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The Spectrum as Commons

Digital Wireless Technologies and Radio Administration

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Abstract

The shortage of radio spectrum is the major roadblock to the development of wireless communications. This problem is usually attributed to the *scarcity* of spectrum, but in fact it is due to the *inefficiency* of spectrum management through government licensing. To improve the situation, spectrum auctions were held, with mixed results. Now such fragmentation of spectrum is harmful, because wireless LAN technologies that share a wide band enabled much more efficient communications than cellular telephones. Therefore it is better to open the spectrum as *commons*, instead of dividing it into narrow bands. Here I will propose new mechanism *spectrum buyouts* by which governments buy back spectrum from incumbents and then open it without license.

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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 Department of 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 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. It worked fairly well when there were many vacancies in the spectrum, but growing demand for wireless communications such as cellular telephones have led to a serious “spectrum shortage”.

This “shortage” is not a problem of natural resources, but instead is the result of inefficient radio administration. Government licensing is an exceptional mechanism in a market economy. It is usually justified by the claim that spectrum is a “scarce resource”, but economists have argued that the market mechanism serves as a means to allocate scarce resources efficiently (Coase 1959). In accordance with their recommendations, spectrum auctions started in the 1990s in the U.S.; these auctions were very successful. However, the auctions in Europe in 2000 for 3rd-generation (3-G) mobile telephones ended with tragic results.

On the other hand, Wireless Local Area Networks (WLAN) have been proliferating phenomenally, because WLAN realized much higher speed than cellular telephones by sharing a wide band. This “second coming of the Internet” (Werbach 2002) will change the wireless communications as fundamentally as the wired Internet changed the telephone networks. 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 license than to divide it as small pieces of private property. Thus it is necessary to change the regulatory frameworks inherited from the age when there was no transistor, no radar, and no television.

This article is organized as follows. In section 2, I will examine the assumption of spectrum auctions that spectrum is a scarce resource. Because the scarcity is made by inefficient technologies and old regulations, it can be overcome by new wireless technologies such as spread spectrum, cognitive radio, software-defined radio, and ultra-wide band. In section 3, a new radio administration system is proposed: the government buys back spectrum from incumbents and opens it without license. In the concluding section I will argue that this new regulatory framework will realize more efficient communication based on facility-based competition between wired and wireless communications.

2. Sharing the Spectrum

Success and Failure of Spectrum Auctions

When spectrum auctions for cellular telephones (PCS) began in the U.S. in 1994, FCC officials were skeptical, because these were the first large-scale auctions, conducted for 99 licenses across the U.S. simultaneously, managed by complicated mechanisms designed by economists, and implemented by computer networks. As it turned out, the PCS auctions were a dramatic success. The U.S. government earned more than 20 billion U.S. dollars in six PCS auctions through 1996, and the cellular-phone industry in the U.S. developed rapidly through the entrance of new operators and enhanced competition (Milgrom 1995).

European countries, which had been leading the world in mobile communications, embraced the auction to promote competition and regional integration through the entrance of international operators to many countries. When 3-G auctions were held in 2000, at the peak of the "wireless bubble", license fees skyrocketed far above their value; the fees amounted to more than 100 billion *euro* for all of Europe. After the bubble collapsed, however, 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 - some of them were even aborted – because of technical problems and financial difficulties.

Economists offer the excuse 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 be better than traditional licensing by paper examinations, known as "beauty contests", in promoting competition and in realizing the full value of spectrum (Klemperer-Binmore 2002). Yet it is undeniable that auctions induced the "winner's curse", which is not rational but regular behavior in financial markets. A more important problem is that spectrum auctions depend on the legacy systems of telephone switching. It is inefficient and expensive in the Internet age, as the tragedy of 3G evidenced.

Another problem is that very little spectrum is available for auctions. Relocation of spectrum is conducted by governments after the removal of incumbent operators by negotiation, which takes a long time. Because spectrum is allotted by licenses for specific use, even if a band is idle, nobody 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 6 GHz in the metropolitan area of Tokyo is not used. Rural areas must be even less efficient.

