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The first draft of this paper was completed while the author was a visiting researcher at Microsoft in 2016-2017. The author thanks Microsoft for supporting this project, but takes full responsibility for the contents of this manuscript.
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Economic Implications of New Technologies for Licensed and Unlicensed Spectrum

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Abstract

Rapid changes in technology create challenges and opportunities for spectrum regulators. Enabling connectivity and maximizing the value of the very finite amount of bandwidth available will play an increasingly important role in the country's economic development and innovative potential. In this paper, we attempt to clarify the nature of spectrum as an economic resource. We show how and why there will be market failure, and how the tools available to regulators might best be deployed in response. We consider the spectrum needs of emerging technologies and how judicious choices of protocols, regulations, market structures might help satisfy them. In particular, we focus on factors that make licensed or unlicensed approaches the best choice for different use cases. Finally, we discuss the similarities between wireless and wired broadband and what this suggest about net neutrality and market structure in the appendix.

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1. Introduction

Radio spectrum is a scarce resource with many potential uses, from commercial broadcasting to radio astronomy. Allocating scarce commodities over competing ends is the central problem of economics. Spectrum, however, is a complicated resource in a number of ways. It has properties of both public and private goods and can generate a variety of externalities. Regulations regarding radio transmission power, protocols, and permitted uses greatly affect the value that it creates. Technological advances can reduce the value of legacy uses and leave important new ones starved for bandwidth. Creating markets to help allocate spectrum efficiently is extremely difficult.

In this paper, we attempt to clarify the nature of spectrum as an economic resource. We show how and why there will be market failure, and how the tools available to regulators might best be deployed in response. We consider the spectrum needs of emerging technologies and how judicious choices of protocols, regulations, market structures might help satisfy them. In particular, we focus on factors that make licensed or unlicensed approaches the best choice for different use cases. Finally, we discuss the similarities between wireless and wired broadband and what this suggest about net neutrality and market structure in the appendix.

2. Spectrum and Bandwidth

We begin with a brief refresher on the physics of electromagnetic spectrum. The difference between the various parts of the spectrum is the **frequency** at which the transmission energy (carried by photons) oscillates between a positive and negative charge. If this wave oscillates 10 times per second, for example, we say that the signal has a frequency of 10 Hertz (abbreviated 10 Hz). Radio transmitters send information by modulating a carrier wave at a chosen frequency. Radio receivers, in turn, tune into the frequency of a carrier wave and then extract the information encoded in the modulation.

Different frequencies have different properties. In general, lower frequencies carry farther and are less subject to attenuation. AM radio (500-1700 kHz) broadcasts can bounce off ground obstacles and the ionosphere and thereby follow the curvature of the earth. Generally, frequencies below 3 GHz have reasonably good abilities to penetrate walls, trees, and other physical obstacles. The sub-3 GHz frequencies, sometimes called “beachfront spectrum”, include AM and FM radio, and UHF and VHF TV. Most cell phone networks (called Personal Communication Service or PCS networks by the Federal Communications Commission) use frequencies between 700 MHz and 1900 MHz. Higher frequencies between 3 and 300 GHz perform more poorly in all of these dimensions but have the advantage of being in much greater abundance. Frequencies above 300 GHz carry infrared, visible, and ultraviolet light, X-rays, and gamma rays.[2]

Transmitted information spills over into near-by frequencies and so intervals of spectrum must be allocated to a given use. For example, the AM radio band runs from 540 kHz to 1600 kHz and

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[2] The physical nature of these frequencies limits the need for government control. There is no need to license the color yellow (about $5.3x10^{14}$ Hz or 530,000 GHz), for example, since “broadcasters” of yellow light rarely interfere with one another.

is broken up into 106 channels covering a 10 kHz band of frequencies each. Thus, a radio station broadcasting at 540 on the AM dial is allocated an interval of frequencies running from 535 kHz to 545 kHz. A station broadcasting on the 540 kHz channel is therefore using 10 kHz of **bandwidth**. Shannon's law[3] implies that the amount of data that can be transmitted on a given amount of bandwidth is independent of frequency. That is, a 10 MHz channel between 880 MHz and 890 MHz has the same information carrying capacity as one between 60.01 GHz and 60.02 GHz. Thus, all else equal, the amount of bandwidth that should be allocated to a certain use depends on the intensity of its data transmission needs. Beachfront bandwidth is relatively scarce, and so to whatever extent possible, uses with high data transmission requirements should be pushed into higher frequencies. By the same token, uses with high value but low data requirements have a better claim on more desirable frequencies.

3. Economics

3.1 Public and Private Goods

We begin by describing one of the very basic economic properties of goods. If the entire quantity of a good that is produced is available to all agents simultaneously, then it is said to be **nonrival.** Conversely, if each unit of a good consumed by one agent diminishes the total available to the remaining agents by exactly one unit, then it is said to be **rival**.

Rival goods are often called **private goods**. Examples include housing, clothing, food, cars, and electricity. The common property is that if I eat a hamburger, you cannot eat it as well. A hamburger is a zero sum game. More formally:

$$\sum_i H_i = \dot{\bar{H}}$$

where H_i is the number of hamburgers eaten by a given agent i, and $\dot{\bar{H}}$ is the total number of hamburgers produced.

Nonrival goods are often called **public goods**. Examples include national defense and knowledge. The common property is that the fact that I know something like $E=MC^2$ in no way prevents or impedes you from knowing it as well. Formally:

$$K_i = \dot{\bar{K}}$$

for all i, where K_i is the amount of knowledge consumed by any agent i, and $\dot{\bar{K}}$ is the total amount of knowledge that exists.

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[3] More accurately, the Shannon–Hartley Theorem says: The upper bound on the information rate of data that can be communicated at an arbitrarily low error rate, using an average received signal power S through an analog communication channel subject to additive white Gaussian noise of power N is: $C=B\log_2(1+\frac{S}{N})$. The key point is the channel capacity, C, is linearly proportional the amount of bandwidth allocated to the channel, B, regardless of where in the spectrum this frequency is located.

3.2 Broadcasts

Commercial broadcasting uses a **one-to-all** open channel model in which all receivers in range can hear whatever is transmitted. The FCC grants or sells licenses for certain parts the spectrum to private entities for radio, television and other uses. A part of the spectrum is also reserved for unlicensed uses and amateur broadcasts such as citizen band radio.

Broadcasts are often cited as an example of a nonrival good. This is literally a half truth. On the receiving side, the observation is correct. All receivers within range can listen to anything that is broadcast on a channel. On the transmission side, however, the story is quite different. If one agent is broadcasting on a particular frequency at a particular time, then no other agent can. Each transmission time-slot on a given frequency is fully rivalrous. Thus, time-slots are a rivalrous input good which a single broadcaster can use to produce nonrivalrous transmissions to a group of receivers.

Although broadcasts are nonrivalrous to receivers, they are not always public goods. In fact, they may be public bads.[4] For example, I might want to listen to a broadcast from a country music station. If a pop station broadcasts on the same frequency, however, it may prevent me from tuning in. This varies with the relative wattage of each station and how close I am to either transmitter. It might be that I hate the politics of Rush Limbaugh or NPR, or that I think polka music is destroying the moral fiber of America's youth. In this case, broadcasting such content is a bad for me, and a public bad for all who share my views.

How nonrival commodities (goods and bads) affect the welfare of agents depends on whether they are **excludable** or **avoidable**. Clearly, it is impossible to know everything or listen to every radio broadcast. Agents can consume as much as they wish of these goods and then ignore the rest. For avoidable public goods like these, the consumption constraint is really $K_i \leq \overline{\dot{K}}$, for all agents i. However, there are nonrival commodities that cannot be avoided. For example, global level of atmospheric CO_2 is about 400 ppm. This is a nonrival public bad, and no agent on the planet can avoid the full effects of this 400 ppm level. If television broadcasts are encrypted and can only be decoded by agents who have paid subscriptions, the result is an excludable public good. Even though all agents in the coverage area can receive the transmission, they are excluded from using the content the broadcast contains.[5]

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[4] Public and private goods increase an agent's welfare or add to a producer's output when consumed. Public or private bads decrease welfare or output. "Commodity" is a general term that includes both goods and bads. Agents can also become satiated in a commodity so that additional consumption neither increases nor decreases welfare or output. It is even possible for a commodity to be a good if consumed in one quantity, but a bad if consumed in another. For example, watching an episode of Dr. Who might be enjoyable, but what if one tried to binge watch the entire show? Somewhere between episode 1 and episode 839 most people would find that they are sick of the Doctor, the Daleks, and the rest of it, and would rather just go to bed. On the other hand, while reading a Harry Potter book might be enjoyable, reading a copy that has the last 20 pages torn out would be very frustrating. Thus, commodities can start off as goods and turn into bads as the quantity consumed increases, or start as bads and become goods when a certain consumption level is reached.

[5] Excludable public bads do not have much empirical relevance. If a public bad is avoidable, then it does not matter whether it is excludable. Agents simply ignore it. On the other hand, a nonavoidable and excludable public bad might arise if the producer of the bad somehow had the ability to prevent it from harming specific agents. For example, suppose a mad scientist invented an airborne virus that gives the infected an overwhelming desire to know every detail about the lives of the Kardashians. Once the virus is released, everyone in world would eventually be infected. How-

3.3 Multicast

PCS and WiFi use multicast, **many-to-many,** networks. Instead of one station transmitting to many receivers, multicast networks allow many stations to transmit on the same channel. In most cases, all stations on the network both transmit and receive data.

Multicast networks exist in both licensed and unlicensed spectrum. WiFi is unlicensed and so anyone is free to setup a router or connect a client to a WLAN (Wireless Local Area Network) without seeking permission from the FCC. PCS bandwidth is licensed. The FCC holds auctions and companies bid for exclusive control over other parts of the spectrum. Only the license holder is allowed to set up an access point for the frequencies it owns. Cell phones and other clients can attach to a PCS network only if the license holder gives permission. Usually, this requires paying a monthly service charge to a carrier such as Version or T-Mobile.

WiFi and PCS differ in two fundamental ways. First, WiFi uses low-power transmitters which restricts effective communications to a range of 20 to 50 meters. PCS cells use much higher power and can communicate at ranges of 1 to 20 km (longer ranges are possible, but are seldom used). Second, WiFi shares bandwidth using the 802.11 family of protocols which employ decentralized carrier sense[6] and can be inefficient when traffic is high. PCS uses LTE (Long-Term Evolution) and similar protocols which are centralized and use a control channel[7] to coordinate clients on the network. In many cases, this leads to more efficient use of bandwidth. Centralized coordination is only possible (at least historically) because the bandwidth is controlled by a single private owner. There is no analogous agent for unlicensed bandwidth, and so there is no one who has either the authority or financial interest to provide similar coordination for WiFi clients and routers.

Regardless of the licensing model, the right to broadcast at a specific frequency, time, and place, is a fully rival. Transmissions, on the other hand, are received by all users within range, but are generally only useful (or decodable) to the intended receiver. Given this, is bandwidth used for multicast a public good, a private good, or is it something else?

