THE ECONOMICS OF COLLABORATIVE PRODUCTION IN THE SPECTRUM COMMONS

MARK COOPER
CENTER FOR INTERNET AND SOCIETY, STANFORD LAW SCHOOL

Something there is that does not love a wall…
And on a day we meet to walk the line
And set the wall between us once again….
There where it is we do not need the wall:
He is all pine and I am apple orchard.
My apple trees will never get across
And eat the cones under his pines, I tell him.
He only says, "Good fences make good neighbours."
Spring is the mischief in me, and I wonder
If I could put a notion in his head:
"*Why* do they make good neighbors? Isn't it
Where there are cows? But here there are no cows.
Before I built a wall I'd ask to know
What I was walling in or walling out,
And to whom I was like to give offence.
Something there is that does not love a wall…
He moves in darkness as it seems to me,
Not of woods only and the shade of trees.
He will not go behind his father's saying,
And he likes having thought of it so well
He says again, "Good fences make good neighbours."
~ Robert Frost [1]

Property rights are a solution to the "tragedy of the commons" by allocating property to its most valuable uses.
But property rights assume property is *conserved*.
Yet, *spectrum capacity increases with the number of users, and if proportional to N, each new user is self-supporting!*
~ *David Reed* [2]

Property defines rights inefficiently.
Dynamic utilization of computation, power and bandwidth adjusted every few nanoseconds is more efficient.
Fixing chunks of one factor, subjecting them to transaction costs and strategic behavior,
will lead to artificial limitations of the set of usable combinations.
Property rights in bandwidth inefficiently fence a sub-optimal resource boundary.
~ *Yochai Benkler* [3]

Revised version of a paper presented at 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, Baltimore MD, November 9, 2005.

INTRODUCTION

When Technology Removes the Fences

Using the word commons to describe a superior form of economic organization in early-21st century America is risky business. It runs into the teeth of the dominant analytic paradigm, which relies on neoclassical economics to press for the strengthening and extension of more exclusive property rights, the antithesis of a commons, in all aspects of economic life.

However, the resurgence of interest in the concept of a commons is driven by fundamental empirical facts that are impossible to ignore. The phenomenon of the commons is on the rise across a number of areas. Indeed, the cover story from the August 2005 issue of *Wired* magazine opined that shared, collaborative production is the "main event."

In marking the 10th anniversary of the initial public offering of Netscape, as a landmark in the growth of the World Wide Web, *Wired* sees a revolution that penetrates to the core of daily life with the transformation of consumers into producers.[1]

> At its heart was a new kind of participation that has since developed into an emerging culture based on sharing. And the ways of participating unleashed by hyperlinks are creating a new type of thinking – part human and part machine – found nowhere else on the planet or in history…
>
> What we all failed to see was how much of the new world would be manufactured by users, not corporate interests…
>
> Linking unleashes involvement and interactivity at levels once thought unfashionable or impossible. It transforms reading into navigating and enlarges small actions into powerful forces.
>
> The electricity of participation nudges ordinary folks to invest huge hunks of energy and time into making free encyclopedias, creating public tutorials for changing a flat tire, or cataloging the votes in the Senate. More and more of the Web runs in this mode. One study found that only 40 percent of the Web is commercial. The rest runs on duty or passion.
>
> Coming out of the industrial age, when mass-produced goods outclassed anything you could make yourself, this sudden tilt toward consumer involvement is a complete Lazarus move… The deep enthusiasm for making things, for interacting more deeply than just choosing options, is the great force not reckoned 10 years ago. The impulse for participation has upended the economy and is steadily turning the sphere of social networking – smart mobs, hive minds, and collaborative action – into the main event [4:132].

Over that same 10-year period, the commons approach to spectrum management – the elimination of exclusive rights to the use of parts of the spectrum – has had an equally impressive run [6]. The remarkable success of WiFi in parts of the spectrum that were allowed to go unlicensed because they were considered to be "junk" or "garbage" ranks high in the pantheon of successful contemporary commons approaches.