The FCC advocated a "market-oriented" approach to make spectrum a private property. Faulhaber-Farber (2002) recommends "big bang auctions" proposed by FCC officials in which all incumbents trade their spectrum as private property. It will make matters worse. If companies bought spectrum by high price, they would maximize the value of spectrum by monopolizing it and excluding others. Most importantly, their proposal is based on the old premise of broadcasting: spectrum is a scarce resource. It is pointless to "privatize" spectrum exclusively when WLAN makes it possible to share a wide band. In November 2002, however, the FCC has announced the "paradigm change" of spectrum policy to eliminate scarcity by multiplexing spectrum by frequency, place, and time (Powell 2002).

Is Spectrum a Scarce Resource?

Spectrum auctions have been justified by the assumptions that frequency is a scarce resource, that multiple users cannot use the same frequency due to interference, and that the government should license it. "But is the spectrum government's to sell in the first place?" Noam (1998: p. 771) asks, "Could the state sell off the right to the color red? To the frequency high A-flat?" 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, like amplitude and phase (Benkler 1999). In radio communications, transmitters modulate basebands into airwaves by mixing them with carriers of a specific frequency, and send the wave in radial form. Receivers identify radio signals by tuning to the desired frequency and filtering out other frequencies. Let the radio amplitude be A, the frequency w, the phase P, and the time t. Then, carrier f can be expressed by

$$f(t) = A \cos (wt+P).$$

The amplitude modulation (AM) system modulates basebands by A, and the frequency modulation (FM) system modulates them by the change of 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 is a result of the *confusion* of 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, the 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 signals (Watts), and N is the noise level (W/Hz). In analog radio, as it is impossible to distinguish signals in the same frequency, spectrum should be divided into small portions to avoid interference. And, since N is given physically, there was no other way than 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, $b2$,…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 now.

Although B is limited, it can be increased by multiplying by time and place, because different users can use the same band at different times in separate places or. Cellular telephones enhanced bandwidth using the same band repeatedly by small cells. Yet cellular systems 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. Because packets are identified individually, interference can be avoided even if multiple signals are carried in the same frequency. Spectrum is used efficiently by *statistical multiplexing* that levels traffic in a wide band. As average traffic usually represents a very small portion (less than ten per cent) of the maximum capacity, if 100 users share a bandwidth of 20 MHz, more than 2 MHz is available for each user on average. It is obviously more efficient than to allot 200 kHz for 100 users.

If B is large, it is not necessary to magnify S to increase C. Lowering power make it possible to multiply spectrum by establishing many stations. This *low power and wide band* system makes digital radio more efficient than traditional broadcasting types of systems. The problem is thus not the *scarcity* but the *efficiency* of spectrum usage. Therefore, bandwidth can be better utilized as *commons,* shared by many WLAN terminals. In economic terms, commons (a common resource) is defined as goods that are rival (marginal cost of use is high) but not excludable (externality is large). For example, traffic on the road is rival because traffic jams will happen if too many cars use it, but it is not efficient to sell one lane to each car and exclude others. It is sufficient to establish and to observe traffic rules to prevent traffic jams and accidents. This relies on the fact that cars can be identified one by one. Similarly, if a wide band can be shared by many users identifying signals packet by packet, this will be much more efficient than to divide spectrum into narrow bands and then sell them to individual users.

Packet Radio Technologies

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 developed by researchers at ARPANET, the predecessor of the Internet, in the 1970s. Since packet switching encapsulates data into many packets that can be mixed into one line, many users can send their data in a single line.

Therefore it is much cheaper than circuit switching of telephone systems in which every user occupies one line during communication.

In wireless communications, for we cannot specify the route the packets pass through, interference is inevitable. To avoid interference, a packet radio technology called *spread spectrum* has been widely adopted. In direct sequence spread spectrum (DSSS) adopted in WLAN, transmitters multiply original signals (baseband) by *pseudo-noise* (encryption key) and spread the resulted 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 filters[1]. 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.