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ever, if the scientists also developed a vaccine, then he could exclude anyone he wishes from suffering this dire fate. People would have to pay the scientist to exclude them from the public bad. Let us hope such cases continue to be empirically irrelevant.

[6] "Carrier sense" means that that routers and clients "listen" to a channel to see if it is clear and available. Each station makes its own assessment of when it should transmit without coordinating with any other users of the channel. This leads to "collisions" in which two stations transmit at the same time. Such simultaneous transmissions interfere with one another, and in many cases, neither transmission is intelligible to its intended recipient. These packets are lost and must be retransmitted. When many clients try to share a channel in this decentralized and uncoordinated way, packet loss and retransmission result net data transfer rates significantly less than its theoretical capacity. For a more complete description of LTE and 802.11 approaches to bandwidth allocation see CTC Technology & Energy (2016)

[7] LTE divides bandwidth use between data and control channels. The control channel allows it to coordinate data transmission between access points and clients, and also to hand clients off as they move from cell to cell (the area controlled by a single cell tower). These gains in coordination must be weighed against the loss of data bandwidth to control uses and the latency that processing and transmitting control messages to client creates.

It turns out that a better way to think about multicast bandwidth is to abstract from the time dimension. The right to broadcast on a specific frequency then becomes what economists call a **semirival** good. Multicast bandwidth is like a highway: the degree of rivalry depends on how much capacity is being used. When only a few cars are on the road, an additional car imposes no costs on other drivers as long as it does not cause a collision. As the highway becomes more crowded, traffic slows as drivers coordinate their actions to share the road safely. When the highway is at capacity, one car must exit for another to enter. Thus, highways progress from being fully nonrival to fully rival depending on congestion.

In general, semirivalry is the result of one of two factors. The first is distance. The further an agent is from an otherwise nonrival good, the lower the value of the services the good provides. You are less likely to go to a beach that is 100 miles away than one that is just down the block. An AM radio broadcast is strong and clear when you are near the transmitter, but becomes weak and broken as you move further away. The second is congestion or crowding. An empty beach you can enjoy all by yourself is a rare pleasure. As more people show up, it becomes crowded, noisy, and less enjoyable. As we just outlined above, multicast bandwidth is subject to congestion is a similar way. Formally:

$$\frac{\partial V(G,D)}{\partial D} < O \quad \text{or} \quad \frac{\partial V(G,N)}{\partial N} < O$$

where V(G, D) is the willingness to pay (or the value) a public good G that is a distance of D from the consumer or which is shared with N other agents. The negative derivative means that this value decreases with distance and crowding. For example, the value of a museum (G) to a consumer decreases the further it is from his house (D) and as the number of people who are in the museum at the same time (N) increases.

To sum up, commodities can be goods or bads, rival, semirival, or nonrival, excludable or nonexcludable, and avoidable or nonavoidable. Each of these characteristics has its own implications for optimal policy and market design, and all are relevant to the problem of spectrum regulation and allocation.

3.4 Market Failure

Between the first commercial radio broadcast in 1920 and the passage of the Radio Act of 1927, spectrum use was essentially unregulated in the United States. Stations could broadcast at whatever frequency they pleased at whatever wattage they chose. Listeners would find the program they turned in to suddenly drowned out when a more powerful station started to transmit on the same frequency.

There are two separate market failures here. The first is the result of the rivalrous nature of radio transmissions for producers coupled with nonexcludability. Before 1927, radio spectrum was a kind of electromagnetic commons, freely available to anyone to use on whatever terms they wished. A pasture, a pond, a forest, or any resource owned in common, will typically be over-exploited and used inefficiently unless rules are established to prevent it. An overgrazed pasture, a fished-out pond, a clear-cut forest, or saturated radio spectrum create much less value than they would if they were managed efficiently. This phenomenon is often called the **tragedy of the commons**.

The second market failure is a result of the nonrivalrous and nonexcludable nature of radio transmissions for receivers. It costs money to produce music, movies, news and other content. When this content is broadcast, it becomes a public good available to all agents within the coverage area. The problem, then, is how to compensate producers and broadcasters well enough to get the them to continue providing this valuable service. We could ask for voluntary contributions from the viewers and listeners of these broadcasts. Unfortunately, each individual user will (or should) realize that no matter how much the other agents contribute, his own contribution will have almost no effect on the quantity and quality of broadcasts. His individual contribution is too small to matter. If other agents contribute enough to fund the broadcasts, then he can get the full benefit without paying anything for them. If the contributions of the others fall short, it is unlikely that his will be pivotal. If everyone uses the same logic, total contributions are zero. Thus, the market is unable to provide this public good despite the fact that the collective benefit to agents from its consumption far exceeds the cost of its production. This phenomenon is called **free riding**.[8]

3.5 Coase Theorem and Property Rights

Markets are based on the transfer of commodities from one agent to another through voluntary exchange. For example, I transfer to you the right to eat the goat I raised, and you transfer to me the right to use a piece of land you own for a year. Since the exchange is voluntary, both of us must feel that we are better off as a result. If my goat happens to be worth more to another agent, that agent has an incentive to offer me a better price. Thus, markets tend to allocate goods to those who can put them to the most valuable uses through price signals.

There are many things that can make market exchanges difficult, but for markets to exist at all, there must be property rights that can be enforceabley transferred from agent to agent. I cannot sell you a fish in the common pond because I do not own it. The only way to secure a right to a fish is to catch it. Over-fishing is the result of agents trying to establish such property rights. Similarly, I cannot exclude agents from listening to a broadcast. Just because I created the broadcast does not mean that I own any of the listening rights.

The solution seems obvious: assign property rights to everything. The commons could be enclosed[9] and made into privately owned parcels. The right to cut down each tree in the forest could assigned to a specific agent, and the right to broadcast at a given frequency could be licensed

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[8] For example, Brunner (1998) estimates that about 10% of public radio listeners make contributions. Taken at face value, this would mean that only 10% of the value of NPR's broadcasts is being signaled by the voluntary contrition mechanism. However, a large literature in economics finds that charitable giving is frequently motivated by the warm glow agents get from "doing their part", the desire to avoid the labeled a free rider, and similar private benefits associated with act of contributing. As a result, contributions are not proportionate to the benefits that agents expect to receive from the public good itself (they may even exceed this value). See Andreoni (1995), Conley and Kung (2011) and references therein.

[9] Inclosure (sic) Acts beginning in the seventeenth century converted much of the commonly held pasturage and farmland in England into private plots, disproportionately owned by the local aristocracy.

to individuals by a government agency. Would this create a functioning market? Would agents have an incentive to use their privately owned resources to produce the largest possible return, or to sell their resources to those who could put them to better uses?

For example, suppose two broadcasters wanted to use the same frequency at the same time. Suppose broadcaster A values the right to use the frequency at $100 and broadcaster B at $200. If the goal is to maximize value, broadcaster B should be given the exclusive property right to the frequency. What if we made a mistake and gave the property right to broadcaster A? After all, we might not know the value of the uses they each have in mind. Fortunately, both agents would have an incentive to affect a transfer of the rights. Broadcaster A would be happy to sell his rights for anything above $100 while broadcaster B would be happy to pay anything less than $200. There is a gain from trade here, and a sale at any price between $100 and $200 benefits them both. Thus, no matter how we assign property rights, they end up in the hands of the agent who values them most. It seems that all we need to do is assign property rights and let the market work its magic.

This is the basic message of the famous **Coase Theorem**. Although Coase's paper[10] does not contain a theorem of any type, the idea is often expressed as follows:

Coase Theorem: If transactions costs are zero, then any assignment of property rights leads to a Pareto efficient outcome.[11]

The Coase Theorem is one of the main intellectual foundations for privatization. Private agents have private information about the value of resources in production and consumption. By assigning property rights, the government creates a market. The market, in turn, gives agents an incentive to reveal information that is unavailable to the government or social planner through self-interested market transactions. By extension, regulation can be seen as an erosion or limitation of property rights that prevents the market from operating efficiently. Thus, it is argued, the government should create, distribute, and enforce property rights, but then step back and leave the rest to the invisible hand.

3.6 Theorem Failure

In the example above, agents arrive at a Pareto efficient outcome using a simple bilateral negotiation mechanism. What if such a mechanism is not available? For example, what if the two broadcasters did not know where each other lived or spoke different languages? What if they did not know one another's private values and insisted on prices that were too high or too low? It turns out

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[10] See Coase (1960)

[11] Zero transactions costs mean that the market is frictionless. Property rights can be transferred costlessly and so the price the buyer pays for a good is exactly equal to what the seller receives. Pareto efficiency means that the outcome is optimal in the sense that there is no feasible alternative that benefits all the agents in the economy at the same time. In other words, at least one agent will be worse off at any alternative feasible allocation. Note that there are many potential Pareto efficient outcomes in most cases. For example, any division of a dollar between two agents is Pareto efficient. To give one of the agents a penny more would require giving the other agent a penny less. On the other hand, giving each agent ¢25 is not Pareto efficient since giving both agents ¢50 is both feasible and preferred by all agents.

that the Coase Theorem in the previous section fails to mention a key implicit assumption. A more complete statement of the Coase Theorem is the following:

Coase Theorem (complete): If transactions costs are zero, and agents have a mechanism available that allows them to trade to Pareto efficient allocations, then any assignment of property rights leads to a Pareto efficient outcome.

This version of the Theorem is true. Unfortunately, it is also a tautology. The question becomes: when will Pareto efficient trading mechanisms exist? Sadly, the answer seems to be not as often as we would like, and usually not in the case of spectrum. As a result, the naïve Coase Theorem given in the previous section fails. The major reasons are the following:[12]

Monopoly and Market Power: Suppose that a public park included an apple orchard. Apples are a rival good, but are common property. Any agent walking through the park who spotted an apple that was even marginally edible would pick it knowing that if he did not, someone else would. As a result, all the apples are picked before they have a chance to ripen. A solution might be to give some agent the property rights to the orchard. The agent would then have an incentive to manage the orchard in the most profitable way possible. To make things simple, suppose that the apple orchard produced exactly 100 apples per year.[13] In this case, the marginal cost curve would have the backwards "L" shape in the figure below. Suppose that at a price of $1, 100 apples are demanded by consumers. This means that 100 consumers have reservation prices of $1 or more, and all the others have reservation prices of less than $1. At this market clearing price, the owner makes $100 in profit. Recall, however, the orchard owner was given an exclusive property right to all the apples. He is an apple monopolist. By setting marginal revenue equal to marginal cost, he finds that he can maximize his profits by selling 60 apples at a price of $3 each. This gives him a total profit of $180. Note that all consumers of apples are worse off, and 40 apples are wasted. If the owner could somehow identify the next 40 agents on the demand curve and sell apples to them at $1 while preventing resale to the first 60 agents, he would certainly do so. This would give him and additional $40 of profit. Unfortunately, he lacks this information and cannot prevent resale. As a result, a Pareto improvement (40 apples going for $1 to agents who value them at more than this, and the owner's profits increasing by $40) is not possible given the available mechanisms. The (naïve) Coase Theorem therefore fails.

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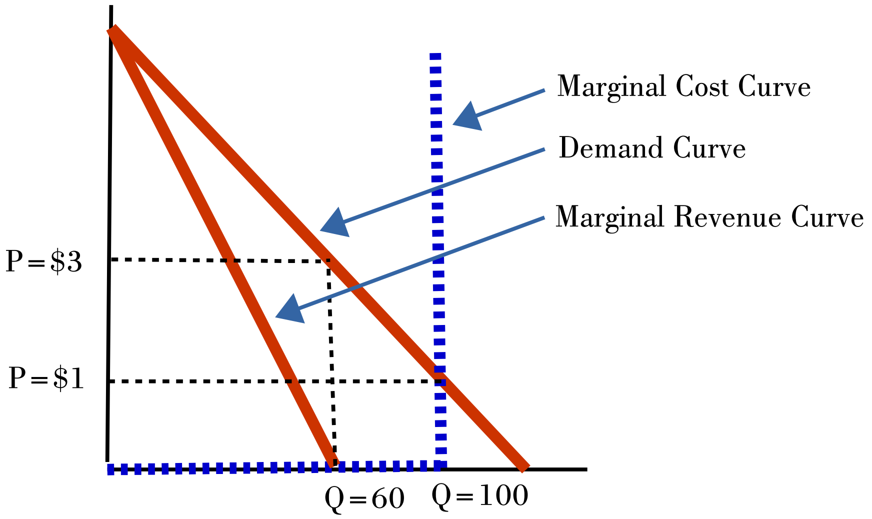
[12] See Conley and Smith (2005) or John P. Conley (2014), slides for the International Society for New Institutional Economics Plenary Lecture: "Coase Theory and the Coase Theorem"

[13] That is, the marginal cost of the first 100 apples to the owner is zero, but the orchard cannot produce more than 100 apples at any cost.



Monopoly Pricing and Social Loss

Public Goods and Free Riding: The Coase Theorem does nothing in itself solve the free riding problem. As a result, the assignment of property rights for nonrival goods may have a significant impact on how efficiently the goods are used. To see this, suppose there is paper mill upstream from 10 small bottled water companies. The paper mill makes $500 per year but must pollute the river to do so. It cannot operate unless it pollutes. Each of the bottled water companies makes $200 per year if the water is pure but must spend $100 on filtration systems if it is polluted. The authority to discharge or prevent the discharge of industrial waste is a valuable property right. It is worth $500 to the paper mill, and $100 to each of the water companies. Note that a clean river is a nonexcludable, nonrival good to the water companies. Either all, or none, enjoy clean water. Suppose we give the pollution rights to paper mill. It would be happy to sell them for anything above $500. Even though the collective value to water companies is $1000, the value to each individual company is only $100. They may or may not be able to coordinate and agree to share the costs. It depends of the economic, social, and legal mechanisms that are available. Free riding is difficult to overcome, and if the bottled water companies fail to do so, the paper mill keeps the rights, makes $500, but the water companies collectively spend $1000 on filtration. Now suppose one of the water companies gets the rights. It would happily sell them to anyone for any price above $100 while the mill would be willing to pay as much as $500. They settle on some price in between, and again the mill ends up with the rights. We see that no assignment of property rights leads to a Pareto efficient outcome. On the other hand, if we had a compulsory taxation mechanism available, we could tax water companies $60 each, transfer $600 to the mill owner, and decree that the river is to remain unpolluted. The mill would have to close, but the owner makes $100 more than if he stayed open and polluted the river. Each water company would be better off by $40 since they would not have to spend $100 to filter the polluted water from the river. The conclusion is that provision of nonrival goods leads to free riding, and the assignment of property rights does not create a mechanism that solves this problem.

Public Interest and Fairness: Suppose I own a 2016, autographed, Cubs World Series baseball, and I am trying to decide which of my children to give it to. Both claim they love it, but I cannot divide it half. Suppose that the truth is that my son values the ball at $500 while my daughter values it at $700. If I give the ball to my son, selling it to my daughter at any price between $500 and $700 leaves them both better off. Coase would argue that since it is in both of their interests to settle on a mutually agreeable price, they will find a way to do so. If my son gets the ball, he might end up $650 richer, my daughter $650 poorer, but in possession of a baseball worth $700 to her. If my daughter gets the ball, my son gets nothing, and my daughter gets a baseball worth $700 to her. In both cases, the person who values the ball the most ends up with it. Note that both of these allocations are Pareto optimal. Regardless of which child I give the ball to, there is no reallocation that improves the welfare of one child without harming the other. The problem is that although both allocations are Pareto optimal, neither seems fair. The ball is valuable and whichever child I give it to is much better off. I value fairness, and I certainly would not want my children to think I am playing favorites. If I sell the ball on eBay, I might get $600 and then give each of my kids $300. This does not maximize family wealth or put the ball to its most valuable use, however, I might think that $100 is a reasonable price to pay for fairness and family peace.

3.7 Economic Lessons so Far

The key conclusions from this discussion are the following:

Property rights are a **necessary** condition for markets to work.

- The tragedy of the commons is a result of nonexcludability. Any resource, from apples to bandwidth, that can be freely appropriated will be over-exploited or used inefficiently.
- You cannot buy or sell a thing unless property rights exist and are transferable. Assigning property rights through granting title or licensing gives owners the legal right to exclude others and creates the potential for reselling rights into their most valuable uses.

Property rights are not a **sufficient** condition for markets to work.

- Even if property rights are assigned, high transactions costs may lead to market failure. In this case, property rights should be assigned to the highest value user in the first place (if possible).
- Even though assigning property rights solves market failures due to nonexcludability, it frequently creates another market failure in the form of monopoly. Distributing property rights to bandwidth may create markets, but these may not be competitive markets.
- Even if the resulting markets are competitive, competitive markets fail, and fail profoundly, for nonrival commodities. Suppose the most economically valuable use of a TV channel is to

broadcast first-run movies. Free riding prevents consumers from expressing their willingness to pay and destroys the market signal that would cause the owner to put his channel to this use. If market prices do not signal economic value, markets cannot allocate commodities efficiently.

- Even if the resulting markets are competitive and do not otherwise fail, they still may not direct resources to their most important social uses. Advertisers value richer consumers, and broadcasters and other users of bandwidth are likely to be focused on catering to their tastes. Is the public interest served if there is no children's, arts, or educational programming? Should telephone and cellular networks be required to provide universal service or be allowed to focus exclusively on the most profitable customers? Would the FCC be willing to trust the market to sell or allocate bandwidth for public safety, radar, radio astronomy, or national defense?

Spectrum belongs to the public and the FCC is charged with regulating its use in the public interest. Determining how to use valuable resources through central planning does not have an especially glorious history. In contrast, the invisible hand pushes agents to use their property and resources in profitable and creative ways. Harnessing this energy by licensing bandwidth to private agents has many attractions.

Competitive markets without frictions or transactions costs do, in general, allocate resources to their most economically valuable uses. Regulating such markets generally reduces their efficiency. Unfortunately, creating anything approaching a frictionless, competitive market for bandwidth or its uses is extremely difficult and probably impossible. Assigning property rights for spectrum to private owners cannot, therefore, be expected to approximate a theoretically ideal free market that maximizes economic value and social welfare.

There is no simple solution to this problem. It is as foolish to decry rapacious corporations exploiting public bandwidth for private profit as it is to complain about unwarranted and harmful government interference in private enterprise trying to provide the best possible communications infrastructure for the future. Pointing to government inefficiency does not imply that corporations should be put in charge of the public interest any more than instances corporate greed and corruption imply that the government should run the economy.

4. Bridges, Protocols, and Standards

Protocols and standards such as 802.11x, LTE, FM, and HDTV are important regardless of whether bandwidth is licensed or unlicensed. To see this, think of bandwidth as a one lane bridge over a river. Traffic can flow over it at a certain rate, but only in one direction at a time. This means that all the cars going in one direction must exit the bridge before any traffic from the other direction starts. The issue is how to allocate bridge crossing time-slots most efficiently.

One possibility would be to leave things completely unregulated. Anyone would be allowed to cross the bridge anytime they wanted. The problem is that this would lead to collisions. If two cars tried to cross in different directions at the same time, they would block each other, and neither would get across. Neither user benefits from the bridge as a result.

People might respond by getting bigger cars, trucks, or even tanks, so that they could force their way through. The more powerful vehicle would win. If only one agent had access to tanks, it might even be that the other agents would simply give up and not try to use the bridge at all. To the outside observer, it might seem that the agent with the tanks is the only one who has any interest in using the bridge and conclude that there really is no resource allocation problem at all.[14] On the other hand, if any agent could buy a tank, we would end up in an arms race and a negative sum game. The most powerful vehicle in any collision would win, but the costs of getting to the other side of the river would rise for all. As we mention above, this was the main motivation for the Radio Act of 1927.

A better approach would be to agree to rules of the road. This might arise through social convention or government regulation. For example, a rule might be that whomever arrives at the bridge first gets to cross. A polite motorist would stop and look down the bridge before entering. If he saw another car, he would wait until it had completed the crossing before starting his. This would stop collisions, and if traffic were relatively light, would be a fairly efficient way to allocate time-slots. The 802.11x protocols listen before talking (LBT) using carrier sense for clear channel assessment, the electromagnetic equivalent of looking down the bridge.

If traffic was heavier, the LBT rule might not be enough to prevent collisions. If there were two cars on either side of the river waiting for a third to complete its journey before starting their own, both would try to enter the bridge at the same moment. Either they would crash or notice each other entering the bridge and decide to back off so the other could cross. If both drivers politely backed off and waited for the other, we would be at an impasse. A better strategy would be to back off, and then look to see if the other driver actually enters the bridge. If it happened that the other car was still waiting, then the first driver could safely cross. Unfortunately, if they both look down the bridge immediately after they back off, they still see one another ready to enter the bridge and back off again. As long as they check the bridge at the same interval, the problem remains. A solution is to have each driver look at the last digit displayed on his odometer and wait that number of seconds before checking again. This reduces the odds that they check the bridge at the same time to one in ten. If they happen to look at the same time anyway, they could each count the number of bugs on the windshield, and then have another look. The 802.11 protocols incorporate a similar sort of random backoff (RBO) when they detect another station trying to use a channel.

What if traffic was heavy, and lines of cars waiting to cross formed on each side of the bridge?[15] The first come, first served, mechanism given above, even with LBT and RBO, would no longer make optimal use of the bridge. What if instead of sending a single car in each direction at a time, we sent cars in groups of five? It takes five cars in a row only a little bit longer to cross and clear off a bridge than one car. We would only have to do LBT and RBO once for the entire group instead

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[14] We will see below that LTE-u may affect WiFi users in a similar way. LTE-u routers may end up using all the time-slots on a channel if it never detects any WiFi routers attempting to transmit.

[15] When routers in a multicast network have a queue of packets waiting to be sent, they are said to have a full buffer. The 802.11 protocols have a very hard time sharing bandwidth efficiently in this situation.

of once for each car. Thus, sending cars in groups would almost quintuple the number of crossings per day. In the case of multicast radio spectrum, how long a station should be allowed to broadcast before going silent and giving other stations a chance to claim the channel is a key element of fair and efficient bandwidth sharing.

Choosing how many cars should be grouped together to cross at one time is more difficult if cars arrive at each end randomly. There may be longer queues on one side than the other, or there may be no queue at all on one of the sides. Sending five cars one direction and then waiting long enough for five non-existent cars to cross in the other direction would be a waste of capacity. It might be better to send twenty in one direction, and then two in the other, given the relative demands for crossings. How could we do this efficiently?

One possibility is to privatize the bridge. The hope is that if the bridge becomes private property, the owner internalizes the crowding externally and uses the resource efficiently. In the case of the bridge, the owner might decide to build a tower that allows him to observe how many cars are waiting on each side. He could station an agent at each bridgehead and signal them by semaphore how many cars to release for crossing at any given time. Drivers would pay a fee for this coordinated use of the bridge. This plan would completely prevent collisions and would reduce the waste of bridge capacity. How much improvement in efficiency would result depends on how good the owner is at allocating crossing slots and how much time his agents spend receiving and interpreting the semaphore signals. Whatever the case, the bridge owner is a monopoly, and we know that monopoly pricing leads to inefficiency. Whether the social loss from monopoly pricing is less than social gain from better use of bridge capacity depends on the details of the situation. All PCS protocols have control channels that are separate from the data channels and must balance gain from efficient use of available bandwidth with the overhead costs of control and coordination. PCS networks also require that someone bear the cost of building towers and other infrastructure.

Perhaps we could accomplish the same thing without privatizing the bridge. Doing so would require somehow knowing the length of the queue on each side of the bridge, and perhaps on the roads leading up to the bridge as well. An engineer would then have to solve an optimization problem to determine the best rules about how bridge traffic should be regulated given the information available. Allowing emergency vehicles priority use would be a good idea, and it would also be nice if lower value bulk users would find an alternative to the bridge, or at least not use it at times of peak demand. This means we would have to know if a truck is carrying cargo that could be moved at less social cost by barge instead of on the free, but congestible bridge. 802.11 routers have neither the information nor the computational capacity to solve this problem. We would need routers to be more knowledgeable about their local environments and to know how use this information intelligently. Cognitive radio, discussed below, is an avenue that might allow decentralized routers to share bandwidth even better than PCS protocols using a control channel.

Suppose we decide to privatize all railway, as opposed to automobile, bridges. Even better, suppose we privatized the right to build railway bridges on different segments of the river. One advantage of this is that the private sector would have an incentive to find the best spot to build and would pay for construction and maintenance. The public gets bridge infrastructure for free (ignoring monopoly pricing issues). Should we leave the private bridge builders unregulated? Suppose that each builder had to decide on his own how widely to space the rails he lays down. If many different rail gauges ended up being used, manufacturers would need to produce small batches of locomotives for each wheel-base. This is more expensive than building all rail-stock to a single standard. In addition, each locomotive would be restricted to a small number of bridges and so would provide less value. The invisible hand is not enough to solve this coordination problem. In fact, competing, but incompatible, standards may be a consequence companies trying to maximize profits. VHS/Betamax, HD/Blue-ray, GSM/CDMA are examples of coexisting standards that were promoted by companies with vested interests. Society benefits when a standard rail gauge is used, and government regulation is probably the best way to get it. This is true even though the railroad bridges are entirely privatized.

Regulation plays a similarly important role regardless of whether bandwidth is used for one-to-all broadcasts or many-to-many multicasts. Suppose that the government allowed local TV and radio stations to choose any broadcasting format instead of HDTV, AM, or FM. Consumers would have to buy separate receivers for each format and this would be wasteful. Suppose that WiFi routers could decide for themselves to use LBT and RBO or how much wattage to use for broadcast. Users who choose the rudest and most powerful routers would get sole use the spectrum. Imposing 802.11 protocols and wattage limitations allows the 2.4 and 5 GHz spectrum to be shared far more fairly and efficiently.

To sum up, protocols, regulations, and standards are necessary for efficient use of spectrum. This is true regardless of whether spectrum is licensed, unlicensed, or reserved for governmental use. Neither the innovative potential of free experimentation nor the incentives for profitable use offered by the free market are compelling arguments for a hands-off approach. Bandwidth is scare, and demand is increasing. Choosing good protocols and standards is at least as important as deciding how bandwidth should be allocated to various uses.

5. Licensed or Unlicensed?

Deciding how much new bandwidth to allocate to licensed and unlicensed uses is one of the most important choices the FCC has before it. The implications for the economy will be enormous whatever the decision. The bandwidth currently allocated to both PCS and WiFi is being used at levels close to its capacity in many cases, and new uses such is autonomous vehicles and IoT will need even more bandwidth to function. This section will discuss the relative merits of licensed and unlicensed solutions to meet these demands.

5.1 Why Licensed?

In general, privatizing bandwidth through licensing does not lead to competitive outcomes, economically efficient use of bandwidth, or achieve social objectives in the public interest. It also tends to create monopoly and oligopoly markets for vital communication services. Given this, how can licensing ever be good public policy?

There are two main arguments in favor of licensing. First, some important uses of bandwidth require the build-out of expensive infrastructure. For example, someone must build towers, connect them to backhaul, and so on if we are to have a nationwide cellular network. The government could do this, but then taxpayers would have to foot the bill (whether they are cell phone users or not). This might be inequitable, and other demands on the public purse may be considered to be more important. Even though private carriers charge users higher than competitive prices for cellular service, consumers may still be better off than waiting for the government to build a local tower.

TV and radio licenses can be justified on the same basis. Producing and broadcasting content is expensive, and the public benefits from these broadcasts. Broadcasters are allowed to use public spectrum and recover these costs through advertising. Cable and landline telephone companies follow a similar model. In this case, permission to use public rights of way is granted instead of the use of public radio spectrum. Companies agree to build and maintain costly infrastructure in exchange for being allowed exclusive, or near exclusive, rights to provide certain types of communications services to customers.

The second reason is that the private owners of bandwidth are able to control how bandwidth is used and shared. PCS carriers use prices to ration usage over subscribers, and employ protocols such as LTE that use centralized coordination to allocate time-slots to users in each cell. This centralized approach allows private PCS providers to use limited bandwidth more efficiently in many cases, and their ownership of gives them an incentive to do so. In contrast, WiFi and other uses of unlicensed spectrum applications rely on regulations and decentralized protocols such as the 802.11 family to share bandwidth fairly. In many cases, this is less efficient and reduces the net data capacity of a channel. The FCC has had to choose between a monopolistic, second best, licensed model, and a wasteful, regulated, unlicensed approach. Licensing was often the lesser of the two evils. Below, we will argue that new technologies and use cases offer the FCC a better set of choices

5.2 Why Unlicensed?

In 1985, the FCC decided to open the ISM[16] bands for unlicensed use. The intention was to encourage experimentation and innovation. As long as a few rules such as limits on transmission wattage were followed, users were free to do pretty much anything they wanted. As it turns out, this policy experiment was a phenomenal success. Simple uses such as cordless telephones, remote controls, and baby monitors, gave way to more sophisticated ones such as WiFi, Bluetooth, ZigBee, and RFID tags.[17] These technologies are completely embedded in our lives now. It is surprising that so much has been accomplished given the relatively small amount of bandwidth set aside for unlicensed uses. In total, only about 100 MHz in the sub-3 GHz bands and another 400 MHz in the 5GHz band are allocated. More recently, an additional 7 GHz in the 60 GHz bands have been allocated, and this may prove to be very well suited to facilitating oncoming technologies.

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[16] The industrial, scientific, and medical radio bands were set of frequencies set asides for microwave heating, metallurgical induction process, medical and scientific imagining and other non-communications uses.

[17] Radio Frequency Identification tags are passive devices that use energy transmitted by a reader to relay stored information on the unlicensed 2.4 GHz band. It is estimated that more than that RFID tags contribute hundreds of billions of dollars the US economy through saving in inventory control, retail loss prevention, reduced medical error and similar applications.

An unfortunate legacy of this history, however, is that the FCC is reluctant to imposes more stringent conditions on unlicensed bandwidth use. The value created by the 500 MHz below 6 GHz allocated at present is huge. These bands are crowded, and demand is rapidly increasing. The FCC's light hand in the 1980s gave us all this, but it is now time to reap the fruits of that experiment. Rules, regulations and protocols should be revised to protect WiFi and other current users of this bandwidth, Why continue to search when you have already arrived at your destination? It would be a mistake to conflate "unlicensed" with "experimental" or "unregulated".

Although the need for experimentation is no longer an strong argument in favor of unlicensed bandwidth, there are still many things to recommend it. Users do not have to pay monopoly, or indeed, any price for transmitting in unlicensed spectrum. The decentralized nature of WiFi allows for greater freedom and privacy. The fact the WiFi routers are required to use low transmission power levels means that the same unlicensed bandwidth can be used by simultaneously without interference by devices that are as close together as 50 or 100 meters. In contrast, licensed PCS cells operate at higher power and this limits reuse of spectrum.

5.3 Choosing Licensed or Unlicensed

Broadcasting such as commercial radio and television uses licensed bandwidth and should continue to do so. The costs of producing and transmitting content generates a free rider problem, and the best solution available remains licensing channels to whomever agrees to bear this expense.

The FCC has set aside a significant amount of spectrum for radar, radio astronomy, communications between aircraft and ships, public safety, military, and other other governmental uses. In a sense, the government has has retained the license to this bandwidth, however, it permits qualified agents to use it in specified and regulated ways. In other words. use of this restricted spectrum is shared using decentralized protocols more similar to what we see for unlicensed bandwidth.

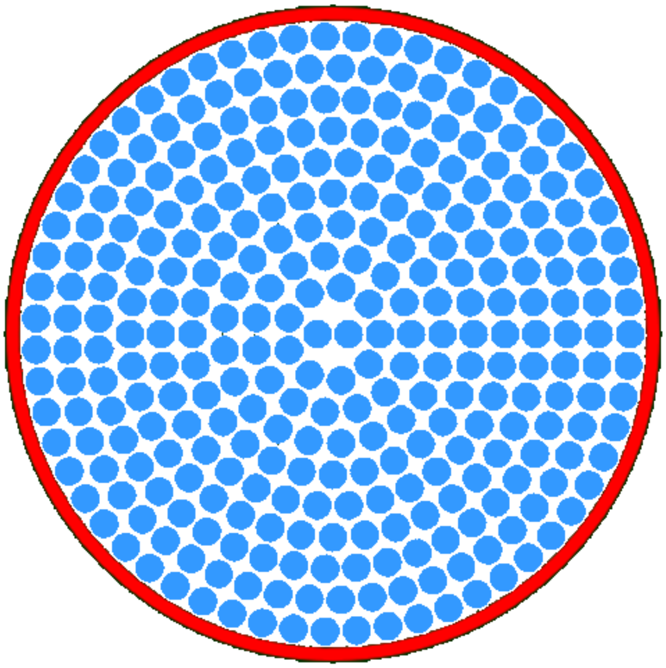
While licensing and restricting bandwidth for such use cases is probably the best approach, the question of how much to allocate is less clear. Cable and broadband has replaced broadcast television as the preferred way to get video content, and the existing channel allocations do not have enough bandwidth to support high definition broadcasts. The FCC has wisely decided to move these channels to higher frequencies and repurpose the beachfront spectrum that is freed up. There are many similar allocations, both licensed and restricted, that made sense when demand for spectrum as low that should now be reassessed.

The central problem facing the FCC, however, is finding more bandwidth for multicast networks and deciding whether it should be licensed or unlicensed. There are two factors that create a strong presumption in favor of unlicensed approaches

First, bandwidth belongs to the people and the FCC is charged with allocating and regulating it in the their interests. Ignoring this default and selling some of this scarce public resource to a private entity is sometimes beneficial to the public. For this to be so, however, the private entity must bring some comparative advantage or specialized ability to the table that makes it possible to generate more public benefit than well-regulated, unlicensed use. Private benefits to the license owners, such as revenue or profits, contribute to the public's welfare only indirectly in as much as they imply that the use may also have generated consumer surplus or beneficial externalities.

For example, if the government gave or sold a national forest to a lumber company, the company would certainly make profits by harvesting the trees. This is not in itself a good argument for selling national forest land. The resulting lumber, however, allows houses to be built and this benefits consumers. We could allow individuals to harvest trees, but this is likely to be inefficient for a number of reasons. Coordinating such activity to get safe and sustainable lumbering would be difficult and the lumber company has the advantages of lower production costs that go with larger scale. For example, it can buy heavy automated equipment to harvest and mill the lumber instead of relying on axes and chainsaws. Thus, selling the rights to some part of the national forest might very well be good policy. Taking such lands away from the public, however, needs this kind of clear justification.

Second, allocating bandwidth for low-power, unlicensed, instead of higher-power licensed use is inherently more efficient. As an example, suppose that 10 MHz of bandwidth could be allocated to PCS or WiFi. Suppose a PCS cell has a radius of 1 km while WiFi routers have a radius of 50 meters. It is possible to pack 308 WiFi routers with non-overlapping signals inside this PCS Cell. In other words, Suppose that a 10 MHz channel is capable of transmitting 100 Mb/s if allocated to licensed PCS usage. Then one cell tower could transmit 100 Mb/s divided over any clients within range. On the other hand, allocating the same 10 MHz to unlicensed WiFi use would allow 30,800 Mb/s to be transmitted to clients within the same 1 km diameter region. If the PCS cell had a radius for 2 km then 1245 WiFi routers could fit, and if it was 10 km, then the number would be greater than 31,000.



<u>**308 WiFi routers fit inside a 1 km diameter PCS cell**</u>

Several potential objections could be made to to these two points

1. PCS uses LTE protocols that include a control channel that is separate from the data channel. This allows a PCS access point to coordinate its clients and allocate time-slots and bandwidth more efficiently. WiFi routers use 802.11 protocols which rely carrier sense to share time-slots on a channel and do not use any centralized control to coordinate clients. As a result, licensed, PCS uses bandwidth more efficiently and achieve higher net transfer rates than unlicensed WiFi.

Answer: Both LTE and 802.11 achieve lower data throughput when packet demand is high. How much bandwidth is wasted depends on number and density of clients, how packet demand is distributed, and so on. It is probably the case, however, that an LTE access point does better than an 802.11 in most highly congested scenarios. In the worst cases, it might even be two or three times more efficient. Unfortunately, LTE would need to be more than 300 time more efficient than 802.11 in order to transmit more net data using on a channel even for very small PCS cells.

2. WiFi routers are often densely packed. In many cases their radio coverage areas overlap and this leads to even greater efficiently losses. PCS towers, on the other hand, are intentionally positioned to minimize interference from overlapping cells. As a result, licensing bandwidth allows it to be used more efficiently from a net data transfer standpoint.

Answer: If router density is high and coverage areas overlap, then even more than 308 routers could share the a channel within the area covered by a single PCS tower. Whether increased interference would outweigh the larger number of WiFi routers transmitting to clients depends on the details of relative placement and demand of each router and client.

3. People generally do not place routers in their backyards or in the middle of streets. Even though the coverage area of WiFi routers and clients may still overlap, it will seldom be the case that 300 or more routers will be found in 1 km PCS cell. People deploy routers as they are needed and most parts of a PCS cell will have no WiFi coverage at all.

Answer: If the connectivity needs of all potential users in a region can be met with inexpensive fixed routers, what does a PCS tower add? Towers are far more expensive to construct and PCS generates social loses through monopoly pricing. Unless there are users who cannot be served by fixed, short range routers, there is no reason to outsource connectivity to a private firm. Suppose there were there are only ten or twenty mutually interfering WiFi routers within a PCS cell. Even if the interference reduced net data transfer to 15%, ten WiFi routers would still achieve more data transfer on a channel than a single PCS access point. Suppose there were even fewer routers within a PCS cell. If the demand for connectivity in a region is too low, then it would not be worthwhile to build a PCS tower in the first place. In this case, the licensed bandwidth would not be used by the license holder and could not legally be used by anyone else. One might respond that this only likely to happen in poor or rural areas. However, such areas may include solar power installations, pipelines, high-voltage electricity transmission lines, or farms, any of whom could use this bandwidth for monitoring or IoT devices This would require higher powered routers and clients, but given the low density of demand, interference with other users would be unlikely. Similarly, large higher powered, WiFi routers could provide connectivity in poor neighborhoods, small towns, or rural areas. The loss of these potential uses needs to be considered when licensing bandwidth to private users.

4. Connected devices of all types have ever-increasing demands for bandwidth. Facilitating the Internet of Things (IoT) is important for the economy and is in the public interest. This is best done over licensed spectrum, both to assure quality of service, and because some devices are remote and would require higher broadcast power levels than are permitted on unlicensed bands.

Answer: For certain types of devices, licensed solutions may be preferred. For large classes of devices, however, using unlicensed bands is clearly better. To begin with, almost any device that is likely to be within range of its owner's WiFi router should simply connect there. Attaching TVs and other video displays, Roombas, ZigBee home automation devices, computers, smart washing machines, and connected thermostats to the owner's WLAN offers several advantages. Most obviously, device owners would not have to pay to use licensed bands. Devices with large data requirements (streaming video and gaming, for example) would quickly use up the data capacity of a PCS cell, and so could not be feasibly served by licensed bandwidth. Most IoT devices with lower data needs are not overly sensitive to latency. It does not really matter if your a text from your dishwasher or an update on the temperature in your office is delayed by several seconds. Latency on LANs is seldom this severe, but even for fire alarms and home medical monitoring devices, a second or two is unlikely to be critical. These same arguments hold for IoT and connected devices used in universities, corporate campuses, manufacturing plants, and office buildings. Quality of service is sufficient on unlicensed WiFi for almost every application. There is more of a case for a licensed solution for remote devices that do not have access to a LAN, but we pick up this question in the section on IoT below.

5. WiFi or other unlicensed approaches are unsuitable to serve mobile clients, such as cell phones. Autonomous vehicles will soon be commonplace, and they will need connectivity for collision avoidance and other uses. There is a need to allocate bandwidth to facilitate this. Meeting the needs of mobile clients is important for the economy and is in the public interest.

Answer: Demand for data over PCS networks is large and growing. One of the major policy questions facing the FCC is how to divide beachfront bandwidth between WiFi and PCS users. WiFi is unlicensed, has small cells, and does not require expensive infrastructure to use. PCS is just the opposite. Cell phones already lay-off a great deal of data traffic to WiFi networks using 802.11 protocols.[18] Of course this adds more congestion and increases the need for additional unlicensed bandwidth. Despite this appropriation of unlicensed bandwidth by PCS license holders, the demand for data outside the range of friendly WiFi routers is likely to exceed the capacity of existing licensed allocations. Technologies such as cognitive radio and software defined radio, discussed below, will make it feasible for decentralized networks to share bandwidth as efficiently as coordinated LTE networks, but this only solves part of the problem. The costs of deploying a nationwide PCS network are high. Individual cell phone user are likely to be willing to install even a single tower for their own use. Selling public spectrum to private agent in exchange for installing this valuable infrastructure may indeed be in the public interests. We will argue below that, however, that unlicensed solutions work better for autonomous vehicles.

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[18] Cisco estimates that "Sixty percent of total mobile data traffic was offloaded onto the fixed network through Wi-Fi or femtocell in 2016. In total, 10.7 exabytes of mobile data traffic were offloaded onto the fixed network each month. See http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html.

6. New Applications

6.1 Autonomous Vehicles

Autonomous vehicles are just around the corner and their impact on society and the economy will be significant.[19] Roads and infrastructure will be used more efficiently since autonomous vehicles can safely travel at higher speeds and greater density. Parking problems will be a thing of the past since cars will be able to drop off passengers and wait in remote locations until called.[20] Lanes on city streets currently used for curbside parking can be converted back into usable road. Those too young or too old to safely drive vehicles will gain or regain mobility. Road safety will be greatly enhanced. Not only are autonomous vehicles inherently better at coordination and collision avoidance, but they do not have accidents as a result of drivers impaired by youth, age, substances, or distractions. Finally, there will be far less need for truck, bus, and cab drivers. Autonomous vehicles in combination with simple robots could even deliver mail and packages.

As has been pointed out in many places, one man's labor savings is another man's unemployment.[21] It is difficult and unpleasant to drive a taxi in a crowded city, or to drive a truck over long distances. We need a degree of trust in our school bus and ambulance drivers. These jobs pay fairly well, as they should. It is not at all clear where equivalent jobs will come from. Nevertheless, this technology is on its way. It may be possible to delay it, but its attractions are simply too great to stop. One way or the other, society must deal with its consequences.

Autonomous cars only need to communicate with the cars immediately around them. In heavy traffic, this might be only 50 feet or so. On the other hand, it takes a car about 250 feet to come to a stop at 70 mph and twice as much on wet pavement.[22] A disabled car might therefore need to transmit as much as 500 or 600 feet to warn an approaching car.

City driving presents its own set of challenges for autonomous cars. Neither humans nor radio receivers can see around corners since buildings block light and significantly degrade radio signals. Humans solve this with traffic lights and stop signs at intersections. Autonomous vehicles could follow the same rules, but this would not take full advantage of their potential to use roads more efficiently. This might be solved by putting repeaters at intersections to give a fuller view, or adding instructions from a city-wide traffic computer that considers demands and congestion as whole and then broadcasts coordinating information to local routers for the use of autonomous vehicles.

Cars move quickly and so collision avoidance and coordination is latency intolerant. In particular, cars may only be in range of each other for a few seconds, so they need to complete the electronic handshake that allows communication quickly or it may be too late. This raises security

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[19] A bad choice of metaphors if ever there was one!

[20] Depending of the choice of implementation, autonomous vehicles could reduce demand for parking by up to 90%. See Zhang (2015).

[21] This is a widely discussed concern in the popular press, but scholarly estimates of the impact are difficult to find. See http://www.cnbc.com/2016/09/02/driverless-cars-will-kill-the-most-jobs-in-select-us-states.html for example.

[22] http://www.driveandstayalive.com/stopping-distances/

concerns since authentication will be weak.[23] Systems will have to be careful how they use information from another car. Can it all be trusted, or might malicious users send false telemetry to cause accidents? In addition, it is important to isolate data transmitted from other cars to prevent viruses and hacks.

Given this, is licensed or unlicensed bandwidth most suitable for autonomous vehicles? There are advantages and disadvantages to both, and we discuss this below.

Security: A licensed approach might involve a PCS type network authenticating cars in advance, maintaining a connection, and passing needed information from car to car acting as a trusted data intermediary. An unlicensed approach would require cars to make rapid independent connections to one another. The proposed 802.11p protocol operating in the 5 GHz band is designed to do exactly this. Without connection to outside data sources, however, checking certificates or otherwise authenticating other vehicles might prove challenging. The protocol might need to use sensor data to verify that other cars are doing what they claim in real time and possibly interact with a vehicle's control modules as well. On the other hand, a licensed approach creates a single point of attack. Compromising the trusted intermediary could lead to a catastrophic loss of life.

Latency and Licensed Network Availability: Using a large licensed cell builds in a certain amount of latency. A signal must travel several kilometers in each direction to reach a tower and be processed and routed back and forth between vehicles. Signal can be lost when going through a tunnel or passing behind obstacles. A traffic jam might require a cell to control thousands of cars which may exceed the cell's capacity. Even if it does not, safety would require that enough capacity be built to handle peak loads. A great deal of bandwidth and capital would be needed that would go unused in off-peak times. Rain, snow, and similar conditions would increase attenuation and would require that towers transmit at higher power to maintain the same level of data connectivity to its clients. This could create interference with other towers and other users. Towers would also need to be deployed in rural areas to cover roads with little traffic and to cover remote stretches of highway where getting power and backhaul may be difficult. City streets and alleys have their own set of coverage challenges. It is unsafe to have "cell holes" anywhere that autonomous vehicles are likely to travel. Finally, power outages or equipment failures could leave roads without coverage unexpectedly. The consequences for real-time control of rapidly moving vehicles are likely to be severe. To sum up, it would be extremely expensive to deploy the infrastructure needed make switch over to autonomous cars safe in the best of circumstances. Building in backups and redundancies to deal with unexpected events may make it completely impractical.

Latency and Unlicensed Network Availability: Using unlicensed bandwidth to carry ad hoc peer-to-peer networks has no built in latency, at least once the handshake is complete. Data travels a few hundred feet between vehicles and needs no additional routing. Roads are generally built to have line of site for a few hundred feet to give human drivers enough time to react to the actions of other vehicles and hazards. This includes tunnels, valleys, and city streets surrounded by buildings. Where visibility is lacking, stop signs, traffic lights, lower speed limits, and so on, are already in place to insure the safety of human drivers. In short, peer-to-peer, ground-level, line-of-sight radio

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[23] See Amoozadeh et al. (2015) for a discussion of this and other security concerns

connections are tailor-made for the autonomous vehicle application. This approach is also much better suited to deal with peak-load problems. A car stuck in traffic only needs to contact other cars within a hundred feet at most (even less if mesh networks are used). Low-power high-frequency signals are blocked by metal and so the broadcast radius of an autonomous car is automatically reduced in radio dense situations.[24] Broadcast power could also be reduced if interference is detected or in proportion to speed. Symmetrically, power could be increased when rain, snow, or similar conditions are detected. A huge advantage of the unlicensed approach is that vehicles carry their broadcast infrastructure with them. There is no need to build out a reliable PCS type networks to cover every farm road and urban alleyway. Peer-to-peer networks can be established anywhere there are peers who need them with no external infrastructure. Finally, any network failures happen on a vehicle by vehicle basis. If a near-by car loses a sensor or drops off the network, surrounding autonomous vehicle can treat it like a human driven car and give it wide berth. The damaged car can sense the loss of connection and exit the road for repair. Thus, failures are local, and unlikely to result is disaster.

Privacy and Cost: Putting critical infrastructure like traffic control in private hands via licensed bandwidths has a number of downsides. Such license holders would have real-time access to the location of every autonomous car on the road (and maybe even off the road). It would become impossible to travel without a company knowing about it. Drivers might not even be allowed to travel at all if a company decides that they are behind on their PCS bill, have violated its terms of service, in response to a false claim from the bank financing the car, to comply with a government order, mistaken or not, or for any other reason at all. Companies would have access to each car's computer and electronic control systems. It might use a camera to see who is using the car or a microphone to listen in on conversations between passengers. It might use location and other data to advertise to drivers on its network or sell this data to third parties. If traffic control PCS is a monopoly or tied to a car's manufacturer, consumers are captured and must pay whatever price and comply with whatever terms of service are demanded. If there are several providers, on the other hand, then coordination of cars on different networks may become a problem. None of these issues arise if an unlicensed peer-to-peer approach is used.

To sum up, the licensed approach to traffic control for autonomous vehicles is extremely expensive from an infrastructure standpoint, and builds in latency and the likelihood of frequent loss of network availability. It would creates a single point of failure at level of individual cells and for the network as a whole. It is creates serious privacy issues and establishes a whole new layer of monopoly or oligopoly firms with the power to control private vehicles. This is likely to lead to high prices and abusive practices. On the other hand, the unlicensed approach must solve the problems of rapid handshakes and how to deal with peers who may not be trustworthy.

6.2 Internet of Things

IoT is another rapidly emerging technology. These devices are widely varied and have different data requirements. It is helpful to consider four classifications.

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[24] The proposed 802.11p protocol uses the 5GHz bands. The FCC might consider moving autonomous vehicle networks to the much less crowded 30 or 60 GHz bands.

Short Range - Low or Medium Data: Many home IoT devices only need to communicate small amounts of data infrequently. The dish washer wants to tell you when a cycle is complete, a light bulb needs a signal to turn on or off. Keyboards and headphones need to transmit more data, but the ranges are generally shorter. The existing Bluetooth and Zigbee protocols on the 2.4 GHz band are well suited for such uses.

Short Range - High Data: A household running multiple TVs with streaming HD content along with games on PC's and other internal device traffic could easily need 30 or 40 MB/s of connectivity. These demands will become much more substantial as virtual reality devices and applications become more widely available. In theory, current WiFi networks can handle this. In practice, it is difficult to transmit at rates this high on 5GHz at any distance, especially through walls. 2.4 GHz is better, but these channels are increasingly crowded.[25] A solution might be to use some of the newly allocated unlicensed 60 GHz spectrum at low power using ZigBee or other mesh protocol. The high frequency and low power creates a tiny commons, perhaps confined to a single room. These frequencies are blocked by walls and other obstacles, and so even in densely populated apartment building and office towers, interfere between devices is likely to be minimal. The amount of bandwidth available (several GHz) has enormous data capacity. To make this work, however, repeaters with a line of sight between the device and the backhaul router would be needed. These could be purpose built, or simply incorporated into IoT devices.

Long Range - Low Data: A valve on an oil pipeline or irrigation system might only need to get a couple of commands each day to turn on or off, and devices monitoring power, rail, and water distribution networks might only need to make contact when they have a problem to report. Smart city applications like coordinating stoplights to meet current traffic conditions, allocating buses to meet unexpected surges in demand, or sending out crews to take care of storm damage, also have low data requirements. These devices are often in remote locations or at least are out of range of WiFi networks. Equipping such devices with a PCS connection costs about $40 per month and is therefore impractical in most cases. Such devices need to communicate at ranges of one to twenty miles, but given the low data usage, do not need expensive infrastructure for coordination. A farmer, a city, a university, or a corporate campus could deploy its own routers to communicate with its own devices. Given the distances and obstacles involved, such transmissions are most suitable for the sub-1 GHz spectrum used for pagers, CB radio, and analog TV. IoT devices are becoming more common every day and the need for spectrum to be allocated for long range, low data use will grow proportionately. The marginal value of a few bytes of information regarding a fire, pipeline leak, or congestion on city streets is large. Using licensed bandwidth is expensive. On the other hand, there is a potential for abuse by data hogs if an unlicensed approach is chosen. In the next section, we will argue that cognitive radio on unlicensed bandwidth may provide a solution.

Long Range - High Data - Latency Tolerant: Traffic and security cameras and smart city applications that gather large amounts of telemetry have large data requirements. A camera on top of a highway sign, or a sensor in a park or a remote location, is not likely to be in range of a WiFi network Sending large volumes of information over PCS networks would be expensive and crowd out other users. However, seeing traffic video with a minute or two of delay may be enough to monitor and optimize traffic flow. Vetting security footage every hour or once per day may be enough to

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[25] See Akbar et al. (2015) and Sharef et al. (2014) for further discussion.

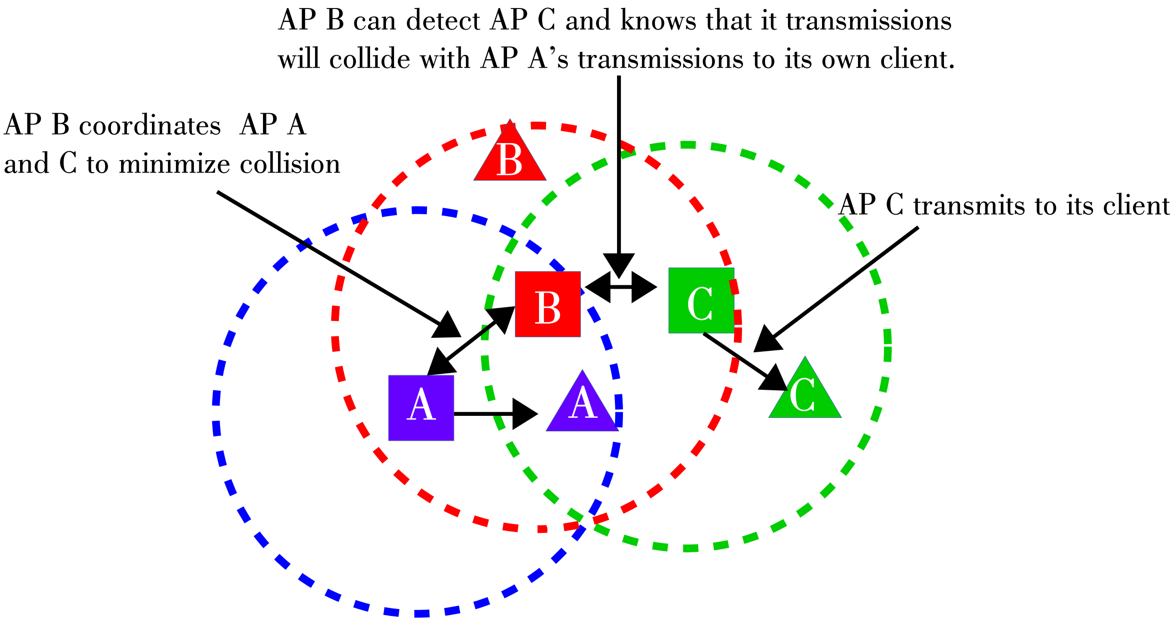
provide the evidence needed to catch criminals. Recordings of pedestrian traffic, weather data, pollution levels, etc., may still be useful after days have passed. Latency tolerant video could be scheduled for transmission on frequencies intended for long-range, low-data uses in periods of slack demand. Another possible solution is to extend 802.11p to allow passing vehicles to cache such data as they get within range, and then drop it off as they get within range of backhaul. This a sort of physical packet delivery, and there might even be a fee or an auction for the provision of such packet transportation services. Thus, an unlicensed approach may provide a solution here as well.

7. Technologies to Improve Spectrum Use Efficiency

7.1 Cognitive Radio

802.11 uses carrier sense alone to share a channel. PCS protocols use a control channel to balance the demands of the clients they are connected to, but ignore the behavior and needs of other users. A great deal of channel capacity is lost through collisions, retransmissions, and attempts at coordination.

A classic example of coordination failure is called the “hidden station problem”. The figure below shows three square access points (APs) and three triangular clients. The dotted circles indicate the maximum range of the APs. Beyond this distance, their transmissions cannot be heard. Note that APs A and C cannot detect each other since they are out of range. Both APs listen, and finding that the channel is empty, try to transmit data to their respective clients. Unfortunately, AP A’s transmissions to its client collide with AP C’s transmissions. As a result, A’s client does not receive the data and either does not acknowledge receipt or requests a retransmission. AP C is completely unaware that AP A is trying to send data to its client. It hears a clear channel and so may claim all of the time-slots for its own use. Meanwhile, AP B’s client is unable to communicate with AP B because AP A is using up the channel to retransmit data to client A.



<u>The Hidden Station Problem</u>

What if AP B told APs A and C that client B was in range of them both? By pooling information and then using it to share the channel, efficiency could be greatly improved. APs and clients could also give one another information about their anticipated data transmission volume, and their degree of latency tolerance.

This is an example of what is called **cognitive radio**.[26] This is not a protocol, but a name for a class of yet to be developed protocols. If stations shared carrier sense data and could anticipate planned transmissions, not only would collisions be avoided, but there would be no more need for LBT and RBO. Cognitive radio could even be adaptive in the sense that it altered transmission power levels to optimally share channels. If very few stations were in range, increasing power would allow communication with more distant clients at higher data transfer rates without imposing externalities on other users. By using high power levels in a coordinated, sequential way, higher data rates combined with fewer dropped packets requiring retransmission might even be more efficient than sticking to lower power levels.

Decentralized protocols using carrier sense become less efficient as demand reaches capacity One reason to license bandwidth is that owners can impose rationing rules on users through prices and other means. Although this can improve efficiency, the mechanisms license holders use are far from optimal. PCS providers typically offer subscribers menus with different bundles of data, SMS text and voice minutes. Sometimes unmetered service is also offered. This means that PCS users pay a marginal cost of zero for use up to their bundle limits. In turn, this means that users do not

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[26] See Sun (2013) for a survey.

internalize the costs that their transmissions impose on others when the network is at capacity. Pay-as-you-go plans price data and minutes at a fixed level that generally exceeds marginal cost. This also fails to provide subscribers with incentives to use channel capacity efficiently.

It is now feasible to place considerable processing power on-board routers, which opens the door to protocols that offer significant improvements over both WiFi and LTE. For example, if the FCC chooses to make bandwidth available for the type of long range, low data, uses discussed in the previous section, what prevents users from trying to transmit large amounts of data, data that has low value, or data that is latency tolerant? A network of cognitive routers could keep track of how much data a given device transmits in a day or month and enforce quotas. The cognitive network could also log requests for permission to transmit larger volumes of data and honor them if and when the channel was not otherwise in use.

An even more sophisticated approach would be to program routers in a cognitive network to run an auction mechanism when there is excess demand data transmission. Outcomes of the auctions could be recorded in a blockchain, and a native currency token used to make automatic micropayments. This approach would make it possible for the FCC to sell or license time-slots on each local electromagnetic commons separately. Prices in the auction would signal their marginal value and allocate them to the highest value user. Even better, when there is excess capacity, the price of time-slots would fall to zero. This is exactly what economic efficiency requires. Going back to the bridge examples, at rush hour, drivers crowd each other and it is impossible to accommodate every driver at the exact time he wishes to cross. If a toll is imposed that adjusts dynamically in response to demand, only the highest value users would be willing to pay. Commuters who could easily choose to travel at off-peak times, cargo trucks, and so on, are given the correct incentives to internalize the costs they impose on other drivers. Auctions are an ideal mechanism to find this price at any given moment. On the other hand, if the bridge has excess capacity, a driver imposes no externalities on others. In this case, a positive toll deters drivers who would benefit from crossing the bridge and could do so at no cost to others. Thus, dynamic pricing could significantly increase social welfare.

To sum up, cognitive networks make it possible to use existing bandwidth much more efficiently. They relieve the pressure to allocate new bandwidth to both licensed and unlicensed uses. Cognitive networks also open up an entirely new possibility for more granular licensing of bandwidth. Rather than selling off exclusive rights to channels on a nationwide basis, the FCC could run a spot market for time-slots in each individual micro-cell. In addition to allocating bandwidth more efficiently, cognitive radio would can reduce the social losses associated with market concentration.

7.2 Software Defined Radio

A problem with any plan to change protocols used on any part of the spectrum is the existing stock of hardware. Current routers are not capable of participating in cognitive networks, and demanding that installed hardware be replaced overnight is costly and impractical. Grandfathering in old hardware and allowing things to improve slowly is more reasonable, but what about the next time a change is needed? Especially with technology and usage patterns changing so rapidly, there is a need for greater agility.

Software defined radio[27] is one way to gain such agility. The idea is that the protocols are built into firmware which can be updated or replaced, instead hardwired into a router. Routers would be able operate with any protocol on the set of frequencies they were designed to use. Not only does this permit network-wide upgrades or even wholesale changes in protocols, it allows on-the-fly optimization. One size may not fit all. A protocol that can deal with high-demand situations in airports or university campuses is unlikely to be optimal in suburban neighborhoods. Similarly, the way to share bandwidth optimally while classes are in session is unlikely to remain optimal after hours. With software defined radio, routers could change protocols to meet local needs and still be able to communicate with other routers and devices in the area (which also adopt the currently optimal protocol).

In short, software defined radio offers an additional avenue to use current bandwidth allocations more efficiently, and to do so on more granular level. It also creates flexibility to reprioritize different types of use, and even to expand or reduce the amount of bandwidth that is used, at least within the hardware constraints of routers.

7.3 LTE-u, LAA, and Other Approaches to Sharing the 5 GHz Band

As we say above LTE protocols do a better job of coordinating traffic under crowed conditions due to their use of a control channel. Unfortunately, the large size of PCS cells prevent local reuse of bandwidth and so less net data transfer is possible on a given channel. The begs the question, why not use LTE-type protocols in for small cells in unlicensed bandwidth?

LTE-u is, a protocol intended to extend the offloading of data traffic to WiFi frequencies in a more integrated way that may deal with some of the coordination failures of 802.11. The idea is that PCS providers like Verizon would be allowed to use the 5 GHz band similarly to how they currently use their licensed bands. Specifically, time-slots on a WiFi channel would be coordinated through a separate control channel maintained on the licensed PCS bands. Subscribers to a provider's service would be told when to transmit and receive. This would avoid losing time-slots though politeness, and prevent collisions requiring transmissions.

The difference between WiFi and LTE type protocols is similar to those between human driven and autonomous cars. Humans are careful, let people cut in, get confused at stop signs, leave large gaps between vehicles, and so on. Humans drive using "sense only" data and seldom have a clear idea what one another plan to do. Being polite avoids collisions, but does not use the road as efficiently as possible. Autonomous cars, on the other hand, communicate with one another. They know when a neighbor needs to get to a turn off or merge with traffic. They can follow each other closely because they know when one another will slow or stop. The carrying capacity of a highway is much increased as result.

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[27] See Kreutz et al. (2015) or Yang et al. (2015) for more discussion.

Sounds great, however, there are several down sides. 802.11 routers are polite, listen before talking, and do random back-off if there is a potential for collision. LTE-u sense for other routers within range, and then decide how much of the available bandwidth to appropriate for themselves based on what they hear. If they detect one WiFi router, the LET-u router might decide on a duty cycle of 50% and then simply broadcast. They do not listen before they talk, and so 802.11 routers are crowded out once an LTE-u router starts to transmit.

Again, think of a freeway packed with autonomous cars traveling 70 mph at five foot intervals. If a human driver is on the freeway at the same time, the autonomous cars will try to share the road. If an autonomous car wants to change lanes, this is quickly and safely coordinated through a control channel. If a human wants to change lanes, he is unlikely to find a gap. If he decides to stop being polite, he might start to intrude on the next lane which denies use of that slot to both him, and the automaton. However, the automaton now senses that there is another car that wants a slot in its lane and so gives it up half the time. Thus, humans must be impolite and bump into the car in the next lane to get access. Now think of a human trying to enter such a highway. He cannot signal his interest in doing so without being impolite and causing a collision. Since he is unlikely to do this, the autonomous cars take up the entire highway. It appears that no one else demands space on the road. The human would be better off buying an autonomous vehicle himself, since otherwise, he can only use the highway when traffic is light. Human drivers become second class citizens when it comes to highway access, just as WiFi users will be in the presence of LTE-u routers.[28]

One might take the view that this is just the survival of the fittest, but the problem goes deeper. Not only do LTE-u routers not work well with WiFi, they also do not work with one another. If a Verizon and a T-Mobile LTE-u router are trying to use the same channel, there may be no winners. Each broadcasts on its chosen duty cycle. Since neither drops off like a polite WiFi router, packets collide and must be retransmitted. LTE-u is not set up to deal with sharing bandwidth with other aggressive routers. Unless there is carrier aggregation that allows data offloaded to WiFi from PCS by all carriers to be coordinated by a single control channel, we are likely to have a disaster. Unfortunately, it may be illegal for carriers to coordinate in these ways for anti-trust reasons. Even if they could, how would they decided internally whose traffic gets priority? Will it be a Verizon or a T-Mobile subscriber?

LTE-u is actually an unofficial version of the LAA (Licensed Assisted Access) protocol that is being developed by the 3GPP. LAA will include LBT, but not RBO and other elements of the more polite 802.11x standards. An additional downside of both LTE-u and LAA is that they require new hardware since existing routers are unable to use PCS frequencies and have no firmware to interpret control channel instructions. LWA (LTE-WLAN Aggregation) is a more advanced version of LAA that can use WiFi frequencies for control channels. It integrates PCS and WiFi channels so that they can be used interchangeably. Using LWA requires firmware updates but can use existing router hardware. MulteFire technology also adds a control channel in WiFi frequencies but does not integrate with PCS networks.

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[28] See Abinader (2014) for technical analysis and CTC Technology & Energy (2016) for a discussion of the impact on consumers and cities.

The main lesson here is that even in unlicensed bandwidth, regulation, standards and protocols are required. The free market will not resolve allocation and standardization problems effectively, and all users of the bandwidth will lose out if we allow the law of the jungle to prevail. WiFi works well up to a certain congestion point, and LAA works well if it has sole control of a channel. Forbidding LAA and allocating more bandwidth to WiFi in order to reduce congestion is one solution. Given the ubiquity of WiFi and Bluetooth and the tremendous value they provide, this is an attractive option. Reserving certain WiFi channels for the use of specific LAA providers is another alternative, but if there are many providers, this would seriously encroach on existing WiFi users. Allowing or forcing LAA providers to coordinate and use a single control channel to allocate time-slots on the WiFi data channel or channels they are permitted to use may be a better approach, but still reduces the bandwidth available to 802.11 users. Neither 802.11 nor LAA and its variants do a particularly good job of solving the problem of efficient use of unlicensed bandwidth when demand is high. Using both protocols at the same time on 5 GHz band may be the worst solution of all. A better approach may be found using cognitive and software defined radio discussed above.

8. Conclusion

We have argued that the nature of bandwidth as a resource almost guarantees that the market will not be able to allocate it to its most valuable uses in either a social or economic sense. Although there are still some cases where content creation or infrastructure deployment make licensing bandwidth to private agents the best alternative available, new technologies and increased demand make this less frequent.

Multicast networks of all kinds are becoming more important than the broadcast networks of the past. Streaming HD and VR content to multiple devices at once will become the norm and will over-burden the carrying capacity of existing unlicensed bandwidth. IoT, autonomous cars, smart cities, and many other emerging technologies will require access to multicast networks with varying range and data capacity. New bandwidth allocations and protocols for fair and efficient sharing will be needed. Wherever possible, low-power transmitters on unlicensed bands should be used order to maximize the potential for bandwidth reuse in different locations.

Cognitive radio creates the potential to use bandwidth far more efficiently and flexibly than existing protocols. It even makes it possible to sell access to bandwidth at a granular level. The FCC could choose to sell individual time slots in millions of small local networks to end users directly instead of selling regional control over bandwidth to a single private agent as it has in the past. This granularity also makes it feasible to price use at socially efficient levels instead of the monopoly prices used by license holders. In short, cognitive radio obviates the coordination advantages that licensed has had over unlicensed approaches in the past.

Software defined radio adds even more flexibility and agility to bandwidth use. Multicast routers could be programmed on the fly to use the best protocol given local conditions and demand. Within the hardware capabilities of the routers, the amount of bandwidth accessed by a local network could be expanded or reduced depending on its current value in alternative uses.

Rapid changes in technology create challenges and opportunities for spectrum regulators. Enabling connectivity and maximizing the value of the very finite amount of bandwidth available will play an increasingly important role in the country's economic development and innovative potential. Regulatory agencies in general will have a hard time keeping up with these rapid changes. We have tried int this paper to capture the essential tradeoffs that emerging technologies will pose.

Appendices

The following two appendices consider the implications of the argument made about for broadband regulation.

Appendix A: Profitability and the Public Interest

A frequent claim made by internet service providers (ISPs), and others, is that unless investing in infrastructure is profitable, it will not be built.[29] By extension, measures to make the connectivity businesses more profitable are in the public interest since it gives companies the capital they need to invest in improving and extending the network.

Sadly, to call this a half-truth overestimates the situation by about forty percent.

The truthful part is that a company will not undertake a project if it does not expect to make a profit. However, that barrier is crossed at the moment a company buys or agrees to accept a license under the conditions imposed by the FCC. Claiming that a project is unprofitable is far more likely to be a sign that the company is simply trying to get an even more profitable deal. Nice for the company, but not in the public interest. Even if the project truly is unprofitable, this means that the company did a poor job of estimating the costs and benefits, or bid knowing that the project was unprofitable and thus never intended to stick to the terms and conditions it agreed to. Rewarding such behavior is unlikely to be good public policy.

If the terms set out when bandwidth was sold or licensed truly made a deal unprofitable, it would find no takers. The government would then have to consider whether to relax the terms or allocate the bandwidth to other uses. If a deal goes through, however, companies should be held to the terms of the agreements they entered into voluntarily.

What about the claim that profits benefit the public since they fund deployment and improvement of infrastructure? Companies make this claim in hopes of being allowed to do a variety of things:

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[29] For example, the National Cable & Telecommunications Association (the main trade association for U.S. broadband and pay television industries) makes the following statement on its website: "But the FCC's misguided 2015 decision to impose heavy government regulation of the internet networks raises costs, which are ultimately born by consumers, and threatens the continued growth and expansion of internet networks throughout America. Consumers are best served by policies that encourage ongoing investment and innovation especially as technology changes, as network demands increase, and as stakeholders focus on closing the digital divide in every community across America." See https://www.ncta.com/positions/supporting-open-internet

- Keep out or hamstring competing service providers.

- Charge higher prices to consumers, especially in the case of old-line regulated telephone and cable companies.

- Allow the creation of new profit centers such as requiring that consumers rent or buy company equipment to use their service.

- Insert advertisements into services.

- Be allowed to harvest usage information and metadata from consumers regarding viewing and browsing patterns.

- Charge discriminatory fees to different users, especially content providers, for access to their networks.

In the most general terms, the claim that unless companies have the cash in hand to make investments of any kind is simply false. All companies, regardless of sector, make investment decision on the basis of marginal cost and benefit, not the overall profitability of legacy capital already deployed. For example, if replacing coaxial cable with fiber to the curb allowed Comcast to raise prices enough to justify the expenditure, it would do so. A bond or stock issue, or simply borrowing the money would cover the cost, and bankers or investors should be willing support the effort. If fiber does not cover its costs, using its profits to build it anyway would be a violation of Comcast's fiduciary responsibility to its shareholders.

In fact, the evidence suggests that competition which makes legacy capital less profitable is what creates incentives to upgrade infrastructure. When Google Fiber moves into a city, or AT&T upgrades from DSL to fiber, Comcast is likely to respond by lowering prices and upgrading its own network. Even though profits go down, they would go down even further if Comcast did not counter in this way.[30]

Should cable and other broadband companies be allowed to collect data on their subscribers? If subscribers had a meaningful choice of broadband providers, then it might make sense to let the market work. Consumers who valued privacy would choose to pay extra to go with a company that respects it. This is not the case, however.

The argument that broadband providers make is that Google, Amazon, Facebook, and other internet companies, are allowed to collect such data, and prohibiting broadband providers from doing the same puts them at an unfair competitive disadvantage.[31] This is a false comparison. Con-

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[30] An Analysis Group study recently found that the entry of a second gigabit internet provider in a market results in price reductions of 34 to 37 percent. In addition, when one ISP upgrades their network to provide higher speed broadband, the likelihood that other ISPs in the market also upgrade their networks goes up by 4 to 18 percent annually. See Mahoney and Rafert (2016) for more details.

[31] For example, in May of 2016 the NCTA (see footnote 17) urged the FCC to treat ISPs like any other company on the internet in order to avoid "consumer confusion" and protect them from a "barrage of opt-in authorizations." The current FCC chairman appears to be ready to do exactly this and the BROWSER Act has been proposed by Rep. Mar-

nectivity providers are not the same as content providers. These are obviously entirely different industries, with entirely different cost structures and business models. We are not forced to use Facebook or Google, but Comcast (or AT&T, or Time Warner, etc.) is often the only pipe available to most consumers for broadband service. Even when a consumer has two choices, one is generally slower and more expensive, and duopolies are a small step up from monopolies from a consumer standpoint in any event.[32]

Arguably, we do not really have a choice about using Facebook or Google. Not being on Facebook is like living in a cave if you are younger than 30. One could always use Bing instead of Google of course... The implication, however, is the opposite of what broadband providers suggest. When a company has a monopoly on a vital service, the public has a right to regulate the company's behavior. If the market cannot discipline a company, then it is not unreasonable for government to keep a close watch. Whether it would be a good idea to prohibit or limit Google's collection of personal information is an open question. Google and Facebook provide valuable services that are costly to produce. The majority of these costs are covered by advertising, which to a great extent, depends on knowing how to target ads. Allowing Google and Facebook to encroach on our privacy might be preferable to having limited or no services from these companies. ISPs also provide valuable services that are costly to produce, however, these costs are fully covered by subscriptions from their users. There is no corresponding public interest in allowing them to infringe on their customers' privacy to further increase their revenues.

Appendix B: Net Neutrality

ISPs were reclassified as Title II common carriers in 2015 by the FCC. In general, common carriers are responsible for transporting things from place to place in a non-discriminatory fashion. Common carriers are not responsible, however, for the legality or potential harm of the things that they carry. Services such as the post office, passenger carriage, and air, rail, and sea cargo transportation, are considered vital basic utilities that are building blocks of commerce and civil society. As such, it is felt they should be available on equal terms to all citizens. It would be burdensome and self-defeating to ask common carries to be responsible for any consequences of their carriage. To do so they would have to inspect every letter, open every box, do a background check on every passenger, and then deny service where they thought liability might result.

ISPs seems to fit this model perfectly. They deliver packets of data, voice phone calls, webpages, email, streaming audio and video, IoT telemetry, and even the occasional fax. Broadband service is an enabling technology that drives innovation and economic growth. It allows persons with disabilities to work from home and anyone to start and run a new business. It lets citizens keep up with and discuss the important events of the day and learn about the problems we will face in the future. It permits artists to share their work and anyone to expand their cultural horizons. Of course, some of the packets delivered by ISPs contain content that is slanderous, obscene, illegal, or violates

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sha Blackburn (R-TN) to cement this with legislation. See https://www.ncta.com/platform/public-policy/fcc-privacy-plan-will-confuse-consumers-and-provides-no-added-protection.

[32] We may as well allow the electric company install microphones and cameras so that they are not at a competitive disadvantage. Of course, consumers could choose to disconnect or install a diesel generator, but this is choosing to live in the dark or pay much more for the same amount of power.

copyrights. Making Comcast or Time-Warner block this content would be extremely expensive and would destroy all privacy in Internet communications. With the growing use of HTTPS, VPNs, and encryption, it might not even be feasible for ISPs to do so.

Title II carriers are clearly subject to net neutrality rules under the regulatory statute. How the FCC can, or must, regulate ISPs if they are classified as Title I carriers is less clear. The FCC attempted to impose net neutrality rules on ISPs before the the 2015 reclassification decision, but federal courts ruled that this exceeded the authority given by the statute. Unfortunately, the FCC reversed itself in 2017 re-reclassified ISPs as Title 1 carriers not subject to net neutrality rules.

Title I information services governed under Section 706[33] which requires that the FCC "shall encourage the deployment on a reasonable and timely basis of advanced telecommunications capability to all Americans" and "promote competition in the local telecommunications market, or other regulating methods that remove barriers to infrastructure investment." Exempting ISPs from net neutrality rules does nothing to advance either of these objectives. Charging discriminatory prices to users of their networks may increase profits, but as we point out above, does nothing to speed investment in infrastructure, promote competition, or lower prices to consumers. Given this, it is hard to see how revoking net neutrality in order to make existing network infrastructure more profitable to ISPs is in the "public interest," as Section 706 requires.

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[33] *Telecommunications Act of 1996, Pub. L. No. 104-104, § 706(a), 110 Stat. 56, 153*

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