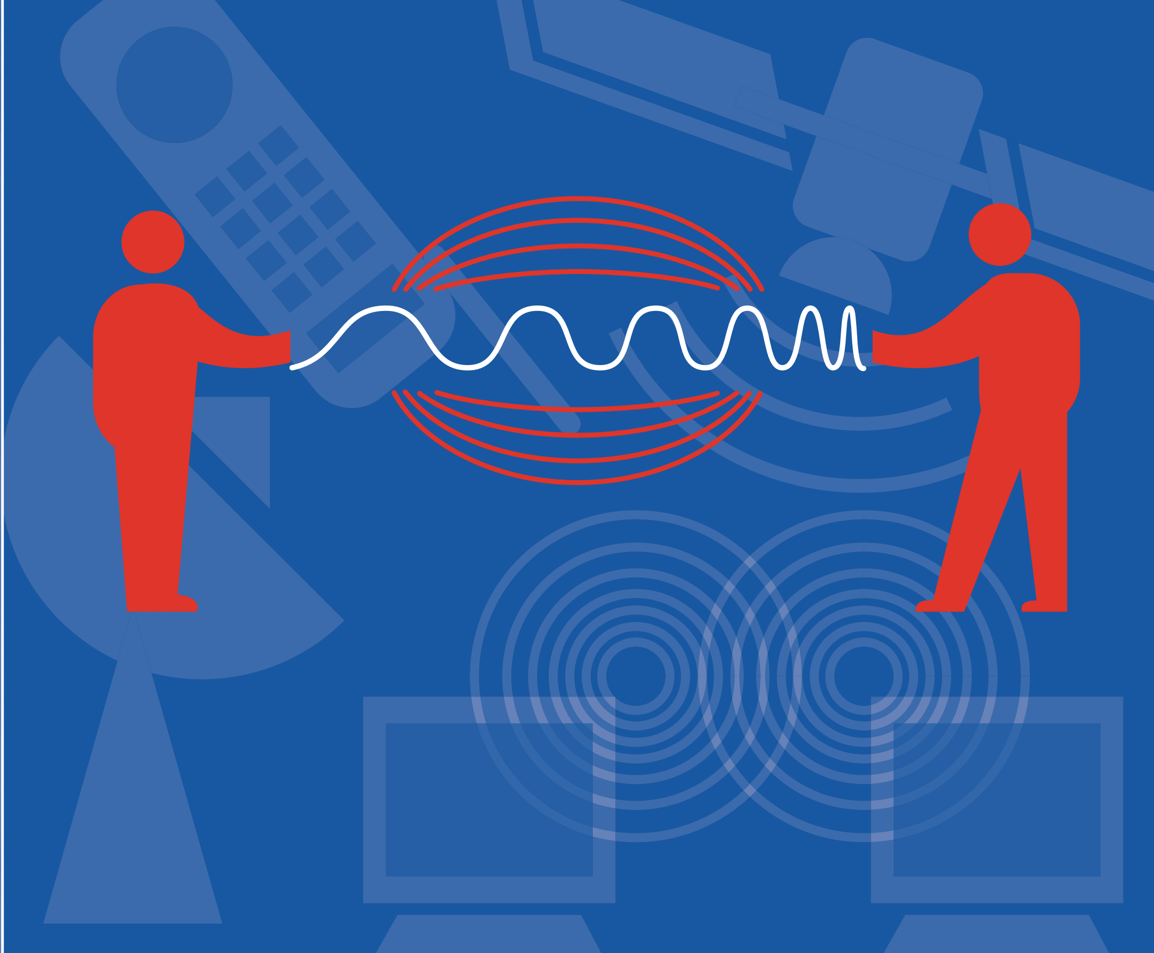

# Radio Revolution

## The Coming Age of Unlicensed Wireless

By Kevin Werbach

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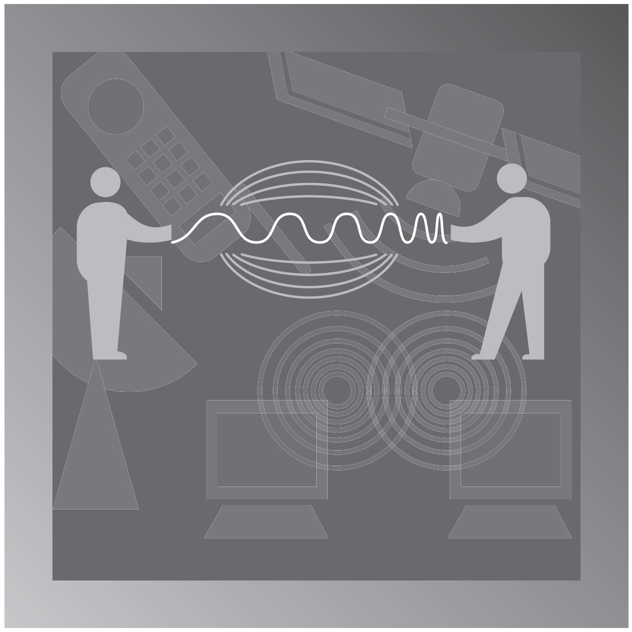

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## Author

Kevin Werbach is the founder of the Supernova Group, a technology analysis and consulting firm. He advises organizations on the strategic and legal implications of emerging trends in communications, digital media and software. As Counsel for New Technology Policy at the Federal Communications Commission from 1994 to 1998, he helped develop the United States Government's e-commerce policy, shaped the FCC's approach to Internet issues, and authored *Digital Tornado*, a seminal analysis of the Internet's impact on telecommunications policy. He has also served as editor of the influential publication *Release 1.0*. His writing has appeared in *Harvard Business Review*, *Fortune*, *Wired*, *Harvard Law Review*, *Slate*, *Red Herring*, and *Business 2.0*, among other publications, and he appears frequently as a commentator in print and broadcast media.

*Radio Revolution* is the second publication Kevin Werbach has authored for the New America Foundation. His Working Paper, "Open Spectrum: The New Wireless Paradigm" was published in October of 2002 and is available at www.spectrumpolicy.org.

NEW AMERICA FOUNDATION

The New America Foundation is a non-partisan, non-profit, public policy institute in Washington, D.C. Relying on a venture capital approach, the Foundation invests in outstanding individuals and ideas that transcend the conventional political debate. Through its Fellowship Program and Strategic Initiatives, New America sponsors a wide range of research, published writing, conferences, and events. New America's Spectrum Policy Program advocates a more fair, efficient, and democratic allocation of the public airwaves. Many additional publications on this topic, including New America's *Citizen's Guide to the Airwaves*, can be found at www.spectrumpolicy.org.

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## Contributors

Nigel Holmes, who is principal of Explanation Graphics, www.nigelholmes.com, created four original illustrations for this report; two of his illustrations from the *Citizen's Guide to the Airwaves* are reprinted here as well. In addition, Donald Norwood Design created the layout and design of the report.

Matt Barranca, a Program Associate at the New America Foundation, wrote the WISP profile sidebars. The Acoustic Analogy sidebar was adapted from New America's forthcoming "The Cartoon Guide to Government Spectrum Policy: What if the Government Regulated the Acoustic Spectrum the Way it Regulates the Electromagnetic Spectrum?" by J.H. Snider. Hannah Fischer led the copy-editing and production efforts and was assisted by New America's Michael Calabrese, J.H. Snider, Matt Barranca, and Max Vilimpoc. Spectrum experts Dewayne Hendricks, Anthony Townsend, Patrick Leary, and Mark McHenry provided valuable feedback for some of the technical content of this report.

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# Contents

# Introduction

We stand at the threshold of a wireless paradigm shift. New technologies promise to replace scarcity with abundance, dumb terminals with smart radios able to adapt to their surroundings, and government-defined licenses with flexible sharing of the airwaves. Early examples suggest that such novel approaches can provide affordable broadband connections to a wide range of users.

These are not just incremental advances. The fundamental assumptions governing radio communication since its inception no longer hold. The static wireless paradigm is giving way to dynamic approaches based on cooperating systems of intelligent devices. It is time for policy-makers to consider how regulation should change in response.

The radio revolution is the single greatest communications policy issue of the coming decade, and perhaps the coming century. The economics of entire industries could be transformed. Every significant public policy challenge could be implicated: competition; innovation; investment; diversity of programming; job creation; equality of access; coverage for rural and underserved areas; and promotion of education, health care, local communities, public safety, and national security. Yet the benefits of the paradigm shift are not guaranteed. Exploiting the radio revolution will require creativity and risk-taking by both the private and public sectors. At every step, there will be choices between preserving the status quo and unleashing the forces of change. The right answers will seem obvious only in hindsight.

The only way to appreciate the opportunity before us is to comprehend the fundamentals of radio communication, and the profound ways they are changing. For all its significance to daily life and economic activity, wireless technology is poorly understood. This paper seeks to explain the established "static" wireless paradigm, the emerging "dynamic" alternative, and the implications of the coming revolution.

### Wireless Fundamentals

Wireless. The very word belies its significance. Wireless communication is defined by what it is not, like the horseless carriage or the fat-free muffin.[1] Yet the real value of a satellite television broadcast, a WiFi connection to a laptop, or a mobile phone call from your car to your mother isn't the absence of dangling wires. Mobility, portability, ubiquity, and affordability are all enhanced when signals pass through the air rather than through strands of copper or optical fiber. Talking on a mobile phone is different, and in many ways better, than using a landline connection. If it weren't, more than one billion people wouldn't have signed up for mobile phone service, despite the alternative of a century-old wired phone industry.

> **"The existing legal and policy framework for spectrum management has not kept pace with the dramatic changes in technology and spectrum use."**
>
> – WHITE HOUSE MEMO TO FEDERAL AGENCIES, JUNE 2003

Wireless communication is the foundation of industries generating hundreds of billions of dollars in revenue and selling hundreds of millions of devices every year. It is crucial to how we communicate, work, learn, entertain ourselves, access health care, and protect our nation. It is also heavily regulated everywhere in the world. Governments today face critical decisions concerning the future of wireless communication. Is there a "spectrum shortage," and if so, how can it be alleviated? Should more spectrum be set aside for "unlicensed" uses? Should spectrum licensees be given property rights to resell or otherwise control their spectrum more thoroughly? Do we need different rules to deal with interference? Should new "open spectrum" technologies be allowed to "underlay" or "interweave" with existing licensed services? Can government, military, and public safety spectrum be managed more effectively? These questions will shape the communications environment of the 21st century.

Unfortunately, wireless communication remains deeply misunderstood and under-appreciated. Basic concepts like spectrum and interference suffer from widespread misconceptions. Technological developments of recent decades have not penetrated the public consciousness, even as the fruits of these developments become part of daily life for hundreds of millions of people. The great paradigm shift from static to dynamic wireless communication has barely registered in business and policy circles. Just as economists know that information technology must have a role in productivity growth but have trouble finding it in their statistics, the wireless industry is experiencing a transformation that even many of its own experts do not fully appreciate.

### Believe in Magic

In the words of legendary science fiction author Arthur C. Clarke, "any sufficiently advanced technology is indistinguishable from magic."[2] Wireless communication is a form of magic. Words and pictures fly over invisible pathways with near instantaneous speed. We control devices at a distance, with no apparent means of connection. Scores of signals, carrying many different types of messages, traverse the air simultaneously. A time traveler from the Middle Ages would surely see divine intervention – or witchcraft – all around.

Yet for us, wireless communication is a familiar form of magic. It drives the radios we have had in our homes since our grandparents' day, the mobile phones that many of us use to communicate, the televisions we watch an average of seven hours each day, the remote controls that start those TVs, and even the throwaway boxes that open our garage doors. This familiarity breeds contentment. We think we understand how wireless communication works. We don't.

Our intuitions about wireless, by and large, are mistaken. They are based on outdated technologies and inaccurate analogies. If we hope to move forward in exploitation of the airwaves, we must take a step back. We must understand wireless communication for what it really is. And then we must re-evaluate our assumptions about what it could be. This paper presents a set of analogies to help explain the basic physics of radio, and the radical shift that emerging technologies represent. The strangeness of wireless communication vanishes when we see that it is no different than acoustic communication, otherwise known as speech.

Paradigm shifts are both difficult and essential for progress.[3] Copernicus and Galileo showed that the Earth revolves around the sun, contrary to the perceived wisdom of the day. Eventually their view prevailed, launching an age of extraordinary discovery. In the last century, quantum mechanics overthrew the long-established Newtonian worldview. A hundred years of subsequent physics experiments confirm that our universe contains no such thing as solid matter or definite cause and effect. These ideas are so weird that most of us simply refuse to accept them. We live in the familiar classical environment of our commonsense awareness. At the same time, we blithely accept technologies such as the integrated circuit and the laser, which could not exist without the scientific fruits of the alien quantum world.

The new dynamic paradigm reveals that wireless communication is more magical than we assume. More than one service can occupy the "same" spectrum, in the same place, at the same time. The frequencies that now carry one signal could someday carry thousands...or billions. There could be as many video broadcasters as today there are mobile phone subscribers. Government could cease the frustrating and inefficient task of parceling out spectrum, and instead allow users to share the airwaves without licensing. Broadband Internet connections could be far more ubiquitous and affordable. Innovation could proceed by leaps and bounds rather than a hesitant, drawn-out shuffle.

Appreciating the potential of wireless technology has always been difficult. When Guglielmo Marconi invented the radio, he envisioned it being used for person-to-person communication, not one-to-many broadcasting. Alexander Graham Bell invented the telephone while developing tools to help deaf people, and thought it would be used to broadcast music concerts. If these scientific giants could be so wrong about their own creations, might we not be wrong in our assumptions about wireless?

This is not mere idle speculation. Decisions made in the 1920s to zone spectrum by service and to assign exclusive licenses to users have defined the contours of wireless communication ever since. A huge market sits atop the existing regulatory framework, which in turn sits atop conceptual and technical assumptions. Alter those assumptions, and we can alter the framework. Alter the framework, and the market could become something far greater than it is today. Maintain the status quo or worse, and the opposite might result.

**A huge market sits atop the existing regulatory framework, which in turn sits atop conceptual and technical assumptions. Alter those assumptions, and we can alter the framework. Alter the framework, and the market could become something far greater than it is today.**

"Unlicensed" wireless communications systems are the manifestation of the dramatic change from the static to the dynamic paradigm. The word unlicensed, like the word wireless, emphasizes what is missing rather than the true significance of the concept. What is so extraordinary about unlicensed devices is what they can do, and the incentives they create for innovation and growth. Already, wireless Internet service providers (WISPs) and non-profit community networks are using unlicensed systems to deliver broadband connectivity where it was otherwise unavailable. Several are profiled in sidebars throughout this paper. In the future, unlicensed systems may support more significant new communications scenarios, which are detailed in the last section.

# Wireless Fundamentals

## Basic Concepts

*The Secret Life of Radio Waves*

A wireless communications system involves one or more transmitters and one or more receivers. There is nothing in the middle. Transmitters radiate, and receivers receive, within a certain range of frequencies known as the radio frequency spectrum. However, these are properties of the equipment, not some distinct medium the signals pass through. By the same token, what governments regulate are the capabilities of transmitters, and to a lesser extent receivers, rather than the spectrum itself.

Radio waves are a form of electromagnetic radiation, like lasers or lightning bolts. "Radio frequency" signals oscillate at frequencies between about 3 kilohertz (kHz) and 100 gigahertz (GHz). Their propagation characteristics are well-understood by physicists. In free space, radio waves can propagate indefinitely, with declining power over distance, unless dissipated by obstacles such as walls or the Earth's atmosphere. Their susceptibility to such obstacles depends on the frequency, bandwidth, and power of the transmission.

The point of this physics lesson is that most of the topics spectrum policy concentrates on, such as "interference" and "spectrum," are value judgments based on our uses of wireless communication. Radio waves do not bounce off one another, or cancel each other out. When two or more signals share the same space at the same time, it can be difficult for receivers to distinguish them, just as the human ear has difficulty focusing on two simultaneous sound sources. In practical terms, the TV picture gets fuzzy or the mobile phone drops a call (see Figure 1).

We call this interference. The effect is identical to what happens when you try to listen to a radio broadcast and a CD at the same time. The sounds still reach your ear, but you may have trouble sorting them out.

## The Acoustic Analogy*

The sound waves used in ordinary speech are analogous to the radio waves used in wireless communication. Both are radiation employed to send messages between transmitters and receivers. The acoustic spectrum involves lower frequencies than the radio frequency spectrum, but this has no effect on the physics involved. Our ears are tuned to pick up acoustic waves, just as radio receivers are tuned to receive radio waves. And our vocal chords produce acoustic waves, just as radio transmitters produce radio waves.

The major difference between acoustic and radio communication is that humans and other animals have evolved exquisitely sophisticated tools for encoding and interpreting speech. Our vocal apparatus and ears are magnificently precise yet highly adaptive. Standing behind them is the human brain, the most powerful computing device ever created. Our brains can pick out sound waves from the surrounding background noise and quickly interpret them with phenomenal accuracy. We take all this for granted, because speech is so basic to our very existence.

Radios have historically been far less intelligent than the human systems for voice communication. In particular, radio receivers are simple devices that tune to a specific frequency. Because radio devices haven't been smart enough to distinguish among overlapping signals, government regulates the electromagnetic spectrum to minimize interference in ways that would be inconceivable for acoustic communications.

Dynamic wireless systems are closing the gap between acoustic and radio communication. Newer devices employ sophisticated computer processing to encode and decode wireless signals. They also employ cooperative techniques and adaptive mechanisms that bring to mind the social behavior of human beings. The more wireless systems can discriminate the way the human ear does, the less regulation is needed to avoid confusion.

Imagine a crowd of people at a football stadium.[4] Though thousands of them are talking at the same time, many of them screaming at the top of their lungs, there is no need for regulation to ensure effective communication. There isn't even a need for rules to ensure that the public address system can be heard over the thousands of independent voices. A private regime of property rights to speak in the stadium is just as superfluous as a government licensing system.