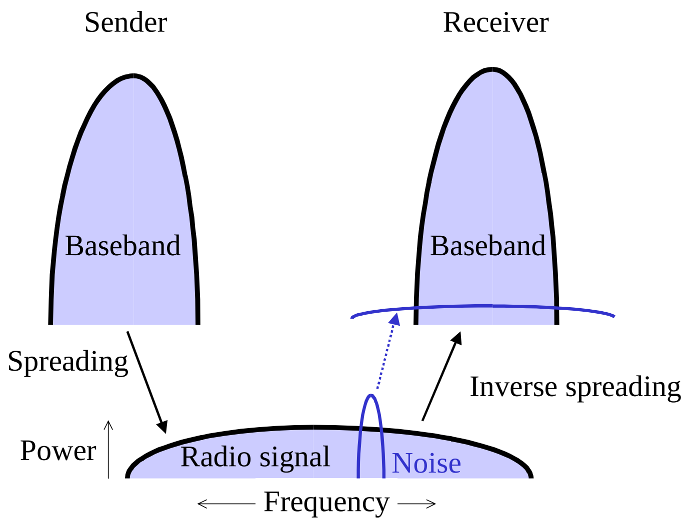

Figure 1: Spread Spectrum (DSSS)

Spread-spectrum technology was invented during World War II to prevent interceptions and electromagnetic jamming of military communications. It was 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 use without licenses by hospitals, factories, and so on, rather than for communication purposes.

WLAN technology, standardized in the IEEE 802.11 committee, initially attracted little attention,

[1] There are a few kinds of technologies referred to as spread-spectrum technologies. *Frequency hopping* changes transmission frequencies randomly in very short periods. CDMA and OFDM are sometimes included in spread-spectrum technologies in a broader sense. For more technical details, see Rappaport (2001) for example.

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 has grown to more than 30 million (2002 figure). It is because 802.11b realized up to 11 Mbps (3-4 Mbps on average) by sharing the wide ISM band (22 MHz per channel)[2]. In contrast, the speed of data communications in current 2-G mobile telephones is around 10 kbps due to the limit of bandwidth; for example, the PDC adopted in Japan allocates only 25 kHz (12.5 KHz in "half-rate" mode) per user.

If different signals collide, packets must be sent again, and throughput will fall. Therefore the WLAN band is separated into a number of channels, which are allocated to different base stations in the same area. If there are many channels, you can use the same band repeatedly by allotting a *microcell* (very small area) to each low-power station. As is shown in Figure 2, channel A can be used as many times as you divide an area. If the band is so wide as to allow division into many channels, users can coexist without interference by separating channels.

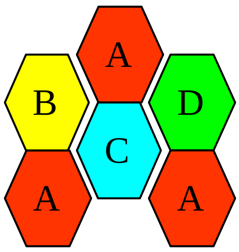

Figure 2: Microcells

For WLAN terminals can be used as base stations in *ad hoc* mode, completely distributed multi-hop networks which link terminals each other directly can be built by WLAN terminals[3]. In this regard, WLAN is even more revolutionary than wired Internet. TCP/IP is characterized by the 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, the routing and addressing are mostly done by Internet Service Providers (ISP) because networks are built on the telephone-type topology. WLAN has deconstructed the centralized architecture and enabled E2E structure physically. Such *ad hoc networks* have been built in 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 2.4-GHz band is unsatisfactory. Industrial dryers and medical equipment, for example, emit large power of airwaves and generate great interference to communications in the vicinity. Different types of communication terminals such as Bluetooth

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[2] WLAN transmits the same signal repeatedly using the spread code. As a result, the transmission efficiency per frequency of 801.11b stands at 11 Mbps/22 MHz = 0.5, similar to that of cellular telephones.
[3] Shepard (1995) analyzes the efficiency of multi-hop networks and designs its architecture. Such *wireless meshes* are being deployed using IEEE 802.11a.

interfere with WLAN. And the bandwidth, less than 100 MHz for 4 channels simultaneously, would not be sufficient when many operators build base stations in the same place.