> But reality has a way of forcing debates. The most immediate debate-forcing fact is the breathtaking growth of the equipment market in high-speed wireless communications devices, in particular 802.11 or WiFi family of standards, all of which rely on utilizing frequencies that no one controls…. It now appears that serious conversation between the two radical critiques of the licensing regime is indeed beginning to emerge [7:5].

This dramatic success and growth of several different types of collaborative activities that rely on non-property or non-market relationships and exchanges, including, in addition to the World Wide Web and unlicensed spectrum, open source software and peer-to-peer networks, poses a challenge not only to the dominant economic paradigm, but to a broad range of received social science thinking. Political scientists, applying the *Logic of Collective Action* [8], believed that the collaborative process would breakdown under the weight of a free rider problem. Sociologists feared an acceleration of the *Bowling Alone* [9] syndrome, as the focal point of interaction shifted from the face-to-face physical world to anonymous, fleeting interactions in cyberspace [10]. Marketers believed that huge bundles of information goods would come to dominate online distribution [11]. There is steadily mounting evidence that they were all wrong as new forms of collaboration bind people together in productive, social and economic relations to produce and self-supply an increasing array of micro-products to meet their needs.[2]

Purpose and Outline of the Paper

This paper offers an economic explanation for the success of these collaborative activities. Rather than regurgitate the tit-for-tat debate between those who advocate expanding the role of property in the spectrum and those who advocate more reliance on a commons approach,[3] it demonstrates the positive case for the spectrum commons. The paper offers a comprehensive framework for analyzing the key technology components of the ongoing digital revolution that are transforming communications in the spectrum. The framework is used to explain the economic organization and institutional structures that underlie the success of collaborative production in digital, networked industries.

Section II draws from the literature on industrial organization and institutional economics to create an analytic framework. The framework emphasizes transaction costs and the possibility of divergent successful organizational structures and governance rules for access to resources.

Section III presents the general definition and description of the concept of collaborative production by extending well-known economic concepts. It focuses on market failure in property regimes that are turned into successes by collaborative production.

Section IV describes the key elements of the digital, networked platform that is the contemporary environment for the growth of collaborative production. These embody technological and institutional changes of the digital revolution that took place over the latter part of the twentieth century.

Section V shows how key characteristics of spectrum make it a candidate for treatment as a commons. It shows that open wireless networks are one example of the broader phenomenon of collaborative production and describes the economic and organizational features of the spectrum as a commons that create the conditions for success.

Having demonstrated the viability of the alternative form of economic organization, Section VI discusses policies that should be followed to strengthen and promote collaborative production in the spectrum commons.

THE ECONOMIC PARADIGM

This paper combines two common economic paradigms as the framework to explain the success of collaborative production (see Figure 1). It adopts the structure conduct performance for analysis of industrial organization, which has been dominant in America over the past century, and blends in critical observations from institutional economics.

Structure Conduct Performance

The SCP paradigm identifies a long list of factors that affect the economic organization of production. The critical factors that play a role in the argument presented below are prominent in the framework. Paraphrasing one of the leading texts in the field, I identify the following characteristics, replacing the word "market" with "economic" where necessary [17:4-6]

The performance of economic systems is the focal point of analysis. "Performance is multidimensional and complex." An economic system should be efficient in the use of scarce resources, progressive in exploiting the opportunities opened up by science and technology to increase output, responsive to consumer needs and equitable in the distribution of income.

Performance depends on the conduct of participants in the economic organization "in such matters as pricing policies and practices, overt and tacit interfirm cooperation… research and development commitments, investment in production facilities, legal tactics (such as enforcing patent rights), and so on."

Conduct depends upon structure – the number and size of economic units, the extent of vertical integration, barriers to entry, the degree of differentiation of products, and the cost function.

Economic structures are affected by basic conditions. On the supply-side these include technology, ownership of raw materials, and durability of the product. On the demand-side these include the rate of growth and elasticities of demand and substitution as well as purchasing and marketing characteristics. Additional, critical factors are the framework of law within which economic entities operate and the socioeconomic values of the community "such as whether sympathies run toward aggressive individualism or cooperation."

The paradigm should be agnostic with respect to the choice of economic structures. The structure that produces the best performance should be preferred. There is, however, a presumption in general practice. The case for competition comes first and is the baseline from which the analysis launches.

A competitive industry has three general properties with important normative implications:

> The cost of producing the last unit… is equal to the price paid by consumers for that unit. This is a necessary condition for profit maximization, given the competitive firm's perception that price is unaffected by output decisions. It implies efficiency of resource allocation…

> With price equal to average total cost… [I]nvestors receive a return just sufficient to induce them to maintain their investment at the level required to produce the industry's output….
>
> [E]ach firm is producing its output at the minimum point on its average total cost curve. Firms that fail to operate at the lowest unit cost will incur losses and be driven from the industry. Thus, resources are employed at maximum production efficiency under competition.
>
> One further benefit… Because of the pressure of prices on costs, entrepreneurs may have especially strong incentives to seek and adopt cost-savings technological innovation [17:20]

Market Failures

No sooner is the case for competitive markets made, however, than qualifications are offered. Aspirationally,

> good economic performance should flow automatically from proper market structure and the conduct to which it gives rise. But for a variety of reasons, markets may fail, yielding performance that falls below norms considered acceptable. The government agencies may choose to intervene to attempt to improve performance by applying policy measures that affect either market structure or conduct [17:7].

Several market failures have been identified. The fundamental assumptions about consumer sovereignty and the single-minded maximization of profits by individuals or corporations come into question. The failure of competition to obtain, where firms can exercise market power, is a frequent focal point of analysis and public policy.

Two sources of market failure that receive a great deal of attention are central to the analysis in this paper – the production of public goods and the creation of externalities. They are particularly interesting situations because they occur not where competition is absent, but where competition exists, but fails to perform well.

> We consider two kinds of markets that are not likely to allocate resources efficiently, even though they might otherwise be competitive: markets with externalities and markets with public goods… [a]n externality arises when the action of any consumer or producer affects the costs or benefits for other consumers or producers in some way not transmitted by market prices.
>
> A public good is a good that benefits all consumers, even though individuals may not pay for the costs of production….
>
> Why worry about externalities and public goods? The short answer is that, in a competitive market, the *invisible hand* may not guide the market to an economically efficient amount of production when there are externalities or public goods [18:727].

While market failure frequently elicits public policy responses, it may also create the opportunity for alternative forms of economic organization.

Institutional Economics

The institutional economics critique of the neoclassical paradigm argues that the assumptions underlying the profit maximization-rational action model are unrealistic and the factors included too narrow to properly explain economic performance. The critical uncertainties of the neoclassical paradigm are the focal points of the search for other systematic factors that affect performance.

> It was Ronald Coase (1937 [20] and 1960 [21]) who made the crucial connection between institutions, transaction costs and neo-classical theory, a connection which has yet to be completely understood by the economics profession. Let me state it baldly: the neo-classical result of efficient markets is only obtained when it is costless to transact. When it is costly to transact, institutions matter [23:4].

Institutional economics focuses on cooperation and transaction costs as a challenge to economic systems. These are deemed to be of equal, if not greater importance than the transformation costs of production processes.[4]

> There is a different, and I think, better story. It concerns the endless struggle of human beings to solve the problems of cooperation so that they may reap the advantages not only of technology, but also of all the other facets of human endeavor that constitute civilization…[19:133]
>
> Institutions provide the basic structure by which human beings throughout history have created order and attempted to reduce uncertainty in exchange. Together with the technology employed, they determine the transaction and transformation costs and hence the profitability and feasibility of engaging in economic activity…
>
> In examining stability and change in history, the initial issue is… What combination of institutions permits capturing the gains from trade inherent in the standard neoclassical (zero transaction cost) model at any moment of time? [19:118]

The two unique market failures identified above are, in many ways, the central problematics of institutional economic analysis. Public goods and externalities are, respectively, gains from cooperation and trade that competitive market structures may fail to capture.

Transaction costs constitute a substantial part of the total cost of production, equaling the transformation and transportation costs that are typically modeled in the production function. [24:48-54]. Transactions have two aspects – a physical exchange "when a good or services is transferred across a technologically separable interface [24:40]" and a legal exchange, which is the "alienation and acquisition between individuals of the rights of future ownership of physical things [24:40-41].[5]

Information asymmetries between individuals on the opposite sides of a transaction and the costs of monitoring behavior and enforcing obligation are central causes of the institutional constraints. Search and bargaining costs become a primary concern. Diverse motivational bases for action beyond profits maximization can also play an important role in institutions including altruism, honesty, integrity, commitment, fairness, and justice.

Political action to create the institutional context that favors certain interests and activities is not an afterthought in the institutional perspective, but a central part of the analysis. Institutional economics accepts the question of property rights as a central political issue, not a foregone conclusion. This discussion is carried out under the rubric of governance structures [24:5], which focus on property rights. These are the product of the political system. "[T]he property-rights configuration existing in an economy is determined and guaranteed by a governance structure or order. The latter can be understood as a system of rules plus the instruments that serve to enforce the rules [24:5]." Properly approached, the analytic framework is agnostic with respect to governance structures.

Adaptive efficiency is the key institutional measure of performance. Efficiency is the result of the manner in which economic organizations mediate between the institutional context and the environment over time. Adaptive efficiency is relative and tolerant. Some institutions are better, some are worse, but all are far from perfect. Less efficient institutions can persist for long periods of time. They persist because they meet minimum needs for survival and apply force to preserve themselves against threats.

Persistence is not necessarily prosperity, however. Better institutions will produce greater wealth and resources. Viewing adaptive efficiency as a long-term trait, North identifies critical qualitative characteristics[6] at the heart of the concept

> Adaptive efficiency, on the other hand, is concerned with the kinds of rules that shape the way an economy evolves through time. It is also concerned with the willingness of a society to acquire knowledge and learning, to induce innovation, to undertake risk and creative activity of all sorts, as well as to resolve problems and bottlenecks of the society through time [19:80].

DEFINING COLLABORATIVE PRODUCTION

Traditional Categories of Goods

In the neoclassical paradigm, scarcity is about rivalry and property is about exclusion (see Figure 2). A private good is **rival** since "consumption by one person reduces the quantity that can be consumed by another person [18:G-7]" and **exclusive** since "consumers may be denied access [18:G-3]."

The central argument on private goods, as suggested by the Reed quote in the subhead of this paper, is that where resources are rival or subtractable, efficiency requires they be devoted to their highest valued use. Exclusion gives the owner of the resource the incentive to husband the resource, especially where investment is necessary to replenish it. The classic "tragedy of the commons" to which the quote refers is the case where the failure to grant rights of exclusion leads to underinvestment in the resource and overuse.

When the rivalry and excludability conditions are absent, the provision of goods in markets become problematic. These characteristics lead to difficulties in production by private firms. **Nonrivalry** occurs where increased consumption of the good by one person does not decrease the amount available for consumption by others. **Nonexcludability** occurs where consumers cannot be excluded from consuming a good. This gives rise to a familiar typology of goods.

The most frequently studied type of non-private goods is that of a **public good**. A public good exhibits *nonrivalry in consumption* and *nonexcludability.* In the world of private goods where individuals cannot be excluded, individuals may withhold support for the provision of public goods, seeking a free ride. This prevents these public goods from being provided, even though they are good for the public.

But other problems and issues have also been identified. Robert Frost's complaint about excessive exclusion as a social problem is transformed into an economic problem by Benkler's observation. If there are no cows, we do not need fences to keep them out, but those fences may prevent other, socially desirable transactions from taking place.

Transactions may not take place for a variety of reasons including excessive transaction costs and the inclination to try to "hold-up" transactions, seeking a larger share of the rents [24:131, 139]. The "tragedy of the anti-commons" in the excessive fragmentation of property rights, which prevent transactions form taking place, has also been recognized [26].

Common pool resources and their associated governance rules have increasingly received attention [25]. If private rights prevent socially desirable transactions from taking place, then shared rights may allow them to occur. This has come to be known as the comedy of the commons [27].

Although all goods can be said to fall on a continuum, rather than be ideal types, in the traditional view spectrum appears to have the characteristics that approximate a common pool resource [CPR].

> Common-pool resources share with what economists call "public goods," the difficulty of developing physical or institutional means of excluding beneficiaries [creating] the strong temptation to free ride on the efforts of others will lead to

> suboptimal investment in improving the resources, monitoring use, and sanctioning rule-breaking behavior. Second, the products or resources from a common-pool resources share with what economists call "private goods" the attributes that one person's consumption subtracts from the quantity available to others. Thus common-pool resources are subject to the problems of congestion, overuse, pollution, and potential destruction unless harvesting or use limits are devised and enforced [25:54].

The solution to the problem of subtractability of common-pool resources is not necessarily private property.

> Private property is not the only social institution that can encourage efficient use of resources. If exclusion costs are comparatively high, common ownership solutions may be preferable. If the latter alternative is chosen, rules would, of course, have to be formulated… Further, there would have to be an institutional structure that could enforce the rules established. Conceivably, this approach may represent the best hope for finding a low-cost solution to the problem of ensuring efficient use of a common resource. In general terms, the most efficacious institutional solution for the CPR problem may be anything between perfect centralization… and perfect realization of the principles of private property and freedom of contract [24:101-102]

The possibility of co-existence of different governance regimes is particularly important for common-pool resources.

> Many CPR institutions are mixtures of "private-like" and "public-like" institutions…
>
> Ostrom, in reporting on the institutional-economic analysis of a number of long-enduring, self-organized, self-governed CPRs, finds that private property and communal property can exist side by side [24:102]

The next section argues that collaborative goods in general and spectrum in particular are quite different from common-pool resources, requiring us to extend the two economic dimensions used to define types of goods.

Collaborative Goods

The burgeoning of user-generated content on the web, the growth of peer-to-peer production, and the success of open source software suggest activities at the opposite extreme from the anti-commons problem.

I have already asked what good fences are if the cows do not subtract from the resources, but the challenge of collaborative goods extends this question. What good are fences if, instead of subtracting, the cows add to the resources when they are allowed to roam freely?

In analyzing open source, Weber argues as follows:

> The solution to this puzzle lies in pushing the concept of nonrivalness one step further… to positive network externalities. Call it a network good, or an antiviral good… The system as a whole positively benefits from free riders who will provide something of value to joint production… the more "free riders" in this setting, the better.
>
> This argument holds only if there are a sufficient number of individuals who do not free ride – in other words a core group that contributes substantially to the creation of the good. [28: 154].

This suggests an extension of the two traditional dimensions. **Antirivalry** is a situation in which increased use/production of the good by one person increases the amount/value of the good available to others. **Inclusiveness** is a situation in which the value or amount of a good available for use/production increases as the number of people using/producing the good increases. The latter characteristic is akin to a **network externality. Network externalities,** also known as demand side economies of scale, are situations in which the costs of producing or the benefits of consuming a good spill over onto those who are producing or consuming the good, beyond the transaction.

A great deal has been written about the motivations that secure the critical condition for collaborative production – how does one ensure a "core group that contributes substantially to the creation of the good?" von Hippel provides interesting insights in his study of user-driven innovation and their free revealing behaviors. He calls this a **private/collective** good. This is a good for which individuals volunteer to support the supply of the good to the community of producers because they can

> *inherently* obtain greater private benefits than free riders. These provide incentives for participation in collective action projects that need not be managed by project personnel. In summation: Innovations developed at private cost are often revealed freely, and this behavior makes economic sense for participants under commonly encountered conditions… When the conditions are met, society appears to have the best of both worlds – new knowledge is created by private funding and then freely revealed to all [29:91].

Network externalities have been known for quite some time and von Hippel shows that free revealing has existed as well. They have influenced economic behavior to some extent. However, when these traits become embedded in a new techno-economic environment and become pervasive, they have a revolutionary effect.

A **collaborative good** exhibits *antirivalry* and *inclusiveness.* These increase value to the group through positive externalities and motivate individuals, who capture non-rivalrous benefits, to voluntarily participate. In the world of collaborative goods, the challenge is to understand the willingness of producers to support or freely reveal innovations that enhance shared benefits, even though they do not appear to capture as much private value as they could by withholding.

The key is to recognize the large positive externalities associated with collaborative production. Free revealers recognize that the potential gains of opportunistic behavior will evaporate if the cooperative behavior breaks down. Cooperation becomes the rule, rather than the exception.

Conditions for Collective Action

> Weber's discussion engages the issue of collective action directly.
>
> This dynamic yields a twist on conventional collective action arguments, where large groups are less likely to generate collective goods. The conventional view coming down from Mancur Olsen is that the larger the group, the smaller the fraction of total group benefits any person acting in the group can expect to receive, so that person gains more on the margin by allocating her effort toward a selfish pursuit. Second, the larger the group, the less likely there will be oligopolistic interaction that might help obtain the good – because any particular small group that wants to cooperate will again get a small fraction of the benefits. And finally, the larger the group is, the greater the costs of organizing it in a way that can compensate for either of these problems.
>
> The twist is this: under conditions of antirivalness, as the size of the Internet-connected groups increases, and there is a heterogeneous distribution of motivations with people who have a high level of interest and some resources to invest, then the large group is *more* likely, all things being equal, to provide the good than is a small group [28:155].

Weber's twist on the collective action problem is geared to collaborative production of open source. It may be invoking too many conditions. Because open source is oriented around a common task, Weber needs heterogeneous, motivated individuals with resources. He offers a comprehensive framework to explain why the conditions will be met and von Hippel's discussion of user-driven innovation supports Weber's model.

The existence of heterogeneous resources available in the network definitely improves the efficiency of collaborative responses, but this may not be a necessary condition. The critical condition is the ease of communications.

> The Internet was the key facilitating innovation. It wiped away networking incompatibilities and the significance of geography, at least for sharing code. As a result, the Internet made it possible to scale the numbers of participants in a project… As the numbers scale and the network grows, the likelihood of proliferating weak ties – that is, pulling into the process people with very different sets of expertise and knowledge – goes up as well…
>
> To simply share code over the Internet became a seamless process. As bandwidth increased over time, the Internet also enabled easy access to shared technical tools, such as bug databases and code versioning systems, that further reduced the barriers to entry for user programmers….
>
> What practice does reveal is that open source developers make enormous use of Internet-enabled communications to coordinate their behavior [28:83-84]

Viewed more broadly, ease of communications is seen as the critical change in the collective action context.

> Evolving communications technologies affect several factors that used to distinguish effective collectives from ineffective ones. Technologies that reduce the cost of sending information long distances (or to many people) can reduce organizational costs, increase noticeability, and make ineffective communicative networks effective. If group members' interests are sufficiently common, or if they interact in contexts that induce them to share information, these technologies can also make selective incentives a more viable recruitment strategy. Evolving technologies, as a result change which groups can and cannot act collectively; doing so in a way that undermines many widely held beliefs about the logic of collective action. In particular, evolving technologies can erase the disadvantages of being large – which should change the rule of thumb that many people use to distinguish latent groups from other kinds [11:329].

TECHNOLOGICAL AND INSTITUTIONAL UNDERPINNING OF COLLABORATIVE PRODUCTION IN THE DIGITAL AGE

From the point of view of industrial organization, the need to create a new category of goods reflects a very fundamental shift in the means of production. From the point of view of institutional economics, the importance of new institutional relations must reflect a fundamental shift in transaction costs as well as in the flow of technology and knowledge. The underpinning of the argument in this paper that collaborative economics in the spectrum commons is a superior form of industrial organization rests on the intersection of changes in the technologies of transformation, transaction, and knowledge.

Computers and Communications

Historically, dramatic changes in communications and transportation technology have affected society deeply, but the convergence of a highly interrelated set of activities in the communications, computer, and information industries in the late twentieth century created not merely a new environment in which information is produced and distributed, but also a revolutionary change in a wide range of economic activities.[7] The digital communications platform "links the logic of numbers to the expressive power and authority of words and images. Internet technology offers new forms for social and economic enterprise, new versatility for business relationships and partnerships, and new scope and efficiency for markets [36:1]." Those societies that adapted quickest prospered, as institutional economics predicts [37][38].

The Internet unleashed competitive processes and innovation exhibiting the fundamental characteristics of audacious or atomistic competition. Decentralized experimentation by users who had command over increasing computing power created the conditions for a dramatic increase in innovation.

Because computing intelligence can be distributed widely, and the activities of the end-points communicated so quickly, interactivity is transformed. "As rapid advances in computation lower the physical capital cost of information production, and as the cost of communications decline, human capital becomes the salient economic good involved in information production [39:2]." Users become producers as their feedback rapidly influences the evolution of information products.

> It is a proven lesson from the history of technology that users are key producers of the technology, by adapting it to their uses and values, and ultimately transforming the technology itself . . . But there is something special in the case of the Internet. New uses of the technology, as well as the actual modifications introduced in the technology, are communicated back to the whole world, in real time. Thus, the time span between the process of learning by using and producing by using is extraordinarily shortened, with the result that we engage in a process of learning by producing, in a virtuous feedback between the diffusion of technology and its enhancement [40:28].

This makes it possible for a wholly new form of information production – based on peer-to-peer relationships – to exist on a sustainable basis [39:22-23]. By drawing on a broad and diverse supply of physical and human capital, a loose, collaborative approach can provide a potent mechanism for production.

The institutional forms that will expand more in this environment are those that economize on the most valuable factor of production – human capital – by facilitating communications to reduce cost or maximize output [41:25].

Thus, the revolution in communications and computing technology combined with the institutional innovation of the Internet to create not only a potentially profound change in the environment in which information is produced and distributed, but it opened the door to greater competition among a much wider set of producers and a more diverse set of institutions.

> Taken together these critical features of the Internet are understood by economists by generalizing the concept of the Internet's bearer service through the idea that the Internet acts as a general-purpose technology or platform technology. The reduced transaction costs and positive network externalities often found on the Internet enable new products to be brought to market more easily and quickly than in the past [41:45].

The National Research Council depicted the Internet with an hourglass shape. A vast array of applications and users in the top half of the hourglass is interconnected through an open communications protocol to an array of networks in the bottom half [42]. The picture underscores the importance of the Internet as a bearer service with an open data network (ODN) and protocols at the waist of the hourglass. These are the link between diverse networks and a broad range of applications. The principles of openness the National Research Council identified bear repeating:

> *Open to users.* It does not force users into closed groups or deny access to any sectors of society, but permits universal connectivity, as does the telephone network.
>
> *Open to providers.* It provides an open and accessible environment for competing commercial and intellectual interests. It does not preclude competitive access for information providers.
>
> *Open to network providers.* It makes it possible for any network provider to meet the necessary requirements to attach and become a part of the aggregate of interconnected networks.
>
> *Open to change.* It permits the introduction of new applications and services over time. It is not limited to only one application, such as TV distribution. It also permits new transmission, switching, and control technologies to become available in the future [42:44]

Technology and Knowledge

There is an even more profound change that the technological revolution has wrought, as Joel Mokyr argues:

> There have been few comparable macroinventions since the emergence of electricity in the late nineteenth century…What has happened is the emergence of a large cluster of separate innovations with an unusual propensity to recombine with one another

> and to create synergistic innovations which vastly exceeded the capabilities of the individual component… The significance of ICT, then, is not just in its direct impact on productivity but that it is a *knowledge technology* and thus affects every other technique in use [43:42].

Recent analyses of technological innovation provide strong evidence that the digital communications platform transformed the very fabric of the innovation process – a process Arora, Fosfuