

Lecture 19- Pre-lecture reading

Unlicensed spectrum- New Products and Economics

The cellular systems we have looked at so far and the strategies we have considered have been strongly influenced by issues related to spectrum— its availability, its cost, and its limitations as a carrier of information. We have seen how the definition of rules for cellular licensing, and the licensing process itself, can result in years of delay. In this lecture, we will compare the world of “licensed” spectrum to the very different world of “unlicensed” spectrum, which has also had a dramatic impact on the public in the last quarter-century.

The differences between licensed and unlicensed spectrum are simple but significant. Licensed spectrum, by its very nature, gives specific people or organizations permission to use specific spectrum for specific purposes in specific places. A licensee like Verizon, for example, received exclusive permission to use the “Cellular B band” to provide cellular service, according to specific rules, in the New York metropolitan area. If two cellular operators in the same city had permission to use the same channels they would be unable to prevent interference. This would jeopardize a huge investment in base stations, so licensing may be expensive but it protects the provider as well. Cellular licenses are always exclusive.

Other rules are more situation-dependent. In the first round of cellular the FCC thought it was important to have nationwide access, so they included a specific set of rules that guaranteed any cell phone could operate in any system, nationwide. Note, however, that they considered the questions about how much spectrum to provide for cellular and how many systems would be allowed to compete in any location were most important. They took more than a decade to resolve those issues, but they let an industry committee write the rules for nationwide compatibility in a few months in 1980. And as we have noted, for 2G the FCC gave up on nationwide compatibility for CDMA and TDMA. As a result, certain cell phones could only operate in particular systems. One grid might have been more fully available in a given area, but it was up to the users to find that out and to subscribe to the system that would best met their needs. On the Other hand, in the world of 4G, smart phones tend to operate everywhere in the world.

The FCC granted a cellular license for a specific area (generally severally thousand square miles), and allowed cellular providers to choose base station locations and tower heights and power levels and channels for each of those million-dollar cells to maximize the capacity of their systems while preventing interference. They recognized that the service providers were best able to “design the grid” and to grow it over time (and that they had a strong incentive to prevent interference while maximizing capacity). The FCC did recognize that interference could result at system boundaries when two systems grew and their service areas met, but they assumed that service providers would solve these “local boundary problems”, since it was in their interest to do so. This has now happened many times, since cellular coverage is now “continuous” in much of the country.

In the older cases of broadcast radio and TV, the FCC directly controlled the details of each system (each tower) to assure good quality over a specific coverage area and to

prevent interference with other (rather distant) areas. It approved the height and power for every station, and even specified antenna patterns to prevent interference with a specific distant coverage area.

In contrast, unlicensed spectrum is a more recent (but important) experiment by the FCC. It has led to the creation of a variety of important products, from cordless phones and WiFi modems to meter readers and garage door openers, with a minimum of bureaucracy and delay. (Cordless phones use radio only to replace the “cord” between the handset and the base of an ordinary home phone, to make it portable around the house.) Anyone can buy a WiFi modem and install it in their home, and can buy a computer or a smart phone with WiFi capability, without getting a license. Multiple users can share the channels without harmful interference; mostly because power is limited (coverage areas are very small, compared to cellular systems or broadcast entertainment). Some unlicensed bands allow many different products to operate on the same channels. This allows many ideas to be tried, of which some may become billion-dollar markets while others disappear. In some cases, no compatibility standards are required. For example, cordless phones use a radio channel to communicate between a specific handset and base “pair”, both of which are controlled by the same person. It wouldn’t matter to users if every cordless phone in the world operated on its own unique standard. Of course, manufacturers prefer to produce a particular variety of phone, and if many manufacturers agree to a standard it becomes possible for chip manufacturers to design low cost and specialized chips that save the manufacturers money. Thus, compatibility may arise out of convenience and cost saving, without regulation.

In the 1990s, some entrepreneurs even tried providing low cost “public cordless systems” that would compete with cellular service. Users could carry their cordless phones away from home and use them with low cost “public bases” to make calls. In London, the public bases were scattered and hard to find, but in Tokyo a huge grid of short range cordless bases provided coverage everywhere in the city. These public cordless systems required detailed standards that would allow a home cordless handset to operate in a public cordless network. They were generally unsuccessful because 2G cell phones were becoming low cost pocket phones and the price of cellular service was becoming more attractive as well.

In contrast, WiFi was also invented using unlicensed spectrum with no compatibility rules, but manufacturers quickly discovered that a high level of protocol standardization was vital to their business. The home modem that connected to the Internet was bought separately from the computers or smart phones that would access the Internet through those modems, so common protocols were needed immediately. New generations of modems would get faster and faster, but had to work with older computers for at least a few years, so long-term compatibility was needed. As computers became smaller and more portable and smart phones emerged, users valued and demanded public access to a growing number of WiFi modems. From early cases like public WiFi at Starbucks, to WiFi at every hotel and office, to “hotspots” in cellular systems, WiFi access has become universal and standards have been essential to that universal acceptance. Manufacturers worked within standards groups to provide

those standards because compatibility was in their economic interest. The FCC could see that this was happening and it didn't have to be involved.

Ultimately, the logic is pretty simple. The FCC is responsible for determining what frequencies are used for what purposes in what locations. Within this process the FCC considers who is using the spectrum, and how, and what sort of problems might prevent the FCC's goals from being met, and what sort of rules might prevent those problems. Sometimes the FCC asks for public comment on these issues, and sometimes they call upon standards committees from organizations like the IEEE to recommend or even control those standards. In some cases their purposes can be achieved without standards, or without knowing who is using the equipment or where they are using it. In other cases, detailed standards are required.

Cordless phones and "citizen's band" radios: the story of two early and unlicensed products

In the late 1970s, a handful of channels were made available for cordless telephones and "citizen's band" (CB) radios. Both were very popular, but the cordless phone went on to become the primary home telephone used around the world while the CB radio is but a distant memory and an old movie. We will explore that story and see what lessons it has to offer.

In the late 1960s, a research group at Bell Labs in NJ demonstrated a prototype of a "cordless phone," a home telephone that used a radio channel instead of a "cord" to connect the telephone handset to its base. There were no channels authorized for cordless phones at the time, but the FCC did soon afterward authorize 10 channels near 50 MHz (just below TV channel 2) for such consumer products as cordless phones, baby monitors and garage door openers. The products using those channels were limited to very low power, but no licensing was required. The first cordless phones cost hundreds of dollars, but they sold well. The advertising typically showed them being used in the backyard, by someone at a barbeque, but people responded to the convenience of a cord-free phone that could be carried around the house. It became the preferred phone for millions, and eventually billions of users.

The 1970s was a period when the Bell monopoly in "rental" phones was broken, and millions of cheap cordless phones from Hong Kong and Taiwan were flooding the US market. Audio quality and performance in general were poor. By the late 1980s, however, many of these problems had been solved, and today, most people use cordless phones as their primary home phones.

The "CB" (Citizen's Band) radio craze was rather a different story. The FCC authorized 40 channels at 27 MHz for a device that was sort of a "walkie-talkie," with more power (several watts) and significantly more range than the cordless phones. It became popular with truckers, who used it to communicate with nearby truckers on the road (to report road problems and police radar traps, for example). A new language was created, with expressions like "pedal to the metal," (for "drive fast") and "10-4 good buddy" (for "signing off"). The CB craze was the basis for a popular movie called "Convoy", but in the days before cellular it was also considered to be an important safety device for motorists in trouble (this was before the cellphone). Motorists bought CB radios, both for fun (talking to nearby motorists) and for safety purposes.

Widespread use led to interference and poor performance. As a result, the CB craze collapsed in the early 1980s, while the cordless telephone market grew, seeming without limit. The reason for these different outcomes is related to the range of usage. Cordless phones operate within about 50-100 feet of their “base station” (i.e., within a 100-foot “cell”). CB needed hundreds of feet or even miles of range (we could say they operated within a 1-mile cell). If we assume that the capacity of their systems is based on channel reuse, with a cell size of 100 feet for Cordless and 5000 feet for CB, cordless has 2,500 times the channel reuse of CB, yet the two applications have about the same number of channels. As a result, when demand grew to millions of users, cordless continued to work well, but CB experienced massive interference and lost its usefulness.

The tiny cordless “cell”



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4

WiFi

Based on the success of cordless phones and other novel products, the FCC embarked on a massive increase in “unlicensed” spectrum. This began with the so-called “ISM” bands at 900 MHz and 2.5 GHz. ISM means “Industrial, Scientific and Medical” but these bands were not used for communications. They were essentially “noise bands,” set aside for high powered radio-heating devices like microwave ovens that could cause radio interference. In an industrial setting this might be a huge microwave oven used to dry lumber. In a medical setting, it might be a diathermy machine, used to warm human organs. These heating devices produce “radio noise”, and certain frequency bands were set aside for this purpose, to prevent interference with communications channels that are received at very low power levels (millionths of a watt). These large noise sources were often in unpopulated areas, and in general they were well shielded. Microwave ovens in the home, for example, use high levels of radio power to heat food, but emit almost no radio energy outside the device. When the FCC ran tests, they found almost no noise in these bands, and they began to allow them to be used for unlicensed communication devices, on an “as possible” basis. The FCC decided that the unlicensed communication devices were generally inexpensive and not used for critical communications (and they didn’t require an expensive “infrastructure” like a

cellular system. If they didn't work in a given location, they could be returned to the store and replaced with a device on a different frequency (or simply not used). Interference from ISM devices has turned out to be rare and to affect only a few locations. For an anytime/anywhere service like cellular, such noisy areas would be a problem, but for devices like cordless phones they simply require us to buy a product that uses a different frequency, or give up on using the product.

The most popular of these ISM bands for consumer communication devices are 902-928 MHz (26 MHz of bandwidth), and 2.400-2.483 GHz (83 MHz of bandwidth). These amounts of spectrum are enough for three nationwide cellular systems, and yet they are free for anyone to use for a variety of products. If this amount of spectrum, in those bands, had been auctioned nationwide for cellular systems, it would have raised \$40-\$200 billion.

Indeed, of all the unlicensed services, WiFi has been the most important. As discussed, it is now common in the home, extending broadband Internet access to laptop computers (or to PCs) without the need to run cables around the home). More importantly, it is increasingly available in public places, such as restaurants, hotels, businesses and schools. Because of the high bit rates that we need for Internet access (which causes a problem for smart phones in cellular systems), the channels for WiFi must be very wide (up to 20 MHz per channel), but the FCC has made a huge amount of spectrum available. WiFi became so popular and important that the FCC followed up the multi-purpose ISM bands with an even larger spectrum allocation specifically for WiFi (300 MHz of bandwidth at 5 GHz frequencies). It was called the "Unlicensed National Information Infrastructure" (U-NII) band. Moreover WiFi transmission (like cordless telephone transmission) is over short distances, so channels can be reused a few hundred feet away. The result of the huge spectrum allocation and the tiny "cells" is that WiFi has the "unlimited Internet access", that cellular providers (with less spectrum and larger cells) have been unable to create for 3G and 4G. (It remains to be seen if huge allocations at 5G "millimeter wave" frequencies will change this situation.) WiFi isn't available "anytime, anywhere" like cellular but it offers high speed and huge capacity for a low cost. "Anytime/anywhere" coverage was important for a voice conversation but less so for data. Studies show that smart phones download most of their data through WiFi, because it is faster and cheaper.

Bandwidth and power—the issue of range

Whether we are using them for 3G or WiFi, however, wider channels require more power. The amount of power we need to send a radio channel some required distance depends not only on the distance, but on the bandwidth as well. For a given distance, twice the bandwidth requires twice the power. This is because the radio noise that limits range also depends on bandwidth, so wider channels therefore have more noise to overcome. If we compare a 20 MHz WiFi channel and a 30 KHz cellular voice channel being transmitted to receivers an equal distance away, the WiFi channel therefore needs 666 times more power. If a 30 KHz cellular voice channel requires a tenth of a watt for a 1-mile range, a 20 MHz WiFi channel would require 66 watts for the same range. This amount of power would drain the battery of a cell phone or laptop in seconds. Moreover, long-range applications would prevent the reuse of a WiFi channel within hundreds of feet, as is possible today. Reuse would require miles of separation,

dramatically reducing the capacity of those U-NII frequency bands. For reasons related to battery and capacity, WiFi devices have a range similar to that of a cordless phone (a few hundred feet).

3G and WiFi—two different approaches to the same problem

Thus, we see that cellular and WiFi, two tremendously successful applications, are polar extremes in terms of spectrum regulation. Cellular was a triumph of technology, standards and regulation (and expensive spectrum). WiFi was a triumph of *laissez faire* regulation, innovation and market competition (and free spectrum).

Both are now trying to provide high-speed Internet access. 3G/4G cellular is providing access anytime/anywhere, but is using million dollar cells and charging about 1.5 cents per MB. We suspect that they should be charging more to make the desired 10% return on investment, but are unable to because of competitive forces. Further increases in capacity will be quite expensive as we have discussed, but users are paying less each year. If a typical cellular system has 100 MHz of spectrum available for data today, the average cell has perhaps 7 MHz of capacity. If 3G/4G technology can improve download by 5x (from the 1.5 bits/sec/Hz that was provided by 2G channels to about 7.5 bits/sec/Hz available with 4G technology, the download capability of a million-dollar cell containing 1000 users is only about $7 \text{ MHz} \times 1.5 \times 5 = 50 \text{ Mbps}$.

The \$1.5M 3G/4G Cell vs. the \$100 WiFi Modem

3G/4G Cell	802.11 WiFi modem
Investment: \$1.5M+spectrum)	Investment: \$100 (free spectrum)
Speed: 50 Mbps (100 MHz for system=50 Mbps for a base station)*	Speed: 1.5-3 bits/sec/Hz using 20 MHz =30-60 Mbps
Investment /Mbps: = \$30,000	Investment /Mbps: = \$1.6-\$3.3**

**The investment to create 1 Mbps downloads is
10,000 times cheaper for WiFi !!**

*With about 1/14th of the spectrum allocation per cell and 7.5 bits/sec/Hz 100 MHz yields 50 MHz/cell. WiFi can use the whole 20 MHz in every location.

** Many WiFi devices advertise much higher rates (in particular when the transmission path is short).

Can we use this low cost device to increase cellular capacity?

A WiFi modem is cheap (say \$100 to be conservative). That is cheap enough to be installed in every home and offered to customers without charge by many businesses (the only additional cost is a high speed connection to the Internet). The portable WiFi radios are cheap enough to be provided in every computer and smartphone. Hundreds of MHz of free WiFi spectrum has been made available by the FCC. The typical \$100

WiFi modem can transmit more than 100 Mbps and can be used within a range of about 300 feet. A WiFi modem costing a hundred dollars has about the same capacity as a 4G cell costing about 1.5 million dollars (about $.0001 \times$ the 4G cost per MB)!

When WiFi is available, downloading a movie is essentially free, while downloading a movie from a cellular system at 1.5 cents per MB would cost about \$15 (depending on quality). Having finally noticed this possibility and being increasingly unable to meet the demand with their 3G/4G cellular systems, cellular operators are installing WiFi “hotspots” and encouraging their customers to use them. Sadly, from a system design point-of view, these hotspots are an alternative to their cellular systems rather than a smoothly operating part of their cellular systems. They are inconvenient for the customer and since the hotspots are free they are not a source of revenue for the operators.

It seems clear that we need to explore this possibility (using something like WiFi to solve the 3G/4G capacity problem) because the economics are so compelling. On the other hand, we want to have a smoothly operating system in which the customer is not required to hunt for hotspots (or even know if the download is coming from a hotspot), and where more traffic is handled with WiFi, and where the customer pays for the “WiFi” download. In short, we want a system where the capacity is much higher and the costs are much lower, and the service is easy to use, and the operator can make a good profit. WiFi offloading in cellular systems has thus emerged as staple of modern heterogeneous cellular system design.

Bluetooth

Bluetooth is a low power unlicensed wireless technology that uses the 2.4 GHz ISM spectrum band (2400 to 2483.5 MHz), which enables a good balance between range and throughput. In addition, the 2.4 GHz band is available worldwide, making it a true standard for low-power wireless connectivity. It initially emerged as a competitor for WiFi but given the disparity in transmit power levels and range (WiFi has much transmit power and consequently range), it evolved into a niche technology for peripheral devices that are short range and low power (e.g. headsets, etc.)