Our mouths and ears are sufficiently adaptive to separate signals from noise when both parties are trying to communicate. This despite the fact that the acoustic spectrum is far narrower than the radio spectrum, and our biological senses are much less precise than today's digital communications devices. When transmitters and receivers are as smart as humans, the best rules to prevent interference are no rules at all.


** Adapted from J. H. Snider, "The Cartoon Guide to Federal Spectrum Policy: What if the Government Regulated the Acoustic Spectrum the Way it Regulates the Electromagnetic Spectrum," New America Foundation, Forthcoming.*

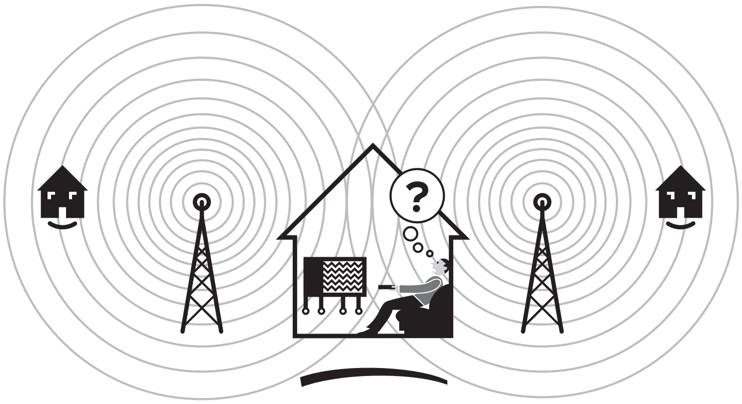

FIGURE 1 – NOTIONS OF INTERFERENCE: When two or more signals share the same space at the same time, some receivers have difficulty distinguishing them and interference can result.

Interference among wireless systems sounds similar to what happens when a landline telephone call generates an "all circuits are busy" message. In reality, the two situations are quite different. In the landline case, the connection literally stops at an overloaded phone company switch. The call reaches that point and goes no farther. In wireless, the signal keeps on going. Only the useful information is lost, not the actual radio waves.

This seemingly arcane distinction is critical. For the blocked phone switch, nothing the caller or the called party can do makes any difference. The electrical or optical signal terminates in the middle of the network. In the wireless case, the signal gets to its destination but cannot be understood. If the transmitter or receiver were smarter, the same signal might be intelligible. Better technology at the endpoints can reconstruct useless noise back into useful information.

In other words, change the communications devices or the regulatory environment, and you change the capacity of the system. Therefore, any statement about interference or spectrum scarcity assumes a particular set of technical and regulatory conditions.

### *Capacity*

As the previous section demonstrates, interference matters because of its implications for capacity. Capacity is the essential metric for wireless communications.[5] Only so many radio stations, TV channels, phone conversations, or Internet connections can successfully operate at once. However, this number is not fixed. Marconi, the inventor of radio, originally thought that only one signal could be transmitted in a given geographic area, because other radios would interfere with it. He later developed a technique for adding capacity based on the principle that tuning forks can be made to vibrate at the same frequency across distances. Using this model, one radio signal can be associated with a carrier wave of a particular frequency, and additional radios on different frequencies can operate in the same area.

In effect, Marconi figured out how to use frequency to multiplex radio signals. Each station got its own unique frequency: hence the familiar radio call numbers like 102.7, 88.5, or 97.1. Because frequency division was the only viable means of operating multiple simultaneous transmitters when radio developed as a commercial service, it became the basis for government radio policy. Regulating radio meant regulating frequencies, by parceling out the usable spectrum to licensees and service categories. And so it remains today. We don't use the same numbers to identify TV channels or mobile phone networks, but these systems are assigned frequencies in a similar way.

Frequency division, however, is not the only means of multiplexing radio signals.[6] Another possibility is time. The government could have allowed each broadcaster to transmit only during a certain hour of the day, for example. Frequency division was obviously a better solution, both on capacity and practical grounds. In other cases, though, time division makes sense. Some mobile phone systems, for example, chop up their licensed frequencies into split-second time slots, and interweave digital communications signals among them.[7] In addition to time and frequency, spatial multiplexing can be done based on the three-dimensional relative location of the transmitter and the angle at which a signal hits an antenna. But again, spectrum regulation talks primarily about frequencies.

These multiplexing techniques, along with improvements in tuners and signal processors, are the reason the radio spectrum can now accommodate services such as television, mobile telephony, satellite radio, and wireless Internet connectivity where once there was only radio. Instead of the original two mobile phone competitors in each market, for example, we now have six national carriers in the U.S. The "usable" spectrum of frequencies is five thousand times wider than it was in 1927, when the Radio Act was passed.

Have we now exhausted the capacity of the spectrum? Yes and no. If we only focus on frequencies, virtually every useful band has been allocated to one use or another. Any new service, such as digital television or third-generation (3G) mobile phone networks, requires that incumbents be "cleared" out of existing bands to make room. On the other hand, if we actually sample the spectrum to test for signals, we get a very different picture. Most of the spectrum is empty in most places most of the time. There may be a rectangle filled in on a frequency chart, but there is no detectable signal actually using that frequency[8] (see Figure 2).

Many advances in wireless technology make use of excess capacity that shows up in the real world but not on the official chart. Because the frequency chart represents official boundaries, however, these

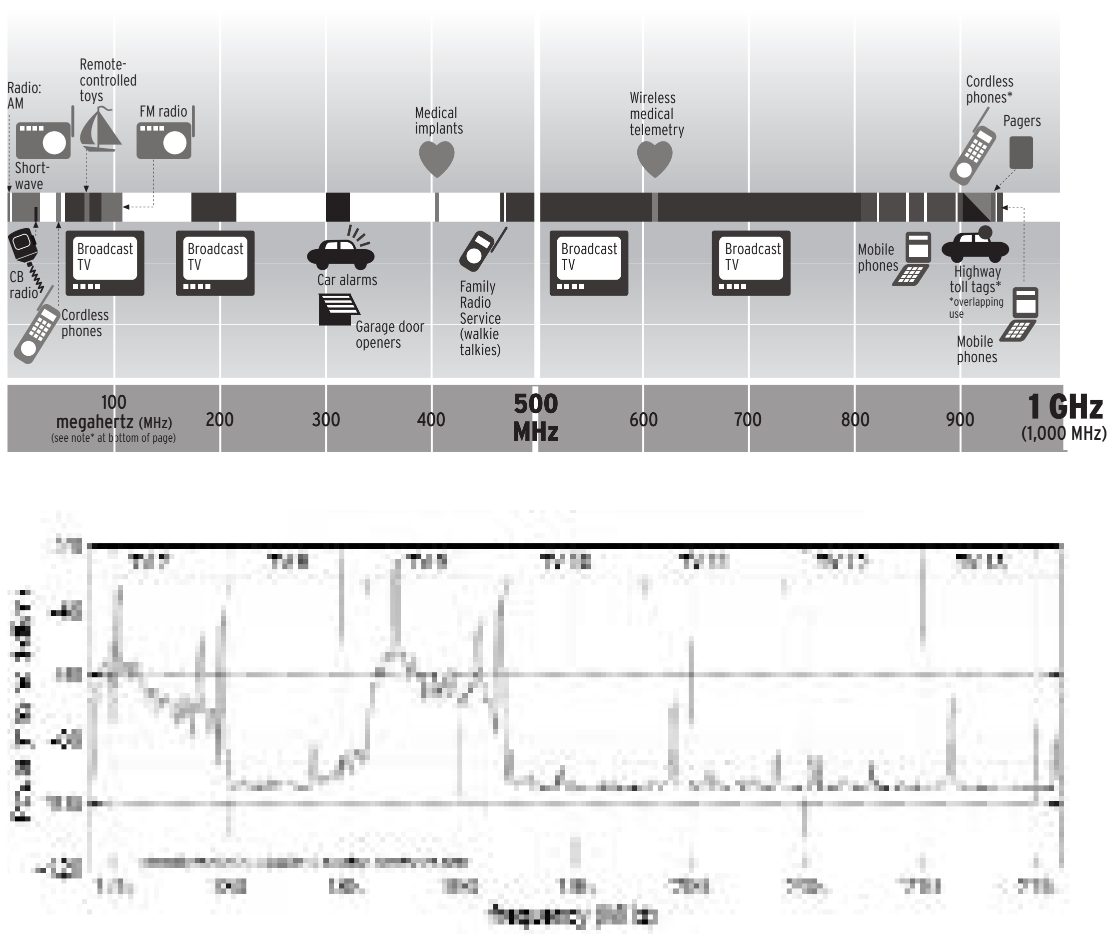


**FIGURE 2 – TWO VIEWS OF CAPACITY:** The top image, from *The Citizen's Guide to the Airwaves*, depicts allocations on the low-frequency, broadcast bands. The bottom image represents the actual usage of the most active channels of the broadcast bands, as recorded in New America Foundation's spectrum usage measurements taken during peak hours in the highly populated, Dupont Circle area of Washington, DC.

technologies can only be used in certain frequency bands. Between the view of spectrum as filled up and the reality of its emptiness lies an almost incalculable opportunity.

*Architecture*

Even the gaggle of capacity-enhancing techniques listed earlier is incomplete. Capacity depends not just on the way a device distinguishes one signal from another, but on the design or "architecture" of the overall communications system it is part of. Two systems with the same "amount" of spectrum may have very different capacity profiles. What matters is the use that can be made of the spectrum, not just the abstract width of the frequency band.

What does architecture mean in this context? A simple example would be to compare a radio broadcast with a mobile telephone call.[9] Radio is a broadcast service, meaning that a tower sends out a signal at the maximum allowed power in all directions. It blankets an area, so that every receiver within range (typically a metropolitan area) can tune in the signal.

Mobile phone networks, by contrast, use a cellular architecture. Each tower sends relatively low-power signals to any handset within a few square miles. For handsets out of that range, there are other towers. Because of the low power, users talking to one tower don't notice the signals that other users are exchanging at the same time with a different tower. The same spectrum is being "reused" (see Figure 3).

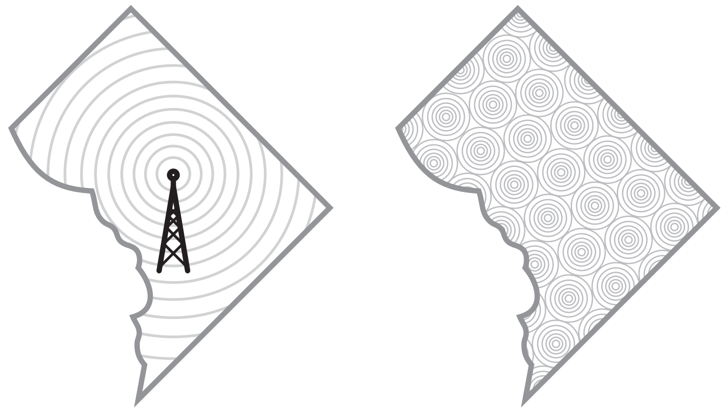

**FIGURE 3 – COMPARING BROADCAST VS. CELLULAR ARCHITECTURE:** The broadcast architecture (left) services more users over a larger area with one signal, while the cellular architecture (right) lets more users receive and send distinct transmissions.

## Shannon's Law

Bell Labs researcher Claude Shannon, in his seminal work in the late 1940s, created the mathematical concept of information theory. Shannon developed equations to measure the ability of a communications channel to carry useful information. As usually explained, "Shannon's Law" defines a maximum capacity, which is proportional to the frequency or bandwidth of the channel. As a result, bandwidth has become almost synonymous with capacity. Because there is only so much bandwidth, and any service can only have a small portion of it, this model implies strict limits on possible capacity.

This paraphrase of Shannon's capacity theorem leaves out critical facts. The version in question describes the simplest possible case – one transmitter and one receiver. Add more of either, and the solution is no longer so easy. More devices may cause "interference," or may create opportunities to interweave signals or otherwise add intelligence to the network. Similarly, a wider band adds capacity, but it's not the only way to do so.

The scientific field of multi-user information theory takes Shannon's work and extends it for these more complex (and more realistic) situations. It is a fruitful area of research and experiment. In the half-century since Shannon's initial work, we have learned many things about what is possible with wireless communications. But there are many things we still do not know. For example, we don't even know the maximum potential capacity of a system with an arbitrary number of devices. This core uncertainty should make us hesitate before uttering any statements about what is or is not possible in the wireless realm.

Notice the distinctions. The broadcast model lets the transmitters and receivers be simple (and therefore cheap), because there is only one transmitter sending data in one direction. The cellular model requires many more towers and more expensive devices, but in return it lets many more conversations occur simultaneously, in both directions. The broadcast system services more users with one signal, but the cellular system lets more users receive separate and distinct transmissions. There are other significant differences, and other network architectures with their own characteristics. Which architecture is chosen depends on technological capabilities and the service being offered. However, the way the legal regime divides and regulates spectrum defines the range of possible architectures to choose from.

Like capacity multiplexing techniques, wireless architectures have evolved over time. Cellular phone service was first conceived in the 1940s, but couldn't have been deployed economically at that time even if there were no regulatory hurdles. Today, thanks to massive increases in computing power and miniaturization of digital devices, many architectures are possible that once were not even imaginable. Asking about capacity or interference without considering architecture and the tradeoffs it enforces is like asking how many people can live in a city. It depends.

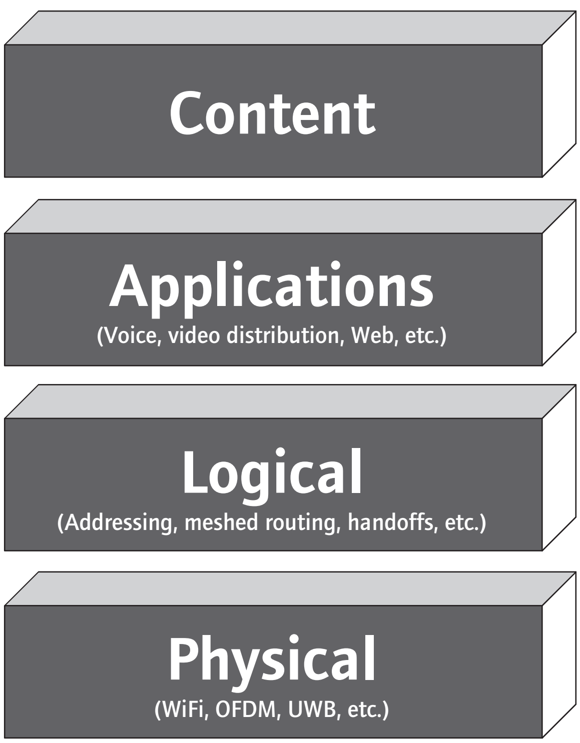


FIGURE 4 – LAYERS: In the digital era, wireless signals consist of a stream of interchangeable digital bits. Engineers use a layered framework to provide order and optimize and manage transmissions.

*Layers*

The third fundamental concept for understanding wireless systems has traditionally not been part of the wireless world at all. Wireless networks have historically used integrated, special-purpose devices. A short-range data connection in a television remote control does one thing; a microwave relay for sending long-distance telephone signals across the country does something else. This self-contained approach mirrors that of pre-digital wired networks. Telephone systems had little in common with cable TV systems, for example.

In contrast, data networks tend to operate using a layered model.[10] Rather than defining the entire system as an integrated whole, engineers split it up into a communications "stack." This allows for separation of functions that can be optimized individually. For example, technology developed for telephone networks to encode voice signals can be applied to different "physical" layers, including cable TV networks and wireless environments. In today's digital world, every signal is just a stream of theoretically interchangeable digital bits. Cable and phone companies can compete to offer voice, video, and broadband services, even though their networks use different types of wires.

Layering has several benefits. It makes systems more flexible, allows innovation in one area to benefit systems elsewhere, opens up new possibilities for competition, and gives users "best of breed" solutions rather than bundles which may not meet their needs.

Network engineers often use a seven-layer model published by the International Standards Organization.[11] A simplified version for policy purposes includes four layers, from bottom to top:

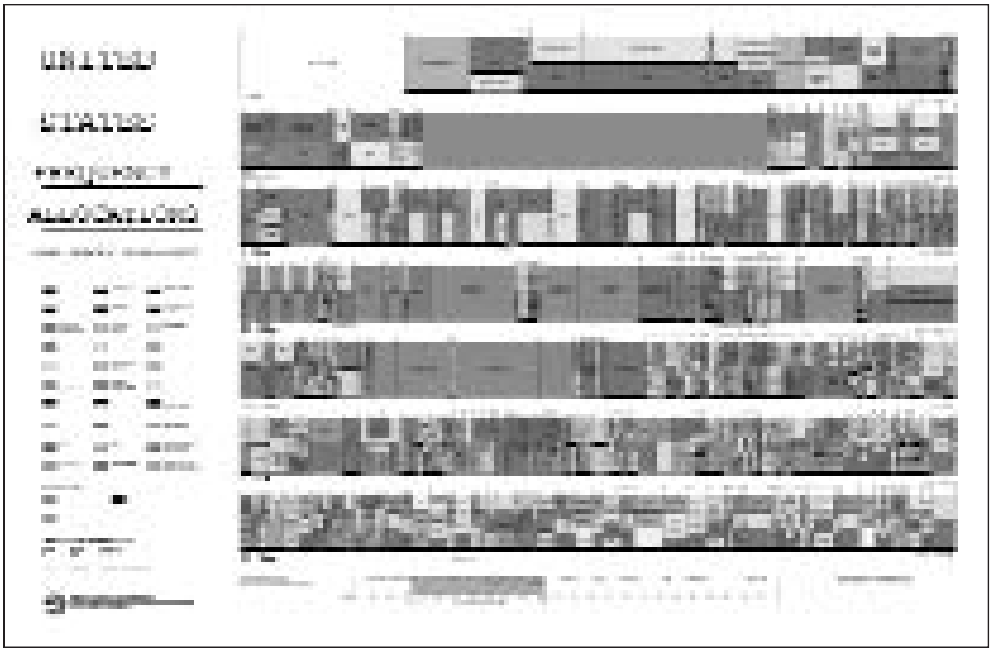

**FIGURE 5 – NTIA SPECTRUM ALLOCATION CHART:** The National Telecommunications and Information Administration (NTIA) uses a complex chart with more than 500 colored patches to illustrate spectrum-use allocations.

physical, logical, applications, and content. The wireless technologies described in this paper operate at the bottom two layers. The physical layer involves how information is actually sent across the communications channel. The logical layer concerns addressing and management functions that ensure the right information gets to the right place efficiently (see Figure 4).

