two-sided Big Bang auction in which governments cannot control prices and monopolistic behavior. In our mechanism, governments can coordinate the trading process by separating buying and selling auctions and can make money if they choose. Therefore the reverse auction can be adopted as a mechanism to facilitate the “hybrid” approach of the FCC because governments can decide whether to allocate the spectrum as unlicensed bands or private property. In practice, new digital wireless technologies are so efficient that it would be sufficient to open a few GHz for unlicensed bands. Thus three kinds of spectrum management can be applied to different spectrum ranges: the bands below 30 MHz can be managed by command and control or exclusive rights; above 2.4 GHz, all spectrum should be vacated as public goods; in the intermediate band, overlay use is recommended.

5. Conclusion

3G was not successful despite so much investment from so many operators and almost 10 years of negotiation in the ITU, while WLAN, which has received so little attention from companies or governments, has been unexpectedly successful. It suggests that the current framework of spectrum management, inherited from the old broadcasting model of 75 years ago, does not fit

Internet technology in which innovation is so rapid that nobody knows the best method of use and who would make the best use of spectrum. Furthermore, the Internet teaches us that non-profit mechanisms can facilitate far more innovations than “market-oriented” ones do. The most important ingredient for innovation is not the market but the *freedom* that is created by decentralized coordination mechanisms. The Internet created the freedom by decoupling the platform from the infrastructure with its *end-to-end* architecture. If we secure more freedom for wireless communications, vast amount of value will be created using new technologies.

Reform of spectrum policy will have a great impact on telecom regulation in general. Peter Huber argues that the monopoly of “the last one-mile” was made by the FCC³⁴. Cellular-phone and spread-spectrum technologies were invented in the 1940s, but the FCC only permitted cell phones in the 1980s and WLAN in the 1990s, because it wanted to allow AT&T to monopolize telephone lines and broadcasting stations to monopolize radio spectrum. If the spectrum had been opened for wireless communications in wider bands earlier, cell phones would have been much less expensive and would have become viable competitors to wired telephones. WLAN made broadband communication much less costly than optical fiber at the edges of networks, so wireless networks may dominate wired ones in residential areas. Moreover, if metro networks are built from WLAN or other fixed wireless stations, wired and wireless networks will be combined in various ways, depending on the applicable costs and demand, as it does not matter which facilities carry them. If such a *facility-based* competition between wired and wireless networks is realized, the least costly network will pull down all facilities’ costs. Then administrative bodies would not need to strictly regulate each individual network, but rather create an environment in which newcomers could join the game at any time, thus encouraging competition in the infrastructure.

If communication were completely decentralized by wireless appliances, there would be no need for “common carriers” that integrate facilities and services vertically. Users can have network nodes (i.e., wireless routers) connected by optical fiber and resell the bandwidth to their neighbors. So competition would occur among manufacturers instead of operators who will be utility companies separated from services. It would be sufficient to control the quality of terminals at the manufacturers’ level, rendering centralized government control of spectrum unnecessary. As in the wired Internet, non-profit organizations could be entrusted with these tasks.

It goes without saying that licensing for broadcasting stations makes no sense in the Internet age when moving pictures are carried over IP. Although advocates of the broadcasting industry demand protection of their vested interests in the name of “culture” or “public concern,” such problems of content are not the subject of spectrum regulation. When content is unbundled from facilities by IP, TV stations should be treated in the same way as newspapers and publishers. This would be good news for broadcasters. The abolition of licensing would bolster freedom of speech and give broadcasters the opportunity to become full-fledged organs of public opinion without government permission. In the broadband age, broadcasters’ key assets are the content they have accumulated and the human resources of creators, not the radio waves whose value is vanishing.

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Appendix

Proof of Proposition 2: Let $v_m = \theta_{(m-1)K+1} + \theta_{(m-1)K+2} + \dots + \theta_{mK}$ be the total valuation in the K -band group indexed by m , $m = 1, 2, \dots, M$, where $M = [n/K]$, the integer part of n/K . Then by Assumption (I), v_m 's are also independently and identically distributed with a CDF, say, $G(\cdot)$, which is the K -fold convolution of F with itself. By Assumption (F), $G(\cdot)$ also has full support. That is, let $g(\cdot)$ be the density function of v_m , then $g(v_m) > 0$ for any $v_m \in [K\underline{\theta}, K\bar{\theta}]$.

Given n and hence M , let $V_{(1)}^M$ and $V_{(2)}^M$ denote the least and second least valuations among M disjoint K -band groups, respectively. According to the VCG mechanism characterized above, it suffices to show that as $M \rightarrow \infty$, $EV_{(1)}^M = EV_{(2)}^M = K\underline{\theta}$.³⁵

Let $g_{(1)}(\cdot)$ and $g_{(2)}(\cdot)$ denote the density functions for the least valuation and the second least valuation, respectively. Then

$$\begin{aligned} g_{(1)}(v) &= M[1-G(v)]^{M-1}g(v) \\ g_{(2)}(v) &= M(M-1)G(v)[1-G(v)]^{M-2}g(v) \end{aligned} \tag{10}$$

Therefore,

$$EV_{(1)}^M = \int_{\underline{v}}^{\bar{v}} v \cdot M(1-G(v))^{M-1}g(v)dv = -\int_{\underline{v}}^{\bar{v}} v \cdot d[1-G(v)]^M = \underline{v} + \int_{\underline{v}}^{\bar{v}} [1-G(v)]^M dv$$

Since $|[1-G(v)]^M| \leq 1$ and $[1-G(v)]^M \rightarrow 0$ *a.s.*, we have $\int_{\underline{v}}^{\bar{v}} [1-G(v)]^M dv \rightarrow 0$ as $M \rightarrow \infty$. We

thus have $\lim_{M \rightarrow \infty} EV_{(1)}^M = \underline{v} = K\underline{\theta}$.

On the other hand,

$$\begin{aligned}
EV_{(2)}^M &= \int_{\underline{v}}^{\bar{v}} v \cdot M(M-1)G(v)[1-G(v)]^{M-2} g(v)dv \\
&= \int_0^1 G^{-1}(u) \cdot M(M-1)u[1-u]^{M-2} du \\
&= \int_0^1 [G^{-1}(u) - G^{-1}(0)] \cdot M(M-1)u[1-u]^{M-2} du + \int_0^1 G^{-1}(0) \cdot M(M-1)u[1-u]^{M-2} du
\end{aligned} \tag{11}$$

Note that the reason we can write the inverse function $G^{-1}(\cdot)$ is due to the full support assumption. It is easily verified that $\int_0^1 M(M-1)u[1-u]^{M-2} du = 1$. Therefore the second term

above is equal to $G^{-1}(0) = \underline{v}$. To evaluate the first term above,

$$\begin{aligned}
&\int_0^1 [G^{-1}(u) - G^{-1}(0)] \cdot M(M-1)u[1-u]^{M-2} du \\
&= \underbrace{\int_0^\delta [G^{-1}(u) - G^{-1}(0)] \cdot M(M-1)u[1-u]^{M-2} du}_{(I)} + \underbrace{\int_\delta^1 [G^{-1}(u) - G^{-1}(0)] \cdot M(M-1)u[1-u]^{M-2} du}_{(II)}
\end{aligned}$$

For $u \geq \delta > 0$, $(1-u)^{M-2}$ goes to zero exponentially, hence $(II) \rightarrow 0$ as $M \rightarrow \infty$. For (I), we have

$$\begin{aligned}
&\int_0^\delta [G^{-1}(u) - G^{-1}(0)] \cdot M(M-1)u[1-u]^{M-2} du \\
&\leq [G^{-1}(\delta) - G^{-1}(0)] \int_0^\delta M(M-1)u[1-u]^{M-2} du \\
&\leq [G^{-1}(\delta) - G^{-1}(0)]
\end{aligned}$$

Therefore, choosing $\delta \rightarrow 0$, we have $(I) \rightarrow 0$ as $M \rightarrow \infty$. This shows that $\lim_{M \rightarrow \infty} EV_{(2)}^M = \underline{v} = K\underline{\theta}$.