The quality of the 5-GHz band is better than that of the 2.4-GHz band. 300 MHz is available within the Unlicensed National Information Infrastructure (U-NII) band at 5 GHz, and the E.U. is planning to open 580 MHz without license in 5-GHz band. 580 MHz can be divided into more than 25 channels in which up to 54 Mbps can be transmitted in each channel, in accordance with IEEE 802.11a[4]. If a channel were to be shared by more than ten people through statistical multiplexing, this would enable at least 250 people in a given area (with a radius of less than 100 meters) to use the full capacity (20 Mbps on average) of each channel simultaneously. This easily exceeds the usual demand for bandwidth in the edge (access) network.

However, there is no unlicensed outdoor band at 5 GHz in Japan; only 160 MHz is available by license and 100 MHz is available indoors without license. And the higher the frequency (i.e., the shorter the wavelength), the heavier the attenuation, and the more vulnerable communication becomes to obstacles. As 802.11b has become so popular and cheap, it may be enough for private use. It remains to be seen how large the market for 802.11a will be.

Overlay Usage

Although new technologies will enable more efficient use of spectrum, incumbents cannot be easily moved to other bands; especially military, marine, and air traffic radars are hard to move. These problems could be solved technically, as FCC Chairman Michael Powell (2002) said,

> 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 policy. How well could we use this resource if our policies fostered access in frequency, space and time?

For example, meteorological radars occupy 5.25-35 GHz, but they use the band less than a few minutes per hour. If other terminals can sense the radar waves and stop emission while radars are working, the same channel can be used by different users. Such adaptive technologies called *cognitive radio* are standardized and implemented into some 802.11a chipsets[5]. Dividing bandwidth by time,

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[4] 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.

[5] DFS (Dynamic Frequency Selection) and TPC (transmission power control) have been standardized in the 802.11h committee of the IEEE. The E.U. committee authorized DFS and TPC in the 5-GHz band.

these technologies enables WLAN base stations to coexist with other terminals in the same 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.

Of course it does not mean that regulation will be unnecessary. Even if there is a sufficient bandwidth, interference will occur between different physical signals, e.g., Bluetooth and 802.11b, within a channel. To coordinate various kinds of terminals to work cooperatively without interference, regulating channels, powers, frequencies, and modulations of different terminals will be the important part of radio administration. Traditional regulation has focused on transmitters, but it is necessary to regulate receivers to control interference among different types of terminals.

One way to prevent 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 argues that such physical regulation will impede innovations (Hazlett 2001), but it is not necessary. For example, if a channel is occupied by Bluetooth, WLAN can use another channel by sensing the carrier. If there is sufficient bandwidth, various physical layers can coexist in different channels.

Software-Defined Radio (SDR)[6] will make such adaptation even easier by changing physical layers by software, just like applications for PC. And *smart antennas*, combining various antenna elements with single processor, can change transmission/reception mode in response to communication environment. If a band is occupied by 802.11a, other terminals can change its modulation to 802.11a by SDR. To deploy SDR, regulatory reforms are necessary: the present Radio Act bans non-standardized communication devices by certification of equipment, but if communication is performed by software, it will make no sense to certify equipment.

In conventional wireless communications, the baseband is modulated by a carrier (sine curve). In contrast, the Ultra-Wide Band (UWB)[7] modulates the baseband by very short pulses (less than nanosecond). This technology makes high-speed transmission (up to 500 Mbps) possible 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, ordinary receivers ignore them as background noise. Therefore, advocates of UWB claim, the system will make overlay use possible over all bands without interference. In fact, 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

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[6] cf. SDR Forum, http://www.sdrforum.org. International Telecommunication Union (ITU) is planning to adopt SDR for so-called “4th-generation mobile communications”.

[7] cf. UWB Working Group, http://www.uwb.org

being, use of UWB will be limited to indoor communications.

These overlay technologies demand a change in regulatory thinking. Regulators have separated spectrum to eliminate interference completely, but since digital receivers are much more tolerant for interference than analog ones, there should be more flexible criteria, *interference temperature* in FCC's term, to enable different systems to coexist in a band. To enforce such rules, surveillance of bandwidth usage will be important. Today abuse of airwaves is regulated by licensing, but it is not effective because abuse is not thoroughly monitored and punishments are rarely enacted. Indeed it is most important to supply sufficient capacity to render abuse unnecessary and harmless, but surveillance and enforcement will have to be intensified, at least transitionally.

3. Spectrum Buyouts

Open Access

To cope with these fundamental changes in technologies, radio administration must be reconsidered from scratch. Noam (1998) proposes such reform referred to as *open access*, which allocates bandwidth packet by packet. His basic idea is simple: 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 freely. If demand exceeds capacity, a "clearing house" charges fees for wireless traffic, as at a tollbooth. But 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. But digital technologies such as spread spectrum have rendered this idea realistic.

If bandwidth were to be supplied to an extent greatly exceeding demand so as to become free goods, open access would be possible without fees. Even if bandwidth did not exceed demand, allocation of packets by spread spectrum would be more efficient than charging for packets. Packets in the wired Internet is stored and forwarded by routers without charge. Congestion leads to waiting, but it is not so serious problem in data communications and can be overcome by widening the bandwidth. Now we can get up to 108 Mbps by using two channels of 802.11a together. UWB has already realized 500 Mbps and its capacity will easily extend to more than 1 Gbps. Thus, if enough bandwidth is opened, technologies such as WLAN, SDR, and UWB will supply more capacity than demand by adding base stations; in other words, network capacity will scale to demand (Reed 2002).

In the transition period, licensed and unlicensed bands will coexist, but the former should be eliminated for communication and broadcasting in the long run. Radars and Global Positioning Systems (GPS) are for the moment exception, but can be substituted by UWB. Governments are advised to reacquire spectrum as licenses expire and then open it. Because incumbents can perform the same services with WLAN systems, governments have only to compensate incumbents for their costs of replacing legacy equipment with digital systems. The Ministry of Public Management, Home

Affairs, Posts and Telecommunications (MPHPT) of Japan announced a plan to enforce such ruling, but incumbents would resist this. It takes a long time to evict incumbents by negotiation; MPHPT estimates that it will take ten years to clear 4-GHz band.

Reverse Auctions

Therefore I propose a simple reform to speed up the process: the government buys back incumbents' spectrum by *reverse auctions* priced by private companies[8]. This would be easily implemented as an ordinary procurement process by which the lowest bidder sells products to the government. The procedure would be as follows:

1. The government announces a public notice to buy spectrum within a budget.
2. Bidders bid their prices to sell their spectrum. As long as multiple bidders remain, the government continues to lower the price.
3. If only one bidder remains, the auction is over. The government buys the lowest bidder's spectrum.
4. If enough of the budget remains, the government will buy from the second-lowest bidder, the third-lowest bidder, and so on.

Then governments will open the bands without license. Some people argued that such an auction would be extremely costly, but this would not be the case. In ordinary spectrum auction, *ascending English auction* is adopted. This is an efficient mechanism, under some standard assumptions,[9] so the equilibrium price will be equal to the net present value of *the most efficient use* of spectrum. In reverse auctions, on the contrary, *descend*ing *English auction* (also efficient mechanism) is adopted in which the lowest bidder wins. Therefore the equilibrium price will be equal to the opportunity cost of *the least efficient use* of spectrum.

Suppose there are n bidders, and a bidder i will bid if the offered price (unit price per Hz) p is higher than her opportunity cost, Q_i. Even though Q_i is her private information, it will be revealed by the auction, because she will lower her bid as long as $p > Q_i$ and will quit if $p < Q_i$. It is the least efficient user j that can bid the lowest price, so the equilibrium price is $p^* = Q_j$. Thus the buy-back prices will be much lower than selling prices of spectrum auctions. For example, an old wireless system referred to as MCA occupies 76 MHz in the UHF band – almost equal to the bandwidth of NTT DoCoMo, the leading wireless operator in Japan. However, as the number of MCA's subscribers fell below a half

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8 As a complementary mechanism to patent licensing, Kremer (1998) proposed a mechanism called the "patent buyout" in which the government buys patents from inventors through auctions and opens the patents free to everybody. This mechanism can supply incentives for inventors and does not prevent others from copying the invention.

9 If the valuation function satisfies the "average crossing condition", there exists an efficient *ex post* equilibrium in the English auction. For more details, see Krishna (2002) p.131.

million, it is losing money. Therefore the value of the MCA band would be less than 1 per cent that of DoCoMo with more than 40 million subscribers. If p is higher than MCA's opportunity cost, they will have an incentive to join the auction.

The opportunity cost of a bidder is the asset value of equipment plus the net present value (NPV) of the spectrum, which is determined by cash flow, terms of license, interest rates, and the asset value. Ignoring the interest rate, I denote the opportunity cost of the least efficient user $Q_j(x) = V_j(x) + a$, where V_j is the NPV, x is the term of expiration, and a is the asset price. Usually x is assumed to be infinite in most countries, so $V_j(x)$ is large even if the usage is inefficient. But MPHPT will rule that, if licenses expire, licensees must return their spectrum with compensation for remaining book value of their equipment. Because the term of license is five years and the term of amortization is six years, the average licensee's remaining value is very small. If governments can credibly threaten incumbents to enforce the return of spectrum, or at least if there is uncertainty as to the duration of licenses, this *spectrum buyout* would be more effective.

This can be shown by simple arithmetic: suppose $V_j(x)$ is subdivided into the cash flow of each term v_i. If the rule of returning is enforced in the second term, $Q_j(x) = v_j + a$. If it is enforced at the probability q every term, the discounted present value of the spectrum is

$$Q_j(x) = v_j + (1\text{-}q)v_j + (1\text{-}q)^2 v_j + \ldots (1\text{-}q)^x v_j + a.$$

If x approaches infinity, $Q_j = v_j/q + a$. Because the user j will bid as long as $p > v_j/q + a$, the equilibrium price will be

$$p^* = v_j/q + a.$$

If enforcement becomes more likely, q will approach 1, so the right side approaches $v_j + a$; one term profit plus the remaining book value of the least efficient user. On the other hand, if the band is privatized, as is planned in the U.S, q will approach zero and v_j will increase because this becomes profitable; therefore p^* will be much higher and buyout will be more difficult. That is, the privatization of spectrum makes it difficult to open it without license.

Bidders should be ranked by their unit price, but more continuous band should be evaluated at a discounted price. Further, the bandwidth might have to be measured in proportion to the logarithm of frequency, because extremely high frequencies are difficult to use. If the first-price bidder's bandwidth is less than the required width, the next bidders should be ranked by their unit price per Hz. For example, if the required bandwidth is 300 MHz and bidders A, B, C, and D bid the following prices,

A: 1 billion yen for 100 MHz (0-100)

B: 1.1 billion yen for 100 MHz (100-200)

C: 2 billion yen for 200 MHz (200-400)

D: 3.3 billion yen for 300 MHz (400-700)

If they are ranked by unit prices, A and C will be the winners. But if D's band is evaluated by a discount rate of 0.9, D will be the winner. The discount rate should be determined by the social cost of adjusting the split spectrum. Then B and C can "collude" to combine their band and make their band cheaper than D. Such behavior would complicate the auction, but this may not be serious if cognitive radio technology is employed. As a fragmented band can be used by overlay use, spectrum will be able to be valued simply by the sums of the bandwidths.

Financial and Technical Problems

Financing is the most difficult part of this auction because the fees would be much larger than in usual procurement. A simple solution is to finance the auction through general government accounts, in view of the fact that governments have made a great deal of money by selling spectrum to private parties in spectrum auctions. This would cure the problem of spectrum auctions raised by Noam (1998): auctions "tax" the communications industry and suppress investment. Through such repayment the government can revitalize wireless operators, who lost a great deal of money in the collapse of the bubble.

Another solution, probably better suited to Japan, would be to compensate the government's cost of reverse auctions through *spectrum usage fees*. It would be more neutral to public finance, and raising the fee would press incumbents to use bandwidth more efficiently or to sell out. 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, this will offer incentives for efficient bandwidth use[10]. As these financing methods are complementary, governments could use them in combination.

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 would be posed whether or not a public band should be sold; for example, the band used by air traffic control could not be sold by the market mechanism.

Spectrum buyouts may arouse controversy. Many people would oppose this reform as an unfair income transfer for incumbents who are underutilizing allocated bands. I argue that, following the Coase Theorem, it is much more efficient to "bribe" incumbents to return their idle spectrum than to

[10] Other considerations are in order. Power of the station and population coverage might have to be considered. Radars and military radio equipment should be charged by different tariff. It would be difficult to charge unlicensed terminals, so the fee would be charged to manufacturers, as a tax for unlicensed terminals.

negotiate with them for a long time. The opportunity cost of wasting bandwidth and time is much more expensive than the cost of buying the band back. In my scheme, the government does not have to negotiate with incumbents and politicians but only has to announce the reverse auction. Incumbents will bid and reveal their valuation of spectrum. Winners will give back their bands even if they are using them, because they can be reimbursed the costs of replacing their old stations and terminals to WLAN.

Probably the greatest risk lies in having the government conduct such a gigantic auction. It is possible that irrational behavior (such as that seen in the 3-G auctions) might lead to extreme behaviors and unexpected results. If sellers rushed to sell their bands as soon as possible, the price would be near zero, but such mistakes would be harmless for the government. If sellers were to collude to keep the bidding high, the government would have the option to quit. Rent seeking and collusion would be most effective because the stakes are so high. It is thus necessary to perform preliminary experiments before the buyout and to keep the procedure transparent. Further, governments should exit from spectrum management after all spectrum is opened.

In the long run, some people would argue, there would be no need for buyouts if the overlay use of spectrum were to be technically feasible. If every terminal could use all empty bands dynamically, it would make no sense to allocate spectrum at all. However, because cognitive radio and SDR is expensive and power consuming, it could take a long time to implement these technologies in small mobile terminals. Furthermore, as the coexistence of different modulation systems in the same band is difficult and risky, regulators are reluctant to admit overlay usage. Thus it would be the first best to communicate in a clean band without expensive technologies and complicated regulations. At least for the next ten years, opening the spectrum will be an important task for governments worldwide.

4. Conclusion

It is a historical lesson that 3G, for which many operators spent a great deal of money and in respect of which the ITU has been conducting negotiations for ten years, has failed and that WLAN, to which few companies and governments paid attention, has succeeded unexpectedly. The current framework of radio administration, inherited from the old broadcasting model of 75 years ago, is obsolete in the age of Internet. Huber (1997) argues that the monopoly of “the last one-mile” was made by the FCC. 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 90s, because the FCC wanted to allow AT&T to monopolize telephone lines and to allow 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 cheaper and would have become viable competitors of wired telephones.

WLAN made broadband communication much cheaper than optical fiber at the edges of networks, so wireless networks may dominate wired one in residential areas. Moreover, if metro networks are built of WLAN or other fixed wireless stations, wired and wireless networks will be combined in various ways, depending on the applicable costs and demands, because it does not matter which facilities carry them. If such *facility-based* competition between wired and wireless network is realized, the least costly network will pull down all facilities' costs. Then administration should not strictly regulate each individual network, but rather should create an environment in which newcomers can join the game at any time, thus encouraging competition in infrastructure.

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

These radical reforms cannot possibly be achieved by the MPHPT. For example, to move the bandwidths occupied by the Defense Agency and U.S. Armed Forces, MPHPT should negotiate with other departments and with the U.S. government. When wireless nodes are built densely and owned by users and resellers, the bottleneck of "last one hundred meters" will depend on the Rights of Way (ROW) that connect these nodes. Therefore spectrum management should be transferred to the Prime Minister's Cabinet Office, in conjunction with the management of other ROW such as dark fiber and dry copper. These ROW should be managed by the Cabinet so that users can choose the cheapest way in these alternatives ROW.

Licensing for broadcasting stations will make no sense when moving pictures are carried over wired/wireless Internet. If the channels are identified by IP addresses, it is not necessary to spare a specific band for broadcasting. Although industry advocates demand protection of their vested interests under the pretext of "culture" or "public concerns", such problems of content are not the matter of spectrum regulation. When the content is unbundled from facilities by IP, TV stations should be treated equally as newspapers and publishers. This will be good news for broadcasters. Abolishment of licensing will establish the freedom of speech and give broadcasters the opportunity to become full-fledged organs of public opinion without government permission.

References

Benkler, Y. (1999) "Overcoming Agoraphobia: Building the Commons of the Digitally Networked Environment", *Harvard Journal of Law and Technology* 287. http://www.law.nyu.edu/benklery/agoraphobia.pdf.

Coase, R.H. (1959) "The Federal Communications Commission", *The Journal of Law and Economics*, 2:10.

Faulhaber, G.R. and Farber, D. (2002) “Spectrum Management: Property Rights, Markets, and the Commons”, manuscript.

Hazlett, T. (2001) "The Wireless Craze, The Unlimited Bandwidth Myth, The Spectrum Auction Faux Pas, and the Punchline to Ronald Coase's "Big Joke", *Harvard Journal of Law & Technology*, Spring. http://www.aei.brookings.org/publications/working/working_01_02.pdf

Huber, P. (1997) *Law and Disorder in Cyberspace*, Oxford University Press.

Klemperer, P. and Binmore, K. (2002) “The Biggest Auction Ever: The Sale of the British 3G Telecom Licenses”, *Economic Journal*, 112:74-96.

Kremer, M. (1998) “Patent Buyouts” *Quarterly Journal of Economics*, 1137-67. http://papers.nber.org/papers/W6304

Krishna, V. (2002) *Auction Theory*, Academic Press.

Milgrom, P.(1995) “Auctioning the Radio Spectrum”, forthcoming as ch.1 of *Auction Theory for Privatization*, Cambridge University Press. http://www.market-design.com/files/milgrom-auctioning-the-radio-spectrum.pdf

Noam, E. (1998) "Spectrum Auctions: Yesterday's Heresy, Today's Orthodoxy, Tomorrow's Anachronism", *Journal of Law and Economics*, 41:765-790.

Powell, M.K.(2002) “Brodband Migration III: New Directions in Wireless Policy” http://www.fcc.gov/Speeches/Powell/2002/spmkp212.html

Rappaport, T.S. (2001) *Wireless Communications* (2nd edition), Prentice-Hall.

Reed, D.P. (2002) “How Wireless Networks Scale: the Illusion of Spectrum Scarcity”, http://www.its.bldrdoc.gov/meetings/art/art02/slides02/ree/ree_slides.pdf

Shepard, T. (1995) “Decentralized Channel Management in Scalable Multihop Spread-Spectrum Packet Radio Networks,” MIT dissertation, ftp://ftp.lcs.mit.edu/pub/lcs-pubs/tr.outbox/MIT-LCS-TR-670.ps.gz

Werbach, K. (2002) "Open Spectrum: The New Wireless Paradigm", http://werbach.com/docs/new_wireless_paradigm.htm