### The Role of Government

What is "possible" in communications always has two meanings: technical and legal. Technical possibility is a function of scientific discovery and commercialization. Legal possibility is defined by the regulatory system. Many things are possible in the technical realm but not in the legal. (Occasionally, the reverse is true!) No discussion of the business and social fundamentals of wireless technology would be complete without taking government rules into account.

From its earliest days, the communications industry has been subject to pervasive government regulation, in the U.S. and elsewhere. In wireless, that regulation takes the form of spectrum policy. The Federal Communications Commission (FCC) tells some entities that they can use particular frequencies, usually for specific purposes and with detailed technical and economic requirements. It tells everyone else that they cannot communicate on those frequencies. And it enforces those rules, punishing violators. The National Telecommunications and Information Administration (NTIA) manages the federal government's use of spectrum, and serves as the principal advisor to the President for spectrum policy formulation.

Extensive government regulation of spectrum is taken for granted. But let us ask for a moment, why should that be so?[12] Communication over the airwaves is speech, just like communication through the wired phone network or through a microphone at a political rally. Government regulation of speech is strictly limited under the Constitution. Yet we tolerate a government agency, the FCC, bestowing the ability to speak upon individual companies, telling them exactly how they can speak, and punishing others who attempt to speak (see the NTIA Spectrum Allocation Chart, Figure 5).

There are several rationales for government regulation of spectrum. The airwaves are considered a public asset, not to be left to the vagaries of the private market. Regulation promotes a diversity of access by different voices, and maximizes efficiency in use of the airwaves. Government involvement prevents the chaos of ruinous interference that might occur in a vacuum. And there are important public safety and national security uses of wireless communication that government promotes and manages.

Behind all these rationales stands a single assumption: scarcity. If spectrum were not scarce, and simultaneous uses of the same spectrum were not mutually exclusive, there would be no reason to treat it differently from other forms of speech. Whether spectrum is in fact as scarce as we assume is a major theme of this paper.

Spectrum regulation developed early in the 20th century in response to two developments: a burgeoning commercial radio broadcast industry, and fears of chaos if government did not step in. The failure of nearby ships to heed the distress signal of the *Titanic* was seen as evidence for more extensive government intervention. Back at home, nascent radio broadcasters were squabbling about interference, arguing over who had the right to transmit on particular channels. Secretary of Commerce Herbert Hoover pushed for federal oversight of spectrum allocation. He was rebuffed by the courts, who found he lacked statutory authority. So the Radio Act of 1927 and the Communications Act of 1934 were passed, establishing the Federal Communications Commission as the prime arbiter of the airwaves.[13]

For sixty years, spectrum policy meant deciding which uses – and which users – were entitled to frequencies.[14] Federal spectrum allocation operates as a kind of industrial policy, choosing some services for favored treatment and often protecting providers from competition. The biggest change in recent years has been the shift to auctions and flexible licenses as the preferred initial assignment mechanism. Responding to the critique first articulated by Nobel Prize-winning economist Ronald Coase in 1959,[15] the FCC and many other governments now use auctions as the primary assignment tool, rather than comparative hearings (“beauty contests”) or lotteries.

An important element of the FCC’s licensing regime is what the licensees receive. In virtually all cases, licensees do not receive the right to control the spectrum absolutely. The Communications Act does not view spectrum as a tangible commodity. Licensees receive a right to use the frequency to provide a particular service, and only that service.[16]

A small amount of spectrum is assigned not to any specific users, but for “unlicensed” operation. The government sets technical requirements, such as power limits, for users of the band, and provides certification mechanisms for devices that operate within it. Users of unlicensed devices have no formal protection against interference from other users in the band, but they need no special permission to operate there. The FCC also allows very low power devices (less than one watt) to operate in significant sections of the spectrum under its Part 15 rules, on the grounds that they are too quiet to interfere with any other service.

# Paradigm Shift: From Static to Dynamic

Wireless systems today are not just better and faster than those of the past. They can be fundamentally *different*. One could explain a car as simply a speedier and more durable horse, or a computer as nothing but a very fast calculator. Those descriptions sound laughable. We know that new technologies have countless benefits and impacts that their predecessors don't. Horses are horses, and cars are cars, even though in some circumstances one can substitute for the other.

So too with wireless communications. Systems built using modern techniques such as spread spectrum, software-defined radio, and mesh networking can serve the same purposes as systems built using older approaches. At this relatively early stage in the radio revolution, the two types of systems look very similar. If the newer dynamic systems can develop and be deployed, however, they will eventually seem as different from their predecessors as a car does from a horse.

## The Traditional Approach

Traditional wireless systems are static. They assume dumb receivers and dumb transmitters, whose function is to blast out a signal at the maximum allowable power level. The model is quite straightforward: Imagine throwing a large rock into the middle of a round pond. Ripples will radiate out from the point of impact, eventually reaching the shore. No skill is required for a person standing on the shore, or sitting in a boat on the water, to come into contact with the ripples.

The good aspect of this model is that it doesn't require much sophistication in the endpoints. Transmitters and receivers that don't think much for themselves are relatively cheap to build. When the costs of radio hardware and computing power are high, such savings make a difference in what's economically possible. The downside of the static approach is that the devices aren't smart enough to get out of each other's way if there are multiple signals in the same space and frequency band. Throw two rocks into the pond, and it will be impossible to determine which originated the resulting ripples.

For wireless communication, the solution to this "interference" problem was to create exclusivity within frequency bands. In the early days, such as when radio and TV broadcasting were established, affordable receivers weren't even smart enough to tell what was in their band. The FCC established wide "guard bands" around licensed frequencies where no one could transmit. That's why the three original U.S. broadcast TV networks are typically on either channels 2, 4, and 7 or channels 3, 6, and 10.[17] The "white space" in between is dark to ensure receivers in each channel don't become confused.[18]

Static wireless systems are static because of the cost and computational capability of hardware, more so even than scarcity of spectrum. As is well known, computers have become more capable over time. In a famous formulation, Intel co-founder Gordon Moore noticed that transistor density on microprocessors doubled every 18 months thanks to advances in manufacturing technology. His observation became a prediction, and then a law, which has held true for 35 years.

The implication of Moore's Law is that whatever a computer can do today, it can do twice as well in 18 months, or twice as cheaply. If you bought a PC for $1000 three years ago, today you'd be able to buy a machine four times as fast for that same $1000. On the other hand, if you bought a color TV three years ago for $300, you might be able to get a slightly bigger screen or sharper picture today, but you'd see the same programming.

A radio itself is not a computer. It is a device for transmitting and/or receiving signals. However, computers can be used to control radios, or to process those signals. Just as devices from automobiles to air conditioning systems benefit from having computer "brains," computers can improve wireless communications devices. With today's computing power, in fact, they can totally transform them.

### When the Devices Get Smart

Intelligent transmitters and/or receivers can engage in a different form of wireless communication than the traditional static systems. Rather than merely waiting for an incoming signal, the receivers can contribute to the communications process. Rather than radiating constantly toward static targets, the transmitters can craft what they send for maximum efficiency. Call this dynamic wireless communication.

Changes in the nature of wireless devices also affect the way devices interact with each other, and with their surroundings. In other words, they change the interference environment. As discussed earlier, interference is a consequence of system design, rather than an inherent property of the radio spectrum. Interference is also inherently a legal construct. No radio signal on planet Earth is perfectly pure. There is always some external radiation that impinges on transmissions. Regulations or other legal mechanisms distinguish between permissible incidental noise and impermissible interference.[19]

The static mechanism to overcome ambient "interference" is to raise power output. The louder the signal, the easier it is to find among other noise. Of course, raising power increases the likelihood of impinging on other signals, especially those adjacent either geographically or frequency-wise. Regulators must therefore define power output and license geography limits carefully. Historically, large amounts of spectrum were kept as guard bands where no one could transmit, to allow a wide "buffer" between licensed signals.

Static wireless systems have traditionally dealt with interference from other transmissions through legal means. No one else may transmit in licensed bands. The FCC's rules provide penalties for "harmful interference," which is defined in terms of the effects of the second signal on the licensed service.[20] When the FCC proposed to authorize a large number of lower-power FM radio stations for use by community groups, licensed radio and TV broadcasters expressed alarm that their transmissions would be threatened. These opponents convinced the FCC to significantly scale back the freedom it granted to low-power FM broadcasters.

Dynamic wireless systems look at interference differently. It's the equivalent of listening closely rather

FIGURE 6 – COCKTAIL PARTY: A good metaphor for the receiver capabilities of smart devices is how people communicate at a cocktail party. Multiple conversations can occur simultaneously despite ambient noise.

than asking the person you're conversing with to talk more loudly. Because of their flexibility, dynamic systems often have the ability to "maneuver" around potential interference, whether by splitting up signals into packets spread across a wide range of frequencies, hopping from place to place in the spectrum, or sending communications through a physically distinct route across a mesh network.

Think about a group at a cocktail party. Many people can hold conversations with one another simultaneously. They can do so not because they each shout over the others, or because they agree on a set of rules to define who can talk when and how. It's obvious to us that the reason so many people can talk at once is that the speakers modulate their volume and the listeners use their brains to distinguish their partner from the ambient noise (see Figure 6). If you've ever tried listening to a piece of music and concentrating on different instruments to pull them out of the mix, you'll understand this process immediately. Now transfer the setting from smart human listeners to smart digital radios.

Another analogy is the Internet. The Internet doesn't have master directories or switches controlling the flow of information. Every router can decide independently where to send traffic. This works effectively thanks to cheap capacity and cheap computers that power the routers and other devices such as caches and Web servers at the edges of the network.

As these analogies show, the switch from static to dynamic approaches has two major consequences. **First, the capacity of the system to transmit useful information increases.** The same spectrum can hold more communications. The intelligence of devices is substituting for brute-force capacity between them. Imagine what highways would be like if cars couldn't be steered quickly to avoid collisions and slowdowns. There would have to be huge buffers between each vehicle to prevent accidents… precisely what exists in the spectrum today.

Dynamic wireless techniques effectively multiply the usable spectrum. Robert Matheson of the National Telecommunications and Information Administration (NTIA) at the U.S. Department of Commerce has proposed an "electrospace" model to describe the ways that today's wireless systems can coexist. He proposes the following variables: physical location (latitude, longitude, and height); frequency; time; and direction of arrival (azimuth and elevation).[21] These seven degrees of freedom for sharing spectrum compare with the single dimension – frequency – under the static approach. And the electrospace framework is still too limited. It does not include techniques such as low-power underlay, cooperative mesh networking, and software-defined radio, which are discussed later.

**Second, the architecture of wireless systems can change.** Instead of cheap, dumb terminals at the endpoints, there are agile, intelligent devices. Networks as a whole become more decentralized and more flexible. Two-way communication replaces one-way blanket broadcasting as the dominant mode of connectivity. What were once single-purpose, hardwired systems dominated by proprietary radio components increasingly become general-purpose, adaptive platforms dominated by commodity computing components. These subtle changes have dramatic consequences. Just as commodity PCs vanquished powerful mainframes by bringing computing to the masses, dynamic wireless systems will replace central transmission towers with millions of interactive end-user devices.

### Survey of Dynamic Wireless Techniques

Dynamic wireless communication is a deliberately broad classification that includes many technical mechanisms, with new ones being developed all the time. Once the transmitters and receivers are seen as computers that can contribute to the efficacy of the communications system, all sorts of possibilities emerge. These possibilities do not require any particular spectrum, or any particular spectrum policy regime. However, as will be discussed later, spectrum policy significantly influences the kinds of techniques that are used, by establishing the economic conditions and incentives for spectrum users.

*Spread Spectrum*

As discussed earlier, wireless systems designers have long understood how to "multiplex" multiple signals by sending them along different frequencies, or by splitting up spectrum into tiny slices of time. These multiplexing techniques are entirely consistent with the industry structure that developed under the dominance of the static wireless approach. Frequency-division multiplexing requires the most limited possible intelligence in devices, with spectrum bands exclusively allocated to specific users. Time-division multiplexing is more complex, but traditionally requires all the devices in a system to synchronize their "clocks" in order to know which signal is in which time slice. Such synchronization effectively requires exclusive control of a frequency.

There are newer multiplexing techniques with different results. The first developed was "spread spectrum." Hollywood actress Hedy Lamarr and musician George Antheil filed for a patent on a spread spectrum communications system in 1942, though real-world deployment occurred later. A spread spectrum system inverts the static model of transmitting with high power on a narrow channel. Using low power and spreading the signal across a range of frequencies, it's possible to carry more

### An Intelligent Device Bill of Rights

A key question in a world of dynamic wireless systems is how to set the proper boundaries on how devices can operate. More sophisticated equipment can reliably transmit signals in situations that would otherwise be subject to interference. "Cognitive" devices can sense the local spectral environment, adjust their transmissions to take advantage of temporarily empty spaces, and move their signals elsewhere as soon as another transmission is detected. Such devices are incompatible with traditional frequency-based licensing, which assumes a frequency is exclusively dedicated to a licensee.

One idea under consideration by the FCC's Technological Advisory Committee (TAC) is an "Intelligent Wireless Device Bill of Rights."[22] It would establish a set of principles to allow effective sharing of the spectrum. A draft of the Bill of Rights proposed in September of 2002 includes three articles:

- Any intelligent wireless device may, on a non-interference basis, use any frequency, frequencies, or bandwidth, at any time, to perform its function.
- All users of the spectrum shall have the right to operate without harmful electromagnetic interference from other users.
- All licensing, auctioning, selling, or otherwise disposition of the rights to frequencies and spectrum usage shall be subordinate to, and controlled by, Articles 1 and 2, above.

The Bill of Rights is at the early stages of discussion within the TAC, which itself has no formal authority. It suggests, though, how significantly the wireless paradigm shift now underway could change the basic framework of spectrum policy.

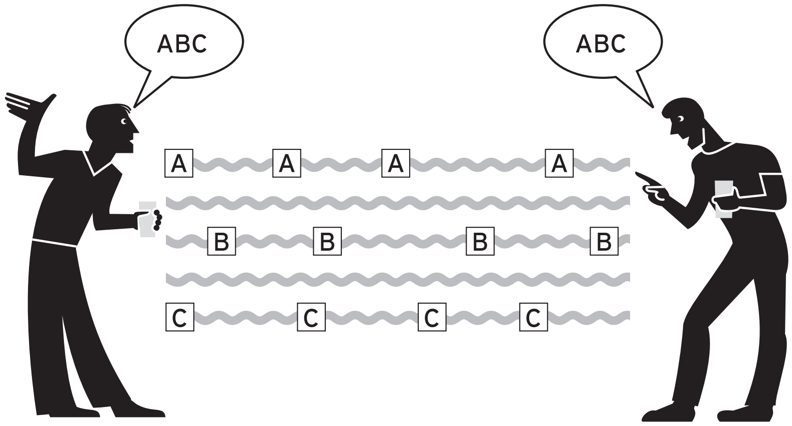


FIGURE 7 – SPREAD SPECTRUM: In spread-spectrum communications, low-power radio transmitters divide their signals into coded packets across a range of frequencies and receivers reconstruct the message.

transmissions simultaneously. The basic notion is that if the transmission is broken into pieces, each of which is tagged with a code, a receiver that knows the code can reconstruct the message. The wider the spreading, the more space there is in between the coded packets to send other signals at the same time (see Figure 7).

Taking spread spectrum to its logical conclusion, if the signal is spread wide enough, the power density can be so low that the signal becomes effectively invisible to other systems in the same bands. Radio frequencies are never totally empty of noise. Radiation-emitting devices such as hair dryers and microwave ovens, as well as cosmic background radiation, create a "noise floor" that all systems must contend with. Static systems do so by using high-enough power that it's easy to distinguish the high-power signal from the low-level noise.

With enough smarts, though, a dynamic system can transmit and receive very faint signals without ever raising above the noise-floor threshold. Only when very large numbers of such devices operate in the same location is interference even a realistic possibility. This approach is known as ultra-wideband (UWB). Many UWB systems employ very short "carrierless" pulses of electricity that give them other unique and beneficial properties.

Because of fears about interference, commercial use of ultra-wideband for communication was illegal until early 2002, when the FCC authorized it for the first time.[23]

*Space-Time Coding*

Many other multiplexing schemes are possible beyond spread spectrum and UWB. For example, companies such as Northpoint Technology have developed systems that multiplex satellite and terrestrial transmissions in the same frequency band.[24] Satellite signals arrive from above, while terrestrial signals are sent horizontally. A smart enough system can distinguish these two signals based on their angle of arrival, and can even do so without requiring modifications to the existing satellite system.

Northpoint's technology is an example of a broader class of techniques that take into account the physical location of transmitters and receivers. Static broadcasting uses a saturation approach. The receivers can be anywhere within the propagation footprint of the signal. The transmitter has no idea where they are beyond that, and the receivers know nothing other than that the transmitter is in the same footprint. As the Northpoint system shows, however, the location of transmitters and receivers is a useful piece of information. A signal arriving from thousands of miles overhead is different from a signal arriving laterally from a few yards away, even if both are within the same frequency band.