Q.E.D.

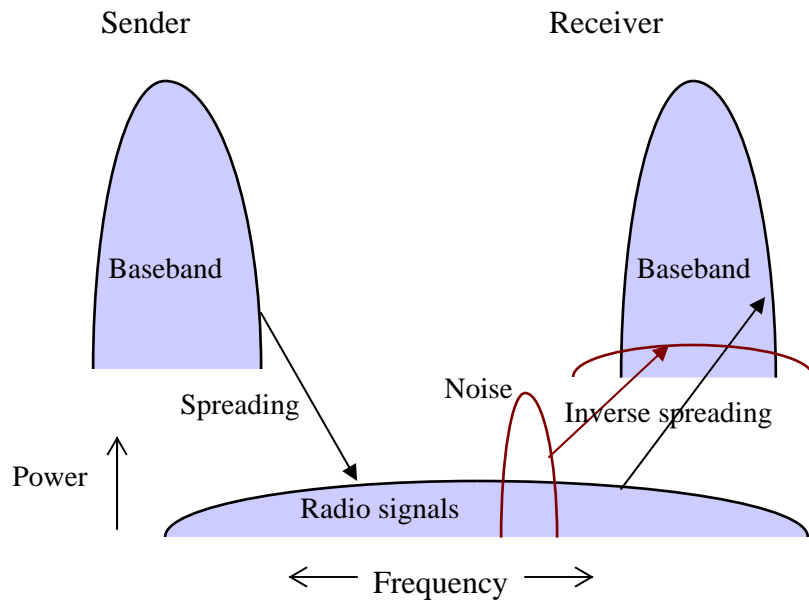


Figure 1: Spread spectrum (DSSS)

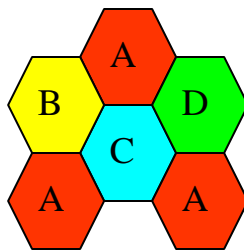


Figure 2: Microcells

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Notes

1 R.H. Coase, The Federal Communications Commission, 2 J. Law & Econ. (1959), p.20.

2 P. Milgrom, Putting Auction Theory to Work, Cambridge Univ. Press, ch.1.

3 P. Klemperer and K. Binmore, “The Biggest Auction Ever: The Sale of the British 3G Telecom Licenses,” 112 Econ. J. 74 (2002).

4 G. Gilder, “Auctioning the Airways”, Forbes ASAP, 1994, p.6

5 E. Noam, Spectrum Auctions, J. Law & Econ. 41 (1998), p.771.

6 Y. Benkler, Overcoming Agoraphobia, 11 Harvard J. Law & Tech. 287 (1999).

7 There are several technologies referred to as spread spectrum. Frequency hopping changes transmission frequencies randomly over very short periods of time. CDMA and OFDM are sometimes denoted as spread-spectrum technologies in a broader sense. For more technical details, see T.S. Rappaport, Wireless Communications (2001)..

8 WLAN spreads the same signal several times, so the transmission efficiency per frequency of 801.11b stands at $11 \text{ Mbps}/22 \text{ MHz} = 0.5$, similar to that of cellular telephones.

9 Theoretically, four channels are sufficient to fill the space, as is known from the four-color problem in mathematics, if the base stations are coordinated. But there are usually many users who use channels randomly, so more than ten channels are needed to avoid serious interference within the same channel.

10 IEEE 802.11a, launched on the market in 2001, operates in the 5-GHz band. 802.11g (compatible with 802.11b), standardized in 2002, operates in the 2.4-GHz band. HiSWAN is the name of the European standard. All of these systems yield a maximum speed of 54 Mbps.

11 M.K. Powell, Broadband Migration III, FCC.

12 DFS (Dynamic Frequency Selection) and TPC (Transmission Power Control) have been standardized by the 802.11h Committee of the IEEE. The E.U. committee authorized DFS and TPC in the 5-GHz band.

13 SDR is included in cognitive radio in the broad sense. The International Telecommunication Union (ITU) is planning to adopt SDR for so-called “4th-generation mobile communications”.

14 FCC, Spectrum Policy Task Force Report (2002), p.38.

15 CPR are often managed by community norms, but it is irrelevant for spectrum.

16 Resources that are non-rival but excludable are best supplied as club goods, e.g., pay-TV and subscription services.

17 Garrett Hardin’s famous article emphasizes that the Tragedy will occur if “[n]o technical solution can rescue us from the misery of overpopulation” (The Tragedy of the Commons, 162 Science (1968), p.1243).

18 Kevin Werbach adopts a neologism “supercommons” to avoid similar confusion with “commons”. See his *Supercommons*, 82 *Texas Law Rev.* 863 (2004).

19 Noam, *supra*.

20 T. Hazlett, *The Wireless Craze*, 14 *Harvard J. Law & Tech.* 335 (2000).

21 FCC, *supra*, p.15.

22 E. Kwerell, E. and J. Williams, *A Proposal for Rapid Transition to Market Allocation of Spectrum*, FCC OPP working paper 38 (2002).

23 This problem is similar to that of intellectual property rights. As a complementary mechanism to patent licensing, “patent buyout” is proposed in which the government buys patents from inventors through auctions and opens the patents to everyone. See M. Kremer, *Patent Buyouts*, 113 *Quart. J. Econ* 1137 (1998).

24 In Japan, the best candidate for the WLAN band is the 3-5 GHz, that is currently used for business communications and as the backbone of mobile telephone networks.

25 When each firm’s bandwidth is not the same, we can normalize the bandwidth by setting the “unit band” as 1 MHz, for example. In that case, a firm sells multiple unit bands at the same time. It complicates the formulation, but will not affect our main results that an efficient mechanism exists.

26 Under a VCG mechanism, all agents are required to report their “types” (e.g., private values). The VCG mechanism employs the efficient decision rule (value-maximizing) and the payment rule is specified such that reporting truthfully is a dominant strategy for each agent. The second-price auction is one example of the VCG mechanism. For details see Milgrom, *supra*.

27 For example, we may use 4.1 to represent the frequencies ranging from 4.10 GHz to 4.19 GHz, and 4.2 to represent the frequencies ranging from 4.20 GHz to 4.29 GHz, and so on.

28 θ_i ' can be correlated.

29 Though it allows for correlations among private valuations.

30 G. Faulhaber and D. Farber, *Spectrum Management* (2002).

31 NextWave, a new carrier that planned to operate mobile phones, bought spectrum licenses for \$4.7 billion in 1996, but filed for bankruptcy in 1998. The FCC seized the licenses and reauctioned them in 2001 for \$16 billion. However, NextWave sued the FCC, insisting that the license was its private property protected by bankruptcy law. In 2003, the U.S. Supreme Court supported NexWave's claim.

32 This is why we think the "liability rules" proposed by Werbach , *supra*, would not work. Such rules assume that the state knows the true damage of interference, but incumbents usually exaggerate it. It would be practical to clear the bands and allocate device rights to each terminals according to property rules.

33 Other considerations are in order. The power of the station and population coverage might have to be considered. Radar and military radio equipment should be charged according to a different tariff. It would be difficult to charge unlicensed terminals, so the fee would be charged to manufacturers, as a tax for unlicensed terminals.

34 P. Huber, *Law and Disorder in Cyberspace* (1997).

35 This condition implies that when M is sufficiently large, the expected buyout price approaches the expected value of the least efficient band. According to the modified VCG mechanism, a K -band does not have to "compete" with a disjoint K -band. But for the purpose of this proof, it suffices to show the proposition based on the competition among disjoint K -bands only.