Space-time coding techniques use the physical topology of the network, or the surrounding environment, to add efficiency to wireless communications systems. For example, the BLAST system developed at AT&T Bell Labs employs antenna diversity and "multiple input/multiple output" (MIMO) technology to increase capacity. Instead of a single antenna at the receiver, BLAST employs arrays of multiple antennas at both the transmitter and receiver. Comparing the signal received at the different antennas makes it easier to distinguish transmissions from noise, increasing effective capacity. Start-ups such as Airgo Wireless are now using MIMO techniques to enhance capacity and range of wireless LAN chipsets.

Even factors that seemingly reduce capacity can be employed to increase it. The bane of many wireless systems is "multipath." When radio waves encounter obstacles such as walls, some fraction bounce off the obstacle and the remainder pass through. The ones that bounce may still reach the receiver. But they do so through a more circuitous, and therefore slightly slower, path. The receiver sees the same signal twice (or more), a split second apart. This multipath effect can confuse the receiver, degrading the signal quality.

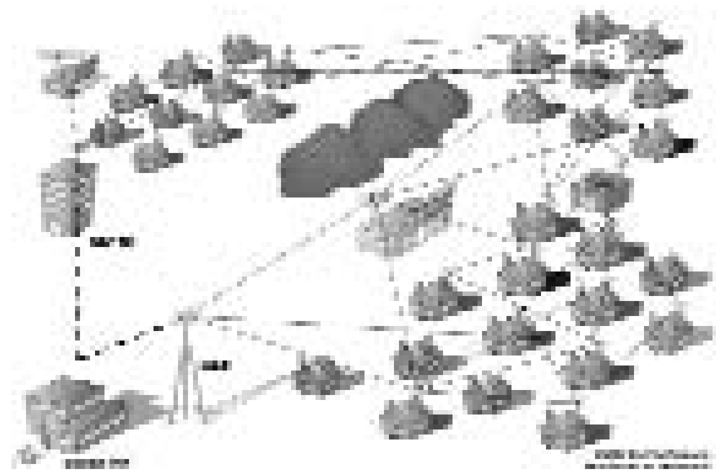

FIGURE 8 – MESH NETWORKING: In a mesh network, every device added to the system augments the network. In the case of a " last-mile," neighborhood network, end-users connect to the Internet by sharing connections with their neighbors allowing for shorter distance, lower power transmissions.

With a properly defined system, however, multipath becomes just another information-adding physical element. Knowing how a signal is bouncing around tells the receiver something about the location and nature of the transmitter. If the two temporally spaced signals are identified as the same transmission, they can be combined in a buffer to enhance the output signal. Similar techniques can be used for other factors that traditionally cause "interference," such as mobility.

*Mesh Networking*

Mesh networking is somewhat different than the previous techniques. It is a family of cooperative network architectures that can be applied through software to any radio technology. The basic definition of a mesh is that receivers talk to each other as well as to the transmitter.[25] A good example of a mesh network is the Internet. Every router has a table that allows it to send packets to many other routers, rather than through a central clearinghouse. Thanks to this architecture, the Internet avoids congestion choke points and single points of failure. When one link is down or overloaded, traffic automatically shifts to other links.

Wireless systems have traditionally used either a pure broadcast architecture (one central transmitter), or a hub-and-spoke approach as with cellular telephone networks, where users connect through local towers (see Figure 3). Many unlicensed technologies, including Bluetooth and WiFi, offer some mesh networking capabilities. Vendors such as LocustWorld sell WiFi access points with sophisticated meshing software to discover and connect to other nodes automatically.

The benefit of a mesh approach is that there are likely to be other end-users of the network closer to you than a tower or central broadcast facility. Shorter distances mean better signals, lower power requirements, and the ability to avoid obstacles such as trees.

Consider the task of providing "last mile" high-speed Internet connectivity to a neighborhood (see Figure 8). The benefit of mesh networking is that every new house brought online adds something to the network, improving performance and reliability. The difficulty is that a mesh network doesn't work with one or two nodes. The system requires a critical mass of devices to operate effectively. That number depends on the service and deployment environment. Several companies have tried to sell last-mile mesh networking gear, including SkyPilot, Omnilux, and RoamAD. None has yet achieved a large-scale commercial deployment, though field trials are ongoing.

Other providers are selling mesh networking gear for public safety applications. One vendor, Tropos Networks, recently built a 17-cell mesh network for the police force of San Mateo, California so that officers could access crime databases from laptops in squad cars.[26] MeshNetworks is in trials with the Orange County Fire and Rescue service in Florida, offering vehicle and personnel tracking as well as mobile Internet connectivity through a distributed mesh network.

*Software-Defined Radio*

At the heart of any wireless communications system is the radio. A radio transmits or receives wireless signals encoded into waves that oscillate at frequencies somewhere within the radio spectrum. Traditionally, those radios have been fixed in hardware. A radio talks to a fixed swath of spectrum, and understands a fixed modulation scheme for coding signals. It's like a dedicated telephone line between two businesses. You simply couldn't use it to call your grandmother, or another business across the street.

Software-defined radio (SDR) uses software to control how the radio works.[27] It's like replacing the dedicated phone line with a connection that goes through an electronic switch. Suddenly many of the characteristics that were immutable become flexible. Capabilities not envisioned when the device was built can be added later.

SDR has several benefits. One device can support multiple services transmitting on different frequencies with different encoding schemes. A mobile phone handset, for example, could receive signals from more than one service provider, or from service providers in different countries, regardless of what technical standard they employ. This is particularly important for markets, such as public safety, where incompatibilities between systems, such as those used by police and fire departments responding to the same emergency, are critical problems. The U.S. military has funded significant research and development related to SDR for similar reasons. The Joint Tactical Radio System (JTRS) is now under development through prime contractor Boeing and subcontractors including Vanu, a start-up in Cambridge, MA that is a leading SDR technology developer.

The flexibility of SDR reduces costs by eliminating duplicate equipment, both for users and for service providers. Imagine a cellular network, for example, where each service provider only had to put up towers where others had not, rather than each of them having to build a redundant national footprint.

The potential of SDR goes significantly beyond cost reduction. Because a software radio is software, it can run on general-purpose computers such as Windows and Linux devices, using mass-produced digital signal processors (DSPs) and other hardware. Such devices benefit from Moore's Law and the competitive dynamics that steadily push costs down and capabilities up. As DSP chips become more powerful for the same price, an SDR system can decode a larger swath of spectrum or perform other new functions. SDR systems can also take the decoded radio signals and feed them into other applications.

Agile or cognitive radios are a sub-category of SDR currently in the development stage. Agile radios can "jump" from one frequency to another in a matter of milliseconds. Combined with processing capabilities that allow such devices to sample the spectrum around them, agile radios can in effect manufacture new spectrum. Even a channel supposedly occupied by a licensed system is empty much of the time in much of the defined physical area. An agile radio could hop among local, short-duration empty spaces in the spectrum, moving whenever it sensed another transmission in the same band. Such devices could effectively become their own virtual networks, creating connections with other nodes wherever they are.

## Implications of Dynamic Approaches

The switch from static to dynamic wireless communication has huge consequences. Technical approaches created to solve technical problems turn out to have major policy, business, and even social consequences. These consequences, such as the possibility of replacing spectrum licensing with "commons," have generated a great deal of attention. They would not be possible without the technical advances we have described so far. In many cases, the technical advances have grown up within the dominant wireless paradigm, as with Qualcomm's CDMA spread spectrum technology for licensed cellular networks. As wireless technology moves forward, however, the possibilities for radical change will become more difficult to ignore.

Author George Gilder identified the disruptive potential of dynamic wireless technologies ten years ago, in a prescient article in *Forbes ASAP*.[28] At a time when policy-makers were infatuated with spectrum auctions, Gilder pointed out that auctions were counterproductive if intelligent devices could share spectrum and avoid interference on their own. The technological paradigm shift of dynamic wireless calls for paradigm shifts in regulation and business as well.

### *Commons*

The first and biggest consequence of the radio revolution is that licensing of spectrum frequencies is no longer required. Recall that the original basis for spectrum licensing by the government was the fear of ruinous and pervasive interference. If devices can operate with sufficiently low power and high intelligence to avoid one another, exclusive rights are no longer necessary to prevent interference. With a properly defined environment, users effectively *can't* prevent each other from communicating. That opens the door for a new regime that allows anyone to transmit within general technical guidelines.

This notion has become known as a "spectrum commons." The analogy here is to common lands in the Middle Ages in England, where anyone could graze their sheep. Not all such environments are subject to the infamous "tragedy of the commons." If there is enough open space, and good enough legal or customary rules governing individual action, a commons can thrive without rapid exhaustion. Until recently, these concepts were rarely applied to spectrum, because capacity constraints were thought to be so severe. As noted earlier, though, the revolution in wireless technology lifts the constraints that made spectrum scarce.

Beginning with the early 1990s challenge to FCC spectrum auctions from Gilder, network engineer Paul Baran, and communications scholar Eli Noam, and continuing in the late 1990s and beyond with the work of Yochai Benkler, David Reed, Lawrence Lessig, Tim Shepard, and myself, the argument for spectrum commons has gradually taken shape.[29] As will be discussed later, there are several varieties of spectrum commons, including unlicensed bands and underlays. Evolving dynamic spectrum management techniques are rapidly creating new possibilities for sharing rather than licensing spectrum.

If there is enough capacity to support a commons, exclusive rights are unnecessary. By analogy, the ocean is not infinite in size, but it is large enough that ships can be trusted to navigate around one another (see Figure 9). The ships, like dynamic wireless devices, can intelligently alter their routes to avoid collisions. There is no need to give companies exclusive shipping lanes, and prohibit other ships from using those routes unless they pay a toll. Such exclusivity would significantly

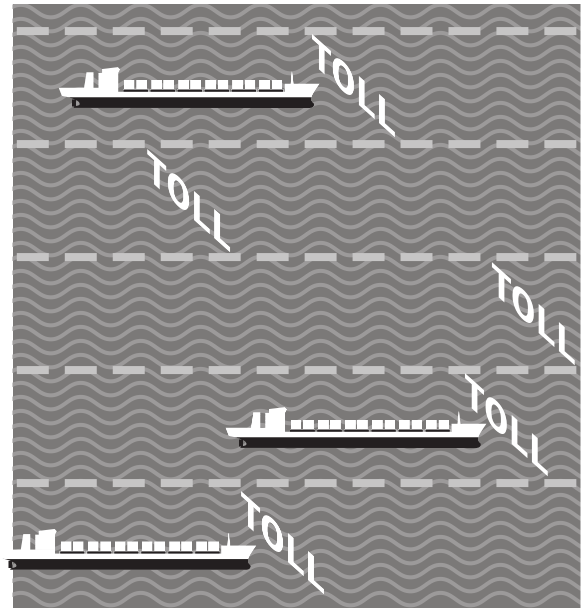


**FIGURE 9 – UNLICENSED VS. LICENSED BUSINESS MODELS:** Technology is transforming the capacity of the spectrum from scarcity to abundance, akin to the vastness of the oceans. But current airwave regulation is similar to giving companies exclusive shipping lanes, and requiring non-licensed users to pay a toll to access them.

reduce the level of shipping traffic, with no corresponding benefits. Technology is making the wireless world look more and more like the ocean.

Well-functioning commons produce several normative benefits. Because access is no longer controlled by a designated gatekeeper, everyone can participate. Virtually anyone could distribute TV programs, promote an idea, or engage in a group conversation using the same mechanism that today supports a limited set of broadcasters and operators. This is freedom of speech on a spectacular scale.

### *Market Structure*

The second implication of dynamic wireless systems is that the business structure of markets changes. Static systems necessitate exclusivity. The downside of exclusivity is that no one else can contribute to a network. The licensee must bear the total cost of building network infrastructure. The licensee typically recovers that cost by charging fees to users for both devices and communications services. Any vendor of user or network equipment must sell to or through the licensed operators. They are the only customers who can take technologies and legally put them into the market.

There is nothing inherently wrong with this "infrastructure" market model. It is traditionally the market structure used for services that have high capital costs and benefit from economies of scale. Having every person responsible for building the roads passing their home wouldn't make much sense, nor would having every person responsible for bringing their own connection to a central telephone exchange. There are, however, serious downsides. Deployment is slow because it is costly and requires proven models for recouping that cost. Innovation is constrained because only a few licensees control access to the market. Uniformity and interoperability are enforced by the licensee, but services and equipment are costly because they are provided in limited volumes and based on proprietary standards.

As wireless devices become more intelligent and commons arrangements become viable, new market structures become possible. If the spectrum is no longer part of the service equation, the primary element of the "service" offered to end-users becomes the devices those users purchase. Because those devices run on standards defined by industry bodies rather than mandated by spectrum licensees, there can be open, competitive markets to build better and more cost-effective equipment.[30] We move, therefore, from a market for centralized infrastructure and proprietary services, to a market for consumer devices, software, and ancillary services. Users pay a significant fraction of the total network build-out costs directly, by purchasing hardware, greatly reducing the expenses service providers must undertake. For many services, there are still core network costs—for access points, backhaul to wired Internet backbones, authentication, roaming, and security—but these are limited compared to the all-encompassing network build-out that licensed operators must undertake.

Furthermore, dynamic wireless devices allow for markets with greater diversity at several points. Many equipment vendors, several providers, and application or content providers can compete, because there is no mandatory control point and each provider can leverage the infrastructure built by others.

**"Change the technology, and the economics and the law of spectrum use must change, too."**

– ELI NOAM, PROFESSOR OF ECONOMICS AND FINANCE, COLUMBIA UNIVERSITY

### *Incentives for Robustness*

Intelligent or dynamic spectrum management techniques may be used in any regulatory environment. However, the nature of spectrum regulation heavily influences incentives for deployment of intelligent devices. The traditional, and still dominant, environment is exclusive licenses for frequency bands. Spectrum licensees have incentives to squeeze as much capacity as possible out of their spectrum. On the other hand, they have incentives to make the devices users must purchase as inexpensive as possible. In a static system, the money is all in the service; the devices are dumb. There is no need to make them robust against interference, because interference from other systems is prohibited and policed by the FCC. Similarly, there is no great incentive to make the devices flexible, because the service provider is focused only on supporting its own service. Indeed, to keep the cost of switching to another service provider high, licensed providers have an incentive to discourage software-defined radios, which could switch frequencies (and hence service providers) at the click of a mouse.

All that changes in a commons environment. Because wireless devices in a commons have no legally guaranteed protection against interference, they must guard against it using technical means. Fortunately, that is what dynamic wireless devices are good at.

> **"We need to think of ways to bring [WiFi] applications to the developing world so as to make use of unlicensed radio spectrum to deliver cheap and fast Internet access."**
>
> – UN SECRETARY GENERAL KOFI ANNAN

Static systems create incentives to make the receivers as dumb as possible. Dumber means cheaper, after all. Because the central transmitter does the heavy lifting, there are no significant benefits from intelligence at the edge devices. When end-user devices become dynamic, however, they contribute to the integrity and performance of the overall system. Making them smarter and more robust improves performance. And without license restrictions keeping other devices from transmitting on the same frequencies, robustness based on intelligence is the only path open.

## WiFi as a Case Study

*WiFi Defined*

WiFi is the most prominent unlicensed wireless technology available today. It is a family of spread spectrum wireless local area networking standards designed to allow users to send and receive data at 11-to-54 Mbps within a few hundred feet of another WiFi device or access point. WiFi is a great case study for the impact of dynamic wireless technologies.

Wireless data networking services have been commercially available since the 1980s, beginning with Ardis, a joint venture of IBM and Motorola, and RAM Mobile Data. Ardis was purchased by American Mobile Satellite and renamed Motient; after reorganizing through bankruptcy in early 2002 it is still trying to right itself financially. RAM Mobile data was renamed Mobitex and is now part of Cingular Wireless. It is the primary network used by wireless email devices such as the RIM Blackberry and the Palm VII. Motient and Mobitex are wide-area systems that target enterprise and messaging markets. Another wide-area wireless network, the Metricom Ricochet system, offered services directly to end-users, providing wireless Internet access in several U.S. cities for laptop users. Metricom filed for bankruptcy in 2001; its assets were purchased by Aerie Networks, which is attempting to re-launch the service.

These early wireless data networks generally used licensed spectrum, though Ricochet employed 900 MHz unlicensed frequencies in some areas. They offered low-speed connections (19.2 kbps or less) with wide-area coverage in cities or nationwide. Today, third-generation cellular networks are beginning to offer packet data networking services as well, typically at higher speeds. None of these offerings has yet become a mass-market success.

WiFi has been exactly the opposite story. The Institute for Electrical and Electronic Engineers (IEEE) ratified the 802.11b standard for wireless local area networking (WLAN) in 1999. Vendors such as RadioLAN and Proxim had been offering proprietary WLAN systems, for both office environments and home networking. 802.11b, related to the 802.3 Ethernet standard, was envisioned primarily as a wireless replacement for wired Ethernet connections in corporate environments. In 1999, though, Apple Computer introduced a consumer 802.11b device, the Airport, using chipsets from Lucent. The market exploded.

The WiFi market grew to $1 billion annually (primarily in hardware sales) by 2002. Most of that period has been a time of contraction in the technology and telecom sector making the achievement even more impressive. More than half of U.S. companies now support WiFi networks, and another 22 percent plan to do so within a year.[31] And WiFi sales are projected to keep growing. Cahners Instat sees the market reaching $4.6 billion by 2005, and other research firms have issued similar projections.[32] By 2008, says Allied Business Intelligence, 64 million WiFi nodes will be shipped annually.

*Secrets of WiFi's Success*

What made WiFi such a success, especially compared to previous wireless data systems? After all, WiFi provides only short-range connections; on its own, one access point can't provide ubiquitous coverage in a neighborhood or city.

WiFi has thrived because it has benefited from an ecosystem that could only exist with the type of technology it uses. Because WiFi is a low-power, spread-spectrum technology, WiFi devices can coexist without the requirement of spectrum licensing to prevent interference. That means there is no need for service providers, cell towers, controlled hardware markets, or expensive spectrum licenses. Anyone can buy a WiFi device and establish a network.

Because WiFi is an open standard and an equipment-centered rather than service-centered market (again, both of which flow from the nature of the technology), costs are subject to computer industry downward pressure. A WiFi access point that cost hundreds of dollars when introduced is available for less than $100 today. Chipsets are down in the $10 range, allowing laptop, personal digital assistant (PDA), and mobile phone vendors to incorporate them with little or no price increase for the overall system. According to Intel CTO Patrick Gelsinger, a WiFi network costs half as much per user per month to operate than a DSL connection, and as little as one-tenth as much as a third-generation cellular network.[33]

The WiFi market wouldn't have taken off without standards – both the technical ones defined by the IEEE and the interoperability testing and certification done by the Wi-Fi Alliance (formerly WECA), an industry trade group. There is a need for such industry standards because there is an entire industry of vendors, rather than one service provider and its chosen suppliers, operating in the WiFi universe. Now that the standards are in place, the market can take advantage of contributions from many competing vendors.

WiFi is now experiencing the next phase of development that can occur with dynamic wireless systems. It is evolving and diversifying. The IEEE has already extended the original 802.11b with several variants which will be discussed later. Meanwhile, start-ups are offering new kinds of devices that add functionality to the original short-range WiFi access points. Vivato, for example, has developed a smart, phased-area antenna technology that can extend the range and capacity of WiFi signals, while remaining completely backward compatible with existing equipment. Locustworld in the UK is shipping 802.11 mesh networking boxes that automatically create ad hoc mesh networks with each other. Vendors such as Engim and BroadBeam are offering WiFi switches that increase capacity of WiFi infrastructure. Sputnik is shipping low-cost yet powerful self-configuring access points. Companies such as Telesym and Vocera are running voice communications over WiFi, opening up whole new market opportunities.

**"[T]he unlicensed bands employ a commons model and have enjoyed tremendous success as hotbeds of innovation."**

– FCC CHAIRMAN MICHAEL POWELL

In a traditional static wireless system, changing the network technology means upgrading the whole network. Not just end-user devices but all the core transmission elements must be upgraded. The costs and time frames involved parallel those of deploying the system the first time. The transition from analog to digital television (DTV) is a perfect example. DTV technology has been commercially available for more than a decade. In the U.S., the formal transition to DTV began in 1996, and still only a tiny handful of customers can receive DTV broadcasts. In Japan, high-definition TV (HDTV) service has been commercially available since the 1980s, but Japan chose an analog standard. Improving digital technology is now considered the best way to deliver HDTV, and Japan had to effectively start the entire process over again.

Compare that to the transition from orphaned WLAN standards. Two standards that competed with 802.11, Europe's Hiperlan for high-speed WLANs and the HomeRF standard for home networking, have lost out in the marketplace. Though some equipment has been orphaned, most vendors have quickly switched to offering 802.11 products.

# The Unlicensed World

Unlicensed wireless is far more than WiFi. Dynamic techniques for efficient sharing of the spectrum, combined with the open field for unlicensed innovation, are creating an explosion of new systems, techniques, and business models.

## The Spectrum of Spectrum-Use Regimes

"Licensed" and "unlicensed" are generally presented as the two models for spectrum usage. There are actually several variations, not entirely mutually exclusive. Put another way, the fact that WiFi uses spectrum bands dedicated to unlicensed usage doesn't mean that is the only mechanism for regulators to create more space for unlicensed devices and systems. Matheson's electrospace model, for example, provides seven dimensions for sharing spectrum, with frequency only one of the variables.[34]

Looking at the possibility of a spectrum commons purely as a matter of what regime to mandate for specific frequencies misses the point. Dynamic wireless techniques, and the systems they make possible, ultimately erode the very rationale for thinking of "the spectrum" as a physical asset that can and should be divided into frequency bands.[35]

For present policy purposes, however, it can still be useful to list prominent mechanisms for sharing spectrum. The New America Foundation and other public interest organizations have urged the FCC to consider four basic spectrum use regimes: exclusive licensed, pure unlicensed, shared unlicensed, and opportunistic unlicensed.[36]

### *Exclusive Licensed*

Most spectrum is exclusively licensed today. Licensees may be carriers, broadcasters, specialized mobile radio, corporations, the military, or public safety agencies. The licensee may have obtained its license for free, or through a competitive mechanism such as an auction. Regardless, it has exclusive control of the frequency band for a period of years subject to the limitations of its license. Other systems are prohibited from producing harmful interference with the licensee. The broadcast television bands are good examples of exclusively licensed spectrum.

Some spectrum is licensed, but not for a single user. Examples include the bands for the amateur radio service, radio astronomy, and private microwave systems. These bands resemble pure unlicensed spectrum, in that one entity doesn't have total control. However, there are still restrictions on who can transmit, and what kinds of services they can provide. A technology that could increase capacity or deliver a new kind of service can't be used in these bands if it doesn't meet those criteria.

*Dedicated Unlicensed*

The opposite regime is to have no exclusive licensees in the band. For example, the 2.4 GHz Industrial, Scientific, and Medical (ISM) band is open solely for unlicensed use. No devices that operate in that band—which range from the WiFi access points to microwave ovens and cordless phones—can claim protection against interference from other approved devices in the band.

"Unlicensed" is actually something of a misnomer. It implies that the government has not made the spectrum available to licensees, when in fact the spectrum has been allocated and assigned

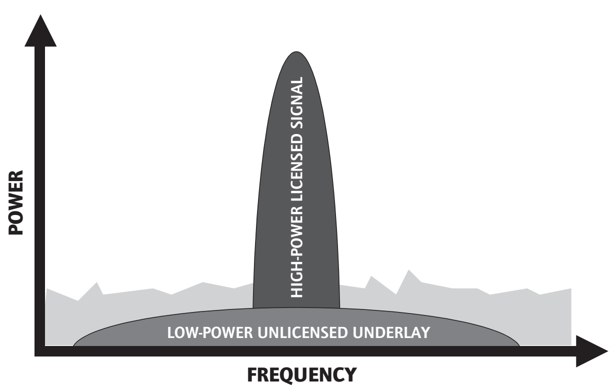


FIGURE 10 – UNDERLAY SHARING: In underlay sharing, low-power, unlicensed devices share frequencies and avoid interference by operating beneath the noise threshold of high-power devices in the band.

like any other spectrum block. Instead of a service provider gaining the rights to control use of the spectrum, subject to limits set in the terms of the license, manufacturers gain the rights to sell devices that conform to FCC-designated standards. The devices themselves must be licensed, generally on a generic and often self-licensing basis known as "type acceptance."

An important point here is that unlicensed does not mean unregulated. In the 2.4 GHz band, for example, the FCC mandates power limits and other technical requirements. New kinds of equipment that use different techniques than those already licensed must receive direct FCC approval. For example, Vivato, a start-up that sells a novel "WiFi switch" based on phased-array antennas, received FCC approval in late 2002 for its technology.

*Shared Unlicensed*

Under certain circumstances, unlicensed devices can share frequencies with licensed devices. This arrangement is sometimes referred to as an easement, by analogy to real property law. It is also known as "underlay," because unlicensed devices operate below the noise threshold of the high-power licensed devices in the band (see Figure 10).

There are two major examples of shared unlicensed use in current FCC rules. The first, Part 15, actually dates back to 1938. This section of the FCC's rules allows devices below a strict power limit to operate in significant portions of the spectrum. The severe power limits allow for only very short-range devices, which do not produce significant interference with licensed systems.

A more recent example of shared unlicensed use is ultra-wideband (UWB). The FCC first authorized this technology in February 2002. It uses transmissions spread across huge frequency ranges at extremely low power, below the detectable noise floor for other licensed devices in the same band. Using spread spectrum techniques, UWB systems are able to reconstruct messages and support high-speed transmissions even under such restrictive conditions. By authorizing ultra-wideband for much of the spectrum above 3 GHz, the FCC effectively created a huge new unlicensed easement shared with licensed services.

*Opportunistic Unlicensed*

Opportunistic sharing means taking advantage of unused spectrum in licensed bands. As noted previously, the official frequency chart paints a misleading picture of how spectrum is actually used. Some frequencies are allocated but not assigned to any user. For example, they may be set aside as "guard bands" between licensed frequencies for older services such as broadcast television. The guard bands were necessary because the licensed equipment wasn't sophisticated enough to distinguish signals otherwise. However, today's smart unlicensed devices could transmit in the guard bands without impinging on the licensed services.[37]

In other cases, spectrum may be assigned but not used in a particular area or for a particular period of time. For example, a cellular phone transmission tower is only active when communicating with a handset nearby. When no user is in range, the spectrum is temporarily available. Other frequencies, licensed nationally, may be used in New York City but not at all in Montana. "Cognitive radios" could detect such holes in the spectrum, switch communications there, and then move away as soon as the licensee began transmitting (see Figure 11). Furthermore, as the electrospace model shows, there are many ways to slice the spectrum pie. An "angle of arrival" system, for example, can opportunistically use "terrestrial" spectrum in bands licensed for communication with orbiting satellites overhead.

There is no reason to believe that all the possible mechanisms for opportunistically sharing spectrum have been discovered or implemented. As wireless systems become more dynamic and more intelligent, they will be capable of coexisting in new ways.

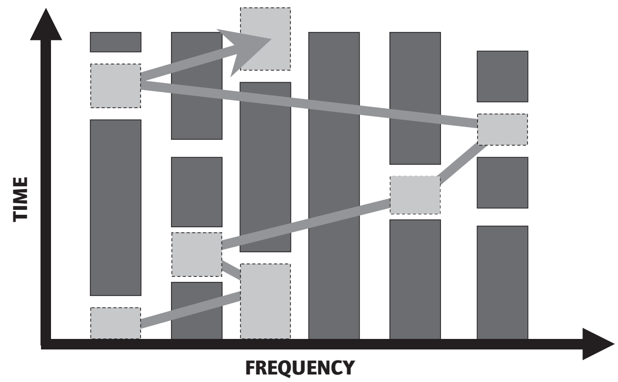


FIGURE 11 – OPPORTUNISTIC SHARING: In opportunistic sharing, unlicensed devices detect and access licensed spectrum that is not currently in use, and then move away as soon as licensees begin transmitting.

## Current Unlicensed Products

Though the WiFi name is getting a tremendous amount of attention and, as a result, has been expanded to include standards other than the original 802.11b, it is important to keep in mind that WiFi is not a synonym for unlicensed wireless. WiFi is a local-area networking protocol. It delivers data, such as Internet connectivity and email, across links of no more than a few hundred feet.

*Local Area Networks (802.11)*

802.11 refers to the Institute for Electrical and Electronic Engineers (IEEE) working group for wireless Ethernet networking. The IEEE defines technical standards, but does not certify compliance with those standards. In parallel, industry associations such as the Wi-Fi Alliance create brand names which vendors are permitted to use if they meet compatibility requirements. The term WiFi, a play on HiFi stereo systems, is such a brand name.[38] Originally referring only to 802.11b, WiFi now encompasses 802.11 a, b, and g.

There are three widely deployed 802.11 technologies:

- **802.11b –** The original WiFi, providing 11 Mbps connections using direct-sequenced spread spectrum modulation in the 2.4 GHz frequency band.
- **802.11a –** A higher-speed standard delivering 54 Mbps connections, but using different spectrum (5 GHz) and modulation (orthogonal frequency division multiplexing, OFDM) than 802.11b. As a result, 802.11a systems are not backward compatible with 802.11b, and require separate radios.
- **802.11g –** A backward-compatible high-speed standard, delivering 54 Mbps through OFDM like 802.11a, but using the 2.4 GHz spectrum.

| TECHNOLOGY | RANGE | CAPACITY | SPECTRUM | REPRESENTATIVE COMPANIES | COMMENTS |
|---|---|---|---|---|---|
| **802.11b (WiFi)** | 300 feet | 11 Mbps | 2.4 GHz | Chipsets: Intersil, Agere, Cisco, Intel<br>Equipment: Cisco, Proxim, Netgear, Vivato, Apple<br>Services: Boingo, Cometa | Primary wireless LAN market today |
| **802.11a (WiFi)** | 150+ feet | 54 Mbps | 5 GHz | Major 802.11b vendors plus Atheros, Bermai | Useful for corporate networks, backhaul, and media applications |
| **802.11g (WiFi)** | 300 feet | 54 Mbps | 2.4 GHz | Major 802.11b vendors plus Broadcom | Backward-compatible with 802.11b devices |
| **802.15.1 (Bluetooth)** | 300 feet | 1 Mbps | 2.4 GHz | Ericsson, Nokia, Intel, Toshiba, Microsoft, 3Com, Motorola | Originally designed for cable replacement; market niche unclear |
| **802.15.3a (WiMedia)** | 30 feet at 110 Mbps or 12 feet at 200 Mbps | 110 and 200 Mbps | Wideband (3.1–10 GHz) | XtremeSpectrum, Motorola, TI, TimeDomain, Philips | High-bitrate personal area networking for media devices |
| **802.15.4 (Zigbee)** | 200 feet | 250 kbps | 900 MHz, 2.4 GHz, or wideband | Philips, Honeywell, Mitsubishi, Motorola. | Low-bitrate personal area networking for sensors |
| **802.16 (WiMax)** | 30 miles | 70 Mbps | 10-66 GHz for 802.16; 2-10 GHz for 802.16a | Motorola, Alvarion Proxim, Fujitsu, Aperto | Broadband metropolitan-area network connections |
| **802.20 (MobileFi)** | 15 km | 1 Mbps | 3.5 GHz | Cisco, Flarion, HP, Nextel Mobile wireless | Ethernet, currently envisioned for licensed spectrum, but may evolve |

TABLE 1 — MAJOR UNLICENSED WIRELESS STANDARDS

The remaining alphabet soup of IEEE 802.11 standards are mostly variants of these protocols. For example, 802.11e, based largely on technology developed by Sharewave (now part of chip vendor Cirrus Logic), adds quality of service mechanisms to better support video and voice traffic. 802.11i adds a new security protocol to the relatively ineffective WEP encryption in 802.11b. 802.11j is a WLAN protocol for the 4.9 GHz to 5 GHz unlicensed spectrum in Japan.

*Metropolitan-Area Networks and Last Mile (802.16)*
Metropolitan-area networks (MANs) operate over longer distances than LANs, typically a mile or more. They are designed to provide relatively high bandwidth to a moderate number of fixed sites, such as homes and businesses, compared to LANs, which connect individual devices. One MAN application is the so-called "broadband last mile," which can substitute for wired solutions such as digital subscriber lines and cable modems.[39] However,

MAN systems are also used to provide "backhaul" connections from such last-mile networks to central aggregation points, point-to-point connections between facilities, or coverage throughout a campus or other geographically defined facility. Increasingly, WISPs and non-profit community access networks are creating MANs using line-of-sight relays on unlicensed spectrum (at 5GHz) and WiFi (at 2.4 GHz, for the last few hundred feet) to offer affordable last-mile connections in rural and low-income areas.[40]

The IEEE has established a standards group, 802.16, for wireless MANs. The original 802.16 specification was designed for very high frequencies, over 10 GHz. A more recent subgroup, 802.16a, is crafting MAN standards for 2-10 GHz frequencies that, unlike the original standards, don't require line-of-site visibility. 802.16 envisions systems delivering 70 Mbps of data over a 30 mile range. An industry alliance called WiMax, including Intel, Proxim, Fujitsu, Alvarion, Aperto, and Nokia, has been formed to promote and ensure interoperability of wireless MANs.

Though designed as LAN technologies, 802.11a and b are being used by some companies such as Etherlinx as the foundation for MAN systems. Generally these systems use the commodity 802.11 physical layer and devices, adding their own media access control (MAC) layer to boost range. Another option, which several service providers are reportedly considering, is to use standard 802.11 devices with enhanced access points from companies such as Vivato that boost the effective range.

Several companies including Motorola (with its Canopy system), Magis Networks, Proxim, IP Wireless, Navini, BeamReach, Aperto, Soma Networks, and Alvarion offer proprietary products that are similar to 802.11b and 802.11a. Typically these systems offer better performance, reliability, or features such as security that aren't well implemented in the 802.11 standards. Today, most of them operate in the 5 GHz band and focus on markets such as last-mile residential and small-business connectivity, especially in rural or otherwise underserved areas. Many of these companies are part of the 802.16 effort. It can be expected that, as with WiFi, many proprietary systems will eventually become standards-compliant. A new industry association, WiMax, hopes to do for unlicensed wireless MANs what WiFi did for LANs.

Other companies are taking a different route to deliver wireless MAN connectivity. Instead of long-range MANs sending data directly to customers, they envision wireless mesh networks using short-range links to cover neighborhoods. One start-up, Skypilot, plans to use standard 802.11b radios in the home connected to rooftop units based on 802.11a with added mesh networking software. Omnilux plans to use free-space optics technology, combined with mesh networking. Free-space optics uses lasers that operate in the visible light range of the spectrum, above the radio frequencies. It is therefore technically outside the scope of FCC licensing, which applies only to communication "by wire or radio."

### *Personal-Area Networks (802.15)*

Moving the opposite direction from MANs, personal-area networks (PANs) are designed for very short-range connections, no more than a few dozen feet. WiFi can cover these distances, but because WiFi devices are designed to serve larger areas and provide relatively high-bandwidth connections, they require more power and have higher equipment costs than would be necessary for close-in, low-speed tasks such as communicating between a mobile phone and a headset.

PAN applications are essentially "cable replacement." They are tasks that people perform today by stringing wires between devices, but that could be done with more freedom if the wires weren't necessary. These include scenarios such as printing from a laptop computer to a nearby printer, sending voice signals between a cordless phone and a base station, and pulling a contact from a PDA to a mobile phone. There are also high-capacity cable replacement tasks involving rich media, such as sending music between an Internet-connected home server and a home theater or stereo system.

The standards body for PANs is IEEE 802.15. Bluetooth was the first prominent PAN standard, incorporated into IEEE 802.15.1. Based on technology originally developed by Ericsson, it is supported by a private industry standards body that now has more than 2000 members. Bluetooth provides approximately 1 Mbps connections over 30 feet by automatically creating network clusters of nearby devices.

Bluetooth received a great deal of media attention when the consortium was first announced, because of its heavyweight backers and excitement about the potential of all things wireless at the time. However, interoperability issues and questions about where Bluetooth really fits in the market have limited adoption. Bluetooth mobile phones, PDAs, and laptops are now available, and costs are coming down as volumes increase.

Even shorter range and lower speed than Bluetooth is Zigbee (802.15.4). The protocol, originally developed by Philips, is optimized for applications such as distributed sensor networks, which must only send a few kilobits of data at a time. Zigbee, like Bluetooth, is currently supported by an alliance of companies including Honeywell, Mitsubishi, and Motorola. It works on various unlicensed frequencies, providing 20-250 kbps connections over 30 to 200 feet. The big advantage of Zigbee is its low-power consumption and low cost, which are essential for remote monitoring and sensing.

Ultra-wideband (UWB) is more than a PAN technology. However, its initial applications in the communications market are for short-range, PAN-type uses. UWB is a form of spread-spectrum transmission that uses such a wide band, and such low power, that it can “underlay” with licensed users in the same band. The UWB signal appears as background noise to other transmitters. The nature of the technology gives it several other advantages, including very low power consumption, security, and penetration of walls. Until the FCC’s decision in early 2002 to legalize UWB for communications, its primary application was for ground-penetrating radar and military uses.

Today, companies such as XtremeSpectrum and Time Domain are building UWB chipsets targeting short-range, high-bandwidth data applications. UWB systems can deliver 100 Mbps or more over short distances, which makes them ideal for uses such as streaming audio or video between media devices within the home. Several companies including HP, Kodak, Philips, Motorola, Samsung, Sharp, Time Domain, and XtremeSpectrum have created the WiMedia Alliance to promote this application. Though UWB was late to the PAN party because of its recent approval, it has recently been gaining adherents within the 802.15 group. Most of the proposals for the forthcoming 802.15.3a standard, a higher-speed PAN protocol, involve some form of UWB.

## Success Stories

*Today’s WiFi Markets*

There are four major WiFi markets today: home networking, corporate/campus networking, commercial hotspots, and public access.

**HOME NETWORKING** means sharing an Internet connection, or a peripheral such as a printer, among more than one PC. Vendors such as Proxim, Netgear, Linksys (now part of Cisco), D-Link, and 2Wire have sold millions of access points and cards to end-users for this purpose. Broadband service providers are now getting into the game, recognizing that there is significant demand for home networking as an add-on to high-speed Internet access.

**CORPORATE OR CAMPUS ENVIRONMENTS** (in both the business and university sense) are slightly different than homes. Except for very small offices, multiple access points are required to cover the facility. These customers generally want security, authentication, and management capabilities to operate the WiFi network in conjunction with their existing wired networking infrastructure. All the major networking vendors, such as Cisco, Lucent, and Nortel, now have substantial corporate WiFi customer bases.

**HOTSPOTS** are access points available to anyone within a location, such as an airport, a café, or a hotel lobby. Sometimes the hotspots require a fee for access. Vendors such as Wayport and Mobilestar (now T-Mobile) deploy hotspots in locations that receive significant foot traffic, as both a money-maker and an incentive for more traffic. The best-known hotspot deployment is at Starbucks coffeehouses, now operated by T-Mobile. Aggregators such as Boingo and iPass allow users to pay one fee and access multiple networks of hotspots.

### NYCwireless: Evolution of a Wireless User Group

To followers of the wireless broadband revolution, New York has been a hotspot of activity among U.S. cities, and the NYCwireless user group has been leading the movement. The group began as an informal network of early WiFi adopters who placed access points on their apartment windows to share their broadband connections with the public parks below their buildings. As the trend gained acceptance, the users organized to form NYCwireless, a non-profit, volunteer organization, to encourage others to share their broadband and foster an ethic of free public Internet access across the city.

"New Yorkers live in cramped quarters, and our goal has been to get people out of their apartments and into the public parks," says NYCwireless volunteer Dustin Goodwin. The group considers ubiquitous broadband access to be a public amenity equivalent to streetlights or water fountains. However, it's difficult, if not impossible, to provide public parks with wired broadband access because of construction impediments on historic or public land. Cheap, and easily installed WiFi technology allowed apartment dwellers with good line-of-site to their parks to install the 802.11b transmitters and address the problem for themselves.

Volunteers from NYCwireless have built networks in Bryant Park, Bowling Green Park, and Tompkins Square Park, among others. This past year, founding members of the group formed a consulting firm, Emenity, to deploy six more public hot spots in lower Manhattan for the NYC Downtown Alliance. The new company was started to provide service to commercial clients, but their mission of building public access networks remains intact.

Emenity has recently built a public network in Union Square Park. This project is unique in that it relies on a wireless backhaul to connect to the Internet provided by the commercial wireless broadband provider TowerStream. Most public access points in the city ultimately access the Internet via a DSL Internet connection.

The efforts of NYCwireless have not gone unnoticed by broadband service providers. Some providers have slapped "acceptable use" clauses on their subscriber contracts in an effort to discourage wireless bandwidth sharing. One large cable operator has been accused of sending out a WiFi "sniffer" to scour the city in search of access points leading back to their customers' connections to close down the transmitters.

However, as WiFi use has reached a critical mass, more broadband providers are trying to enter the public space arena. Speakeasy, Inc., a national DSL reseller, now offers "WiFi Netshare," a service that allows users to resell their broadband connections to neighbors, with Speakeasy handling the billing. And Verizon DSL has built a number of hotspots in New York that are free to their DSL home subscribers.

NYCwireless volunteer Dustin Goodwin sees the commercial efforts to deploy WiFi in the city as a direct response to NYCwireless' success. While some see the entrance of commercial players into the public space as a threat to free access, others see the development as an important step to recognizing WiFi as a free public amenity that companies and organizations should provide as a value-added service to their constituents.

Now that wireless broadband has gained a foothold in New York City parks, Goodwin says that NYCwireless is expanding its mission to resemble a volunteer "Geek Corps" for communities without affordable broadband Internet. NYCwireless volunteers have trained residents of a community housing organization to build and maintain their own wireless network, which will provide more than 50 residents with private, high-speed connections. This effort is part of a growing trend among wireless community groups across the country to bring affordable broadband to underserved communities. – **Matt Barranca**

The spread of hotspots has been remarkable. Boingo now has more than 1,200 nodes on its network. T-Mobile operates 2,300 hotspots, including Starbucks coffeehouses, Borders bookstores, American Airlines Admirals Clubs, and terminals at fifteen airports in North America. It has announced plans to put hotspots in the more than 1,000 Kinkos copy shops throughout the U.S.

This is only a fraction of the total. One Website lists more than 5,000 hotspots worldwide, including both commercial and community nodes.[41] And that's just the beginning. According to Pyramid Research, 1,000 hotels offer WiFi access today, mostly in lobbies and meeting rooms, and 25,000 will have it by 2007.[42] Cometa, a joint venture funded by AT&T Wireless, IBM, Intel Capital, and venture capital firms 3i and Apax Partners, plans to build 20,000 hotspots using a wholesale model, with its first customer being McDonald's.

In addition to the access points intended for public consumption, most private WiFi nodes do not use any security mechanism, making them available to anyone within range. A map of Manhattan prepared last year by the Public Internet Project, whose volunteers systematically drove through the streets with WiFi-sniffing equipment, shows public and home access points already covering most of the island (see Figure 12). Preliminary results from the group's 2003 survey suggest WiFi density has become significantly greater since the original map was published.


FIGURE 12 – WIFI ACCESS POINTS IN MANHATTAN

**PUBLIC ACCESS** means providing free connectivity to users within a particular area. Sometimes this is done by private groups sharing their own networks or promoting the concept of ubiquitous wireless connectivity. In other cases the access is funded by public organizations, non-profits, or corporations as a type of civic amenity.

In all, the number of regular wireless LAN users is expected to grow sevenfold in the next four years, from 4.2 million to 31 million, according to the Gartner Group.[43]

*Independent Community Access Points*

There are dozens of community WiFi organizations in cities throughout the United States, and around the world. Typically, these groups are early users of WiFi technologies. They come together in physical meetings and through online discussions to share experiences, ask questions, and experiment with new technologies. In many cases, they install their own WiFi infrastructure, with access open to all. They deploy these hotspots where they can or want to, rather than follow some master plan.

The most active community WiFi groups include SF Wireless in San Francisco; NYCwireless in New York; SeattleWireless; and the Personal Telco Project in Portland, OR. The infrastructure is typically contributed by members, though increasingly these community groups have formed partnerships with local businesses and community development organizations.

*Hotspots as Civic Amenities*

In several cities, hotspot deployments are being funded by civic organizations or corporate sponsors as civic amenities, like parks or playgrounds. In Manhattan, Intel and the Bryant Park Restoration Corporation supported a project by NYCwireless to establish a WiFi network in Bryant Park, a popular outdoor gathering place in midtown. The University of Georgia has funded a network of WiFi hotspots covering all of downtown Athens, GA. In Long Beach, CA, the Long Beach Economic Development Bureau partnered with several local businesses to establish a WiFi network covering several downtown blocks, with plans to expand it throughout the city's business district.

For the civic groups involved, the costs of these WiFi networks are relatively minor, especially when businesses become involved and provide free Internet bandwidth and other services. Wireless

**A Community Access Model for the Last Mile**

While the success of commercial WISPs has generated much attention, grassroots community access networks or CANs are the originators of the unlicensed movement. Most CANs are groups of like-minded individuals sharing a similar philosophy—that citizens should have open, inexpensive, and ubiquitous access to the Internet. Using affordable and easily installed WiFi technology, community members in Seattle, New York, Austin, San Francisco, Portland, Oregon, and Athens, Georgia have built expanding networks of independently maintained wireless access points.

Most CANs provide access to public spaces, however some groups have made forays into residential space, by connecting neighborhoods with centrally placed access points. One such organization is the Bay Area Wireless Users Group (BAWUG), an informal group of wireless early adopters who began mounting WiFi transmitters on the roofs of their homes to give neighbors free or shared-cost Internet connections via their DSL and cable lines. While the cable and phone companies didn't approve of the practice, consumers did and access points began popping up all over the city. There are now more than 25 BAWUG access points in the area.

But BAWUG has not stopped there. Under the leadership of Tim Pozar, a telecommunications engineer and one of BAWUG's founders, the group has launched the Bay Area Research Wireless Network (BARWN). BARWN is an active wireless network with a mission to discover the best technical solutions to bring wireless broadband to remote and economically disadvantaged communities.

BARWN has set up two centrally located access points atop the San Bruno Mountain and Potrero Hill in south San Francisco, allowing anyone within an 8-mile radius to point a 2.4 GHz antenna at the BARWN towers to share the 11Mbps of bandwidth they provide. Pozar says that a third public access point is soon to be installed on Yerba Buena Island in the San Francisco Bay, which will link to East Bay and light-up an underserved area called Treasure Island.

All of these access points are constructed with non-proprietary equipment and open protocols to keep costs down and to learn what technologies can be most easily adopted by lower income communities.

As evidence of the network's stability and flexibility, BARWN is working with the City of San Francisco to use this network for public safety communications—such as earthquake or disaster response. Pozar says one application for the unlicensed service would be to provide streaming video of a disaster site to command centers to evaluate response tactics. – **Matt Barranca** connectivity is becoming a benefit that draws people into downtown areas.

*Internet Connectivity for Rural Communities*

High-speed Internet connections are available to most of the U.S. population today through digital subscriber line (DSL) or cable modem service. However, there are still tens of millions of Americans who live in rural or otherwise underserved areas, where such broadband offerings are not yet available. In some cases, they are unlikely to be available any time soon. Technically minded citizens in some of these communities have seized upon unlicensed wireless as an alternative route to provide connectivity.

In Laramie, WY, a group of technologists led by Brett Glass established LARIAT, a non-profit community wireless network. It has been in operation since the mid-1990s, originally using pre-WiFi unlicensed equipment in the 900 MHz band. A similar effort is MagnoliaRoad.net, a cooperative in a rural part of Colorado that is offering WiFi connectivity to local residents who have no other good broadband option.

**Revolution in the Rural Last Mile: Unlicensed Spectrum Closing the Technology Divide in Northern Virginia**

Despite their proximity to Northern Virginia's Internet backbone, many towns in Loudoun County have no broadband access. The mountainous western regions of the county are far from the technology infrastructure of Northern Virginia where companies like AOL and VeriSign reside. However, because of license-exempt wireless activity, the technology divide across the county is starting to close.

After the technology bubble of the late 90s burst, Northern Virginia lost as many as 30,000 jobs. Many laid-off professionals accustomed to broadband connections at their work started their own businesses or began working from their homes, creating a large demand for high-speed home services. One start-up, Roadstar Internet, is trying to meet that demand with an expanding rural wireless network.

Started in the autumn of 2002, Roadstar Internet connects more than 150 rural households and small businesses relying only on unlicensed spectrum. Most wireless subscribers do not know exactly how their service operates. What matters most to users is not the technology behind the service, but that their connections are fast and reliable. The Roadstar network is similar to many other WISP efforts, using a combination of point-to-point connections for the long-distance transmissions, and point-to-multipoint transmissions to connect neighborhood access points to subscribers.

The first leg of the network travels 18 miles from a mountaintop transceiver using 5 GHz bands and OFDM (Orthogonal Frequency Division Multiplexing) point-to-point technology. OFDM transmissions make efficient, and secure, use of spread spectrum by dividing data into packets and encoding it over multiple frequencies, without requiring perfect line-of-site.

Long distance point-to-point transmissions are the standard for rural WISPs seeking to reach larger population pockets. Under Part 15 rules for unlicensed usage, the FCC allows operators to make point-to-point connections without reducing Transmitter Power Output (TPO) for the 5.725 GHz and 5.825 GHz band. Because of this regulatory latitude for narrow beam transmissions, providers are able to reach long line-of-site distances with relatively low power.

The Roadstar network makes final, last-mile connections within neighborhoods by using modified WiFi wireless access points mounted on customer silos, barns, and rooftops. WISPs are able to transmit distances greater than the 300-foot standards for WiFi technology by creating sectorized cells with high-gain, directional antennas. These last-mile connections on the 2.4 GHz band are the result of good planning and engineering, and typically reach two to three miles. – **Matt Barranca**

Meanwhile, Dewayne Hendricks of the Dandin Group is spearheading efforts to provide wireless Internet connectivity, using WiFi and other technologies, on several Indian reservations in the U.S. and Canada. More than 1,000 commercial WISPs are providing similar wireless broadband services, mostly in underserved rural areas across the nation (see sidebar, page 34).[44]

*Internet Connectivity for Low-Income Areas*

High-speed connectivity has important benefits for low-income and underserved communities. Broadband Internet access opens the door to educational, informational, job-related, benefits, health, and other materials. However, the costs of wiring low-income facilities such as public housing complexes has traditionally been prohibitive, given that most residents cannot afford to pay typical monthly broadband prices. WiFi is one answer.

In Boston, an MIT graduate student named Richard O'Bryant led an effort to put free WiFi hotspots in Camfield Estates, a 102-unit public housing development in the Roxbury area, with funding from HP and Microsoft. In Philadelphia, the United Way is building two WiFi hotspots in the poor section of West Philadelphia, which will offer broadband Internet access for $5 to $10 per month. It plans to give away computers and wireless cards to people in the community who cannot afford them. In Portland, OR, a non-profit called One Economy is putting WiFi connections into three public housing developments, serving more than 500 residents.

# Future Scenarios

## Expanding the Space of Possibilities

We have only scratched the surface of what dynamic wireless systems can do. The growth of WiFi has been so striking, its possibilities so exciting, that WiFi has become virtually synonymous with unlicensed wireless and open spectrum. This is a mistake. WiFi is not the culmination of the wireless story; it is merely the end of the beginning.

### WIFI HAS TWO GREAT LIMITATIONS: ITS PROTOCOL, AND ITS SPECTRUM ENVIRONMENT.

The engineers who created the 802.11 family of protocols had no idea that WiFi would take off the way it has, and would be used in so many different deployment scenarios. They were creating a wireless Ethernet standard, parallel to the wired Ethernet standard that is the basis for most office computer networks today. Thus, WiFi has limited range, and a routing layer that isn't particularly good at mesh networking, quality of service, interference management, security, or many other functions that are important for many of its potential markets.

At the same time, the government regulators who established the 2.4 GHz and 5 GHz unlicensed spectrum bands where WiFi operates had even less idea of what was coming. Especially for 2.4 GHz, they were looking at "industrial, scientific, and medical" equipment, and devices such as cordless phones. The rules they created for managing those bands have been highly successful, but they were hardly designed to maximize the potential. Based on our current experience, we can design rules expressly to promote efficiency and innovation through unlicensed wireless technologies.

First and foremost, this means making available more spectrum for unlicensed uses, whether it be through dedicated unlicensed bands, shared underlay access, or opportunistic sharing. Second, it means putting in place minimal rules for that spectrum, which may be as little as power limits, to foster an environment of efficient cooperative development.

The wireless future, under any scenario, is likely to be marked by increasingly pervasive but non-uniform connectivity. No wireless technology, let alone one service provider, can address all the markets and deployment scenarios, from short-range low-bandwidth to long-distance broadband. Even if unlicensed systems succeed beyond anyone's wildest dreams, there will be a need for licensed services for many years. Even if there is soon WiFi in every coffeehouse, getting it in every dry cleaner will take longer, as will getting it in every train and airplane.

The downside of such a heterogeneous environment is that everyone is not connected all the time, and any one system or technology will provide only a small percentage of what connectivity does exist. The natural impulse in communications is to

**An Unlicensed Education: A Wireless Model to Connect Rural School Communities**

While U.S. school districts have been issued the command to "leave no child behind," many rural schools are without the resources to bring broadband Internet access into their classrooms. This last-mile problem presents hardships not only for schools, but also for local households and businesses unable to fully participate in the information economy. A public/private partnership has been formed in western Pennsylvania to use unlicensed spectrum and the social capital of local school districts to address the last mile on their own. The efforts of the Broadband Rural Access Information Network (BRAIN) have yielded great results connecting rural areas, and their example could provide a model for rural school communities across the country.

The BRAIN effort began with the vision of a school district superintendent, Andy Demidont, and the help of a large regional WISP, Sting Communications. Demidont wanted to provide high-speed access to Rockwood High School and Kingwood Elementary School in mountainous Somerset County. The schools' existing dial-up accounts were expensive, and rendered connection speeds barely surpassing 14 kbps.

Relying on technical guidance from Sting Communications, and using grant money awarded from the Individuals with Disabilities Act and E-Rate discounts, the school district installed wireless access points on the roofs of both schools, turning both schools into state-of-the-art, wireless hotspots.

In total, Sting Communications installed three towers, creating a pie-shaped hot zone using the 5.8 GHz and 2.4 GHz license-exempt bands. The Rockwood High School gymnasium hosts a 100-foot tower that transmits to a 150-foot tower located at Kingwood Elementary School. The two towers share a narrow beam, point-to-point connection with a third tower owned by the local Seven Springs Ski Resort.

Simply bringing the technology to the area wasn't the end goal – using the network to connect the school with the community is the ultimate design of the project. Both schools have put many classroom operations on-line. Teachers use Palm Pilots and laptops to track student progress and record grades, which are available to parents online.

The project also gives community residents a chance to purchase access from the school's network, with the school district serving as a WISP for the area. Sting has installed access points in many neighborhoods, and the company is offering subscription rates between $11 and $20 per month, depending on the number of subscribers the school can attract. Currently, thirty-five families have been connected, with an additional 65 families expected to be online in the coming months.

From the project's onset, Sting hoped their school-based approach could be replicated in other rural communities. Building on what they have learned in Somerset County, Sting has built a much larger network in Cambria and Clearfield Counties to connect four more regional school districts. Sting vice president Bob Roland says that this new network spans an 1100 square-mile area, and uses both 5 GHz frequency-hopping spread spectrum and 802.11 connections for the last mile.

For the next phase, BRAIN has applied for an additional $7.4 million grant from the USDA's Rural Utilities Service to "light-up" a wide corridor between central Pennsylvania and Maryland. If successful, this effort could provide a model for building a wide-area regional network, one school at a time. – **Matt Barranca** try to build all-encompassing networks, but sometimes that isn't the best approach. WiFi hotspots are spreading because they are cheap, funded by users or facility owners, and go where there is demand today. They don't yet go where there isn't demand, but the good news is that users need not pay for the extra cost of putting access points there. As software-defined radios mature, they will make it possible to stitch together some systems at the end-user device. In general, though, the real question is not how to provide ubiquitous wireless connectivity in the abstract, but how to address concrete needs and market opportunities.

The scenarios below represent examples of opportunities that unlicensed wireless technologies could address. They are relatively straightforward extensions of existing technology. Most, however, will require either spectrum reforms to expand the space available for unlicensed devices, or at the very least no regulatory actions that would hamstring unlicensed devices in the existing areas.

### The Last Wireless Mile

Broadband connectivity to homes is a topic of great consternation in the communications industry today. Telephone companies are deploying DSL and cable TV operators are deploying cable modem systems. However, many millions of Americans still have neither available to them, and a greater number have only one option. Prices of these broadband services, approximately $50/month, are high compared to the rest of the world. These services are generally asymmetric, providing far more bandwidth down to the user than up from the user to the Internet. Combined with terms of service restrictions, this architecture limits users from running home servers and other actions. For business users, who typically need higher bandwidth than homes, the only viable option is often a traditional T-1 line at $1,000 per month or more. There is thus great interest in alternatives.

Basic WiFi or its variants, 802.11a and 802.11g, cannot simply be put into service for last-mile deployments. WiFi is a short-range technology designed primarily for connections to a nearby hotspot. Even if every home in a neighborhood had a WiFi access point, few of those nodes would see one another and there would be no mechanism

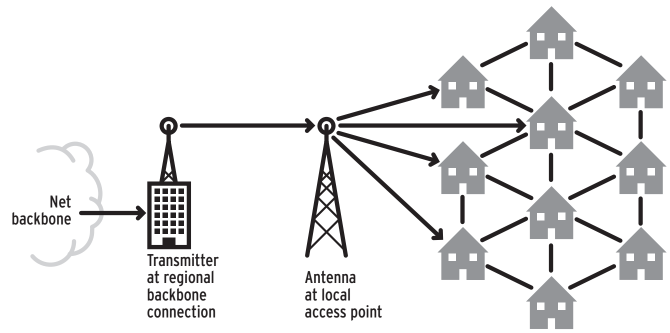


FIGURE 13 – WIRELESS LAST MILE: In one wireless last-mile scenario, a transmitter tower connected to the Internet transmits in a point-to-point connection to a community access point, which makes point-to-multipoint or mesh network connections to households.

to link them together. Even if signals could reach a neighborhood access point, backhaul costs would be significant, because every access point would need a wired connection to a T-1 or larger circuit.

We can, however, envision scenarios for unlicensed wireless last-mile connectivity based on technology that is in the market or likely to be soon. For homes, a mesh network configuration could be used to shorten link lengths, increase robustness through alternate traffic paths, and address impediments such as trees. A range-extending technology such as Vivato's phased-array antennas could also be employed to receive signals from a cluster of nodes in a local area. For businesses or residences wanting more bandwidth, an 802.16 wireless MAN technology could be used to deliver tens of megabits per second over many miles. This same technology, or a variant, could be used to reduce the costs of backhaul, replacing costly wired connections.

An end-user would buy a device, whether a dedicated piece of wireless hardware, a broadband "residential gateway," or a piece of general-purpose hardware such as a laptop. The device could be designed to operate with a particular unlicensed wireless network, it might be deployed by a service provider, or it might have "discovery" capability to automatically locate and connect with nearby access points or wireless end-users.

It is typically assumed today that last-mile broadband networks are designed to provide access to the Internet (see Figure 13). Certainly, any broadband customer will want to access Internet-based services available through the World Wide Web, as well as global email, instant messaging, and other applications. However, these are not the only things that an unlicensed last-mile wireless network could deliver. There is often value in online communications *within* a community, especially when that community has not previously had a high-speed, always-on network. These range from intra-community email to school bulletin boards to decisions of the city planning board. They could be called community intranet applications. Because the traffic is local, there is no need to connect to a backbone provider. In fact, there may not be a need for any provider at all. If users provide their own wireless nodes, and no node is overwhelmed with traffic, the community-wide network would function peer-to-peer, much as local area networks in businesses do today.

**"I am hopeful that unlicensed operations will...eventually provide a last-mile application to connect people's homes to the Internet, offering a real alternative to telephone wires, cable, and satellite connections."**

– FCC COMMISSIONER KEVIN MARTIN

When the network needs to connect to the Internet, an economic problem emerges. Internet backbones charge for use based on bandwidth consumed. Even if Internet-based services and content are a minority of traffic on a wireless community last-mile network, there still must be backhaul connections to the Internet, and these must be paid for. There is a "free-rider" problem if the node connected to the backbone must bear all the costs, independent of whether there is any congestion across the unlicensed wireless links between the community nodes. It may be necessary to develop some sort of pricing mechanism for end-users in such a situation. However, pricing could be implemented in several ways. It does not require central providers or per-packet settlement charges. For example, a cooperative could collect dues from all community members and apply those to the backhaul charge, with some limits on each user's bandwidth to prevent free riding.

### Interoperable Public Safety Communications

Today, public safety agencies use many different wireless communications systems. Many of them use outdated technology. Few if any can talk to one another. In an emergency, if the fire department can't communicate with the police, the consequences could be disastrous. On September 11, 2001, firefighters were trapped in the World Trade Center because they were unable to learn from other public safety officers outside that the buildings were about to collapse. Stories abound, from 9/11 and other times, of firemen using commercial mobile phones because they had better performance and a wider audience than their expensive private radios. And when these networks go down, everything goes down with them. Unfortunately, public safety organizations are saddled with many legacy communications systems that are costly and difficult to upgrade.

As software-defined radios (SDR) mature, they could replace the cacophony of devices with a single set of devices. One phone handset, PDA, or laptop could tap into any of the existing systems. A firefighter arriving on the scene could instantly check police communications as well as data transmissions providing essential information directly from dispatchers, such as building maps. Such a system would require robust security and authentication mechanisms, but these could also be built into the devices. The result would be both lower costs and more effective systems for critical public safety services.

### Adaptive Mobile Phones

Mobile phone networks today are self-contained entities. In the U.S., for example, there are six competing national networks. Each has its own network of transmission towers. If you are within range of five of those towers, but not the one for your service provider, you won't get service. Things are a little better in Europe, where universal adoption of the GSM standard allows for more roaming agreements between carriers, but each carrier still must maintain its own complete network.

As mobile phones evolve into SDR devices, the structure of the business may change. Carriers will be able to share infrastructure much more widely, because their subscribers will be able to transparently access transmissions from whatever tower is closest to them, regardless of what frequency band or encoding mechanism it uses.

Further, there are an increasing number of local connectivity points, such as WiFi hotspots, that are separate from the wide-area wireless networks. When a user was within range of a hotspot, adaptive mobile phones could transparently shift communications from voice transmissions over the mobile networks to voice-over-IP or packet data connections through the WiFi infrastructure. Tapping these local nodes would reduce costs, avoiding the need to send data long distances over wireless networks, and would give users the maximum possible capacity, since WiFi hotspots tend to offer substantially greater bandwidth than wide-area data networks.

### Personal Broadcast Networks

Today, broadcasting is the domain of the few. Only companies with licenses have access to the airwaves to deliver programming. Using a combination of the

### Think Globally, Act Locally: Two WISPs Come of Age

At the onset of the unlicensed movement, most Wireless ISPs (WISPs) were scaled-up WiFi hotspots built from adapted, off-the-shelf, 802.11b equipment. But unlicensed devices have advanced beyond WiFi to include frequency-hopping, non-line-of-sight transmitters, and other technologies such as high-gain directional antennas that reach distances well over 20 miles. The most successful WISPs have outgrown the WiFi model and evolved into sophisticated wide-area networks with a high standard for service, security, and stability.

AMA*TechTel Communications of Amarillo, Texas is one example. With more than 4,000 users on their license-exempt network, AMA is one of the country's largest regional carriers of wireless broadband. AMA's 63-tower deployment is a 20,000 square-mile, contiguous network providing secure service to numerous towns, three college campuses, multiple school systems, hospitals, and banks.

AMA relies on equipment manufactured by Alvarion to access the 900 MHz, 2.4 GHz, and 5 GHz unlicensed bands for backhaul and point-to-multipoint connections. The network's expansiveness is due to AMA's partnership with Attebury Grain, a large grain storage company that initially contracted AMA to wirelessly connect their grain elevators to the commodities market. After the project, the two companies partnered, using Attebury's numerous grain elevators as transmitter towers to provide service to local towns and businesses.

While AMA's wide-area deployment may be a daunting example for WISP entrepreneurs, this ambitious network isn't the only successful model. Hundreds of start-up WISPs have relied on skillful engineering to build smaller networks for remote communities. Prairie iNet, of Des Moines, Iowa has used this localized approach to build a network of unlicensed wireless oases in more than 120 rural communities in Illinois and Iowa.

Neil Mulholland, Prairie iNet CEO, estimates that to reach their standard for "carrier class" service, the company invests $100,000 in each population center for base station, customer premise equipment, and a wireless link to their DS-3 Internet connection. Ideally, the company covers their investment in each local network after the first 75 customers. The company has more than 4,000 subscribing customers in total.

Both models – AMA's wide-area design and Prairie iNet's localized networks – present varying benefits. Regional utility companies can learn from AMA and leverage their tower infrastructure to provide virtual private networks for campus clients and basic service for their residential customers. The East Bay Municipal Utility District in Oakland, California has installed the Motorola Canopy system; Owensboro Municipal Utilities in Kentucky and Wheatland Electric Cooperative in Kansas have both installed Alvarion networks; and Midwest Wireless, a rural cellular provider, has built a broadband business using unlicensed spectrum.

Prairie iNet's localized model has been replicated in smaller scales in rural areas across the country. In-Stat/MDR, a technology research company, estimates that there are up to 1,500 start-up WISPs in operation. Low start-up costs, numerous equipment options, and high consumer demand account for this growth. – **Matt Barranca**

### WiFi Calling: Campuses Turn to WiFi for Voice Applications

Since the beginning of the wireless movement, college and corporate campuses have been fertile ground for extensive WiFi networks. The latest trend for campus organizations is to bypass local telephone carriers and use their unlicensed wireless networks to support voice applications.

In one example, the University of Arkansas invested $4 million in Cisco's call-processing software, CallManager, to traffic local calls over the University's existing WiFi network. The University has reduced their monthly telephone service fees from $530,000 to $6,000 a month. At this savings rate, the University should recoup their call-processing investment in six months.

Dartmouth College has a similar program, offering software to incoming freshman that turns wireless laptops and PDAs into "softphones." Dartmouth implemented their voice over wireless local area network (VoWLAN) when they realized they were spending more money billing students for long-distance calls than they were taking in. The unlicensed VoWLAN provides a similar quality of service to traditional telephone service, but without the billing and administrative costs.

Hospitals have also been early adopters of VoWLAN technology. One company, Vocera, has created an 802.11b communications device that doctors and nurses wear on their uniform collars to communicate with each other remotely. Users speak the name of the person they'd like to contact into the device, and they are instantly connected through the VoWLAN. The device has the potential to eliminate intercoms and speakers that broadcast announcements or pages meant for only one person to an entire hospital floor. **– Matt Barranca**

techniques described in this paper, it is possible to imagine a world in which anyone can be a broadcaster.

As each user sends out video streams, they would be relayed by other users wherever infrastructure was unavailable. Cognitive radios would seek out free space in the spectrum to carry the signals. Content creators could contract with operators of virtual broadcast networks who aggregated together reliable high-speed connectivity to reach an audience, creating a bottom-up division between different classes of traffic.

Who would want to have their own broadcast network? Some people would want to deliver the kinds of creative programming available on television today. These personal wireless networks would become a much more powerful version of the alternative outlets available today, such as public access channels on cable TV systems, public broadcasting stations, low-power FM radio stations, and the Web. If consolidation in the media distribution business threatened the diversity of voices available to viewers and listeners, personal broadcast networks would provide a powerful antidote.

But the existing market for heavily produced, mass-market content would only be a small part of the total. Working parents would use personal broadcast networks to tap into video images of their children at home, streamed from Webcams to their mobile phones. Distance learning courses could be delivered on demand, or specific instructional modules could be delivered dynamically when and where they were needed. Need to change a flat tire and don't know what to do? Need on-the-spot medical advice? Use a personal broadcast network to watch an instructional video or establish a videoconference with an expert.

Predicting the future is dangerous. Any scenarios we envision today will likely miss the specific kinds of applications and content that will be popular tomorrow. But that doesn't matter. The infrastructure of emerging wireless technologies can be adapted to whatever turn out to be the killer apps. Wireless networks built using intelligent, dynamic techniques from the computer and networking industries will feature radical flexibility. Network owners need not predict uses in order to shape their infrastructure build-out, because there will be no owners, infrastructure, or build-out in the current senses of the words.

# Policy Recommendations

Governments should recognize and embrace the tremendous potential of the radio revolution. In the U.S., the FCC's November 2002 Spectrum Policy Task Force report[45] acknowledged that technological changes allow for new forms of spectrum access and interference management. It therefore proposed expanded use of the commons model. In June 2003, the Bush Administration formed a task force to examine government spectrum use, with a similar mandate to propose reforms.

The FCC has begun or announced plans for a raft of spectrum reform proceedings. These include: unlicensed sharing of the broadcast spectrum; changes to allow unlicensed access to underused education spectrum in the 2.5 GHz band currently allocated for Instructional Fixed Television Service (ITFS); incentives for unlicensed deployment in rural areas; investigating the impact of cognitive radio and the unlicensed allocation of extremely high frequency spectrum (above 50 GHz); and, a novel method for noise floor baselines called "interference temperature."

Because radio signals do not respect political boundaries, spectrum policy is inherently international. Equipment vendors can better justify the investment needed to develop new products when they can foresee a global market. Hence, international harmonization of spectrum bands is valuable, especially for unlicensed bands. Participants at the 2003 World Radio Conference agreed to expand the globally unlicensed spectrum in the 5 GHz range, adding 255 MHz to the existing allocation.

Despite these encouraging developments, more needs to be done. Governments cannot merely sit back and wait for technological development to eliminate spectrum scarcity. Spectrum policies around the world remain centered on what the FCC calls a "command-and-control" model, more appropriate for the industrial era than for the coming age of digital networks. Though government regulation of the radio spectrum was designed to manage and mitigate physical scarcity of the airwaves, that regulation now creates scarcity.

As a general matter, the federal government should recognize that the objective of spectrum policy is not to minimize interference, but to maximize usable capacity. It should move away from command-and-control toward more flexible approaches, recognizing that there is value in a diversity of legal regimes. In experimenting with exclusive property rights and secondary markets, it should balance the potential gains against the opportunity cost of making that spectrum available for unlicensed sharing in the future. Wireless devices will continue to become increasingly sophisticated and inexpensive. Policy decisions should take into account the possibility that what is impractical now may be commonplace in the future...if there is room for innovation.

> **"Increasing demand for spectrum-based services and devices are straining longstanding, and outmoded, spectrum policies."**
>
> – FCC SPECTRUM POLICY TASK FORCE

Specifically, policy initiatives should proceed in four areas:

- **MORE DEDICATED UNLICENSED SPECTRUM**

The FCC and other government agencies should continue their efforts to identify additional spectrum for unlicensed use. Some spectrum may become available through return of analog broadcast television licenses as part of the digital TV transition,[46] or from guard bands established to protect obsolete devices. Other spectrum could be shifted from government or military use, or through restructuring of under-utilized bands such as the UHF television and MMDS/ITFS frequencies.[47]

Unlicensed spectrum at low frequencies, below 2 GHz, is particularly important. Transmissions at those frequencies can more easily penetrate trees, walls, and other obstacles, a key consideration for last-mile broadband applications. They also use less power, and thus make more efficient use of batteries, a key consideration for portable consumer electronic devices such as PDAs. Contrary to the recommendation of the FCC's Spectrum Policy Task Force, new unlicensed allocations should not be limited to spectrum above 50 GHz. However, as much spectrum as possible at such extremely high frequencies should be made available for unlicensed use with minimal restrictions.

- **SHARED UNLICENSED UNDERLAY**

The FCC should advance its proceeding on unlicensed sharing of broadcast and other licensed spectrum bands. It should also make good on its commitment to review its rules governing ultra-wideband and low-power FM radio, both of which are subject to significant restrictions. Interference with licensed services is a legitimate concern, but hypothetical fears unsupported by the evidence should not trump innovation and competition.

The FCC should work with companies and standards bodies in the private sector to identify other technical means for unlicensed sharing. The interference temperature concept outlined in the FCC Spectrum Policy Task Force report is promising but undeveloped. Identifying more clearly the boundaries between high-power licensed and low-power unlicensed services in the same bands would benefit both types of systems. However, the boundaries should not be so low as to preclude viable unlicensed devices.

- **OPPORTUNISTIC SHARING**

The FCC should allow for spectrum sharing along the other dimensions of the electrospace model. Depending on the nature of the licensed use, the government can make under-utilized frequencies available for non-interfering shared access by time, geographic area, direction of signals, or other variables. By establishing guidelines for cognitive radios that can sense and respond to the local spectral environment, the government could in effect create "virtual white-space" within spectrum that is already licensed. The Defense Advanced Research Agency's (DARPA) XG sharing technology provides one model for doing this. The XG moniker stands for "neXt Generation."

The FCC should pursue its proposal in the Spectrum Policy Task Force report to examine standards for receivers. Existing rules focus entirely on transmitters, but as discussed in this paper, interference is a phenomenon that manifests itself on the receiving end. Poorly defined spectrum licenses create incentives to build the cheapest, least robust receivers allowed. A poor-quality receiver may not affect the service for which it is licensed, but it will create scarcity by limiting the space for opportunistic and shared unlicensed devices around it.

#### EXPERIMENTATION AND RESEARCH

Because spectrum has long been highly regulated and controlled by a small group of licensees, opportunities for experimentation have been limited. WiFi happened almost by accident, because the 2.4 GHz "junk band" spectrum was so congested with devices such as microwave ovens that it was considered unusable for licensed systems. Because the band was unlicensed and open to public access, engineers and companies interested in wireless local area networking could use it for their commercially and technically unproven technologies.

The government should ensure that its rules for unlicensed bands allow for the broadest possible experimentation. It should also ensure that it provides ample opportunities for experimental authorizations that go beyond the existing rules, so that innovators can develop novel techniques. A large block of high frequency spectrum (above 50 GHz) that is currently unassigned could be designated as an open space for completely unregulated unlicensed activity, as Tim Shepard

### A Universal Communications Privilege for the "Supercommons"

Any set of prophylactic rules for wireless communication, no matter how liberal, will prevent some potential transmissions. The current block allocation system of government-licensed frequencies leaves huge quantities of spectrum fallow, even though today's devices could exploit the unused capacity with no harm to existing systems. Even with unlicensed allocations, underlays, and opportunistic sharing, some non-interfering transmissions will be precluded inefficiently. The optimal arrangement of wireless communications devices depends on location, time, pre-existing systems, the desired service, and technological capabilities. No set of rules determined ahead of time can possibly take all these factors into account.

The very idea of spectrum as a scarce resource divided into frequencies is becoming less and less useful. As devices become smarter, the effective communications space outside designated frequency bands increases. This "supercommons" cannot be exploited fully so long as only certain wireless systems are legally permitted to operate.

An alternate approach would be to establish a baseline universal privilege to communicate.[48] Anyone could engage in any form of wireless transmission they chose, so long as they did not impinge on other systems. Instead of prophylactic interference rules enforced by the government, a liability regime could be used to avoid and resolve disputes. Those suffering harm from other transmissions could sue for damages in court, using principles drawn from the common law doctrine of torts. Various safe-harbor and backstop mechanisms could be used to ensure the system operated efficiently. Equipment vendors and wireless device owners would have incentives to use intelligent mechanisms to increase capacity.

The supercommons regime could operate alongside existing licensed and unlicensed frequencies. It would expand communications capacity without threatening current allocations. Access to the airwaves would become a distributed, real-time decision rather than the result of a government pre-approval process. Innovation and investment would increase dramatically.

and Yochai Benkler have proposed. This would allow for real-world exploration of ideas that may later migrate to lower frequencies where propagation characteristics are better.

The government should also continue to support and publicize research on groundbreaking wireless technology. Among the key questions for exploration are: whether technical "etiquettes" are useful to facilitate efficient spectrum sharing among unlicensed devices, and if so, what those etiquettes should be; what are the fundamental information theoretic limits of radio communications; and how do large numbers of unlicensed devices using different transmission mechanisms perform in the real world.

# Conclusion

A powerful lesson from the history of communications and computing is that a few simple trends have extraordinary effects over time. The shift from analog to digital networks, for example, is revolutionizing all forms of communication and media. That transition has been going on for many years, and hasn't yet finished. Similarly, growing intelligence of computing devices at the edges of networks exerts a powerful force that is magnified over time.

The paradoxical fact is that wireless communications are both more mundane and more remarkable than we currently believe. The mundane aspect is that spectrum isn't somehow special and removed from the forces affecting other industries touched by the relentless improvements in computing and data networking. Spectrum isn't a domain where normal market and technological forces go out the window, replaced by iron scarcities. In fact, it's not a place or a thing at all. It's a mental construct we use to aid understanding. We are rapidly reaching the point where that mental construct does more harm than good.

The real question now is not whether but when. There is absolutely no question that wireless devices will continue to become more powerful, and that enterprising technologists will find new ways to multiplex and interweave radio signals. Whatever obstacles regulators or incumbents throw up will ultimately be routed around. The only immutable barriers are physical, and though they undoubtedly exist, we are nowhere near reaching them.

Through errors of both omission and commission, however, governments can delay and weaken the revolutionary changes that could bring into being the scenarios described in the previous section. If no more unlicensed spectrum is made available through dedicated open-access bands, low-power underlay, and opportunistic sharing, it will take that much longer to overcome the scarcities that define the market today. Such delays would have economic and social costs.

The last time a new networking and communications paradigm took hold, it was called the Internet. There too, it was possible to discern signs and possibilities years before the full commercial realization of the network. The U.S. government, through both affirmative steps (such as protecting nascent data services from domination by telephone companies) and conscious rejection of unnecessary regulation, laid the groundwork for the Internet to emerge as a powerful business and social force whose impacts are still being felt throughout the economy.

The next Internet is before us. It is an Internet of the air, in some ways even more powerful than the Internet of wires. If we put aside our preconceptions and outmoded notions, we can make it real.

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### *Community WiFi Directories*

http://www.seattlewireless.net/index.cgi/SimilarProjectLinks
http://www.personaltelco.net/index.cgi/WirelessCommunities
http://www.afcn.org/
http://freenetworks.org/moin/index.cgi/
http://www.communitywireless.org/

# Endnotes

[1] Albert Einstein reportedly offered an entertaining description of radio with a similar "negative" character: "You see, wire telegraph is a kind of a very, very long cat. You pull his tail in New York and his head is meowing in Los Angeles. Do you understand this? And radio operates exactly the same way: you send signals here, they receive them there. The only difference is that there is no cat."

[2] Arthur C. Clarke, *Profiles of the Future: An Inquiry into the Limits of the Possible* (London: Victor Gollancz, 1962).

[3] The word paradigm, since its popularization in Thomas Kuhn's *The Structure of Scientific Revolutions*, has become dull from over-use. A paradigm shift isn't merely a new technology or a new business opportunity. It's a change in cognitive framework. Our paradigms are the unconscious scaffolding we use to associate concepts and information. Most of the time they can safely operate in the background, but occasionally they break down. True paradigm shifts are rare, but this rarity increases their significance.

[4] This analogy was first developed by Tim Shepard in his comments to FCC's Spectrum Policy Task Force. See Timothy J. Shepard, "Spectrum Policy Task Force Seeks Public Comment on Issues Related to the Commission's Spectrum Policies," Comments to the FCC's Public Notice, ET Docket No. 02-135 (July 8, 2002).

[5] Capacity may not always be expressed in raw throughput such as bits per second. Some services have particular requirements. For example, live voice communication needs low latency (delay), while high-quality video broadcasting requires limited packet loss. An environment that allows these uses may be more valuable than one that does not, even if total carrying capacity is lower.

[6] For a list of some other multiplexing mechanisms, see Robert Matheson, "The Electrospace Model as a Tool for Spectrum Management," Paper presented at ISART 2003 conference, Boulder, CO, March 2003.

[7] This approach is known as Time Division Multiple Access (TDMA), and is the basis of the popular GSM standard for second-generation wireless phone systems.

[8] See New America Foundation and Shared Spectrum Company, "Dupont Circle Spectrum Utilization During Peak Hours," (July 2003) (finding a significant amount of spectrum is unused, even in dense urban areas during peak hours).

[9] Transitioning from analog to digital is another means of expanding capacity by changing the system design. Digital "2G" mobile phone networks support more simultaneous calls than analog "1G" systems, and they can support additional features such as data transmission and messaging. Yet the 2G systems actually use less spectrum.

[10] The layered model also has important implications for regulation. See Kevin Werbach, "A Layered Model for Internet Policy," 1 *Colorado Journal on Telecommunications and High Technology Law* 37 (2002).

[11] The seven layers, from bottom to top, are: physical, data link, network, transport, session, presentation, application. The OSI model is broadly used as a conceptual tool, but not always as a formal part of network design. In the 1980s, efforts to formally require adherence to the OSI standard failed.

[12] Separate from the technological critique developed here, there is a long and distinguished history of economic arguments against the current structure of spectrum regulation, generally advocating private property rights as an alternative to government licensing. However, the spectrum-sharing techniques the new dynamic wireless paradigm makes possible remove the need for exclusive rights to minimize interference. See Yochai Benkler, "Overcoming Agoraphobia: Building the Commons of the Digitally Networked Environment," 11 *Harvard Journal of Law and Technology* 287 (1998).

[13] The FCC has oversight over private spectrum, and NTIA is the lead agency for government spectrum. Several other agencies, including the Defense and State Departments, play significant roles in spectrum policy.

[14] The process of deciding which frequencies shall be available for which uses is known as allocation. Determining who is entitled to use those frequencies is called assignment. In many cases, spectrum bands are assigned to more than one user, or to one "primary" user and one or more "secondary" users.

[15] See Ronald H. Coase, "The Federal Communications Commission," 2 *Journal of Law and Economics* 1 (1959).

[16] This became an issue in the FCC proceeding authorizing ultra-wideband devices to underlay under existing licensed services. Sprint PCS argued that, because it had spent billions of dollars purchasing spectrum licenses and building out its mobile phone network, it had an expectation of exclusive control over the frequencies. The FCC rejected this claim, holding that even for flexible PCS spectrum, the license was not absolute. A licensee may have a reasonable expectation to operate free from harmful interference for the limited term of the license, but the government may give non-interfering users access to the same frequencies. See "FCC First Report and Order: Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems," ET Docket No. 98-153 (April 22, 2002).

[17] There are two different patterns to prevent interference in nearby cities. There is no channel 3 in New York, but no channel 2 in Philadelphia, to ensure the signals are received properly.

[18] In addition, because only a handful of big city markets have more than 13 channels on the air, TV channels 30 to 69 (234 MHz of prime spectrum) are in use in only about 10 percent of the nation's TV market, on average. See J.H. Snider and Max Vilimpoc, "Reclaiming the 'Vast Wasteland': Unlicensed Sharing of Broadcast Spectrum," New America Foundation, Spectrum Series Issue Brief #12 (July 2003).

[19] For an excellent discussion of the FCC's evolving regulation of interference, see Paul Margie, "Efficiency, Predictability, and the Need for an Improved Interference Standard at the FCC," Paper presented at TPRC 2003, Arlington, VA, September 2003.

[20] Harmful interference is defined as "Interference which endangers the functioning of a radio navigation service or of other safety services or seriously degrades, obstructs or repeatedly interrupts a radio communication service operating in accordance with the Radio Regulations." 48 CFR §97.3(a)(23).

[21] See Matheson, *supra* note 6.

[22] See Kalle Konston, "In Pursuit of a Wireless Device Bill of Rights," Presentation to the September 18, 2002 Meeting of the FCC's Technical Advisory Council (TAC).

[23] See "FCC First Report and Order: Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems," ET Docket No. 98-153 (April 22, 2002). UWB was previously used for non-communications applications such as ground-penetrating radar, especially by the military.

[24] Not to be confused with defunct digital subscriber line provider Northpoint Communications. Because its approach is so novel, Northpoint has had to endure a multi-year struggle to get its technology approved by the FCC.

[25] In a pure mesh, every receiver is also a transmitter and a repeater. However, this is not a requirement. The Internet, for example, has many different kinds of routers and networks, some of which are connected hierarchically with "edge" and "core" devices.

[26] See Sabrina Crawford, "Wireless Wheels: Police Now Using Internet to Solve Local Crime Cases," *The San Francisco Examiner* (September 18, 2003).

[27] Any digital wireless system involves some measure of software. SDR involves using software to control most of the functions that traditionally were handled through RF hardware.

[28] See George Gilder, "The New Rules of Wireless," *Forbes ASAP* (March 29, 1993). See also George Gilder, "Auctioning the Airwaves," *Forbes ASAP* (April 11, 1994).

[29] See Kevin Werbach, "Open Spectrum: The New Wireless Paradigm," New America Foundation, Spectrum Series Working Paper #6 (October 2002). See also Kevin Werbach, "Open Spectrum: The Paradise of the Commons," *Release 1.0*, (November 2001).

[30] See Yochai Benkler, "Some Economics of Wireless Communications," 16 *Harvard Journal of Law and Technology* 25 (2002).

[31] See Michael Singer, "Analysts: Wi-Fi a 'Positive Disruption,'" *802.11 Planet*, (April 3, 2003).

[32] See *It's Cheap and It Works: Wi-Fi Brings Wireless Networking to the Masses*, [report] In-Stat/MDR (December 2002). See also *Wireless LAN Equipment: Worldwide, 2001-2007*, [report] Gartner Group (January 2003).

[33] See Patrick Gelsinger, "Wireless Fidelity (Wi-Fi): Leaping Across the Digital Divide," Keynote Address to the United Nations Information and Communication Technologies Task Force (June 26, 2003).

[34] See *supra* note 6.

[35] See Kevin Werbach, "Supercommons: Toward a Unified Theory of Wireless Communication,"82 *Texas Law Review* ___ (forthcoming March 2004), *draft available at* http://werbach.com/research/supercommons.pdf

[36] See New America Foundation *et al*., "Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band," Comments to the FCC Notice of Inquiry, ET Docket No. 02-380 (April 17, 2003).

[37] See J.H. Snider and Max Vilimpoc, "Reclaiming the 'Vast Wasteland': Unlicensed Sharing of Broadcast Spectrum," New America Foundation, Spectrum Series Issue Brief #12 (July 2003).

[38] WiFi stands for "wireless fidelity" only in this marketing sense. HiFi systems actually have higher sound fidelity; there is nothing special about the fidelity of WiFi systems.

[39] See James H. Johnston and J.H. Snider, "Breaking the Chains: Unlicensed Spectrum as a Last-Mile Broadband Solution," New America Foundation, Spectrum Series Working Paper #7 (June 2003).

[40] *Id.*

[41] See http://www.nodedb.org

[42] See Jane Black, "The Magic of Wi-Fi," *BusinessWeek Online*, (March 18, 2003).

[43] See Gregg Keizer, "Wireless LANs Set For Growth Spurt," *Information Week*, (March 27, 2003).

[44] See James H. Johnston and J.H. Snider, "Breaking the Chains: Unlicensed Spectrum as a Last-Mile Broadband Solution," New America Foundation, Spectrum Series Working Paper #7 (June 2003).

[45] See Federal Communications Commission, *Spectrum Policy Task Force Report*, ET Docket No. 02-135 (November 15, 2002).

[46] See New America Foundation *et al*., "Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3GHz Band," Comments to the FCC Notice of Inquiry, ET Docket No. 02-380 (April 17, 2003).

[47] See New America Foundation *et al*., "Amendment of the Commission's Rules to Facilitate the Provision of Fixed and Mobile Broadband Access, Educational and Other Advanced Services in the 2150-2162 and 2500-2690 MHz Bands," Comments to the FCC Notice of Proposed Rulemaking, WT Docket No. 03-66 (September 10, 2003).

[48] See Werbach, *supra* note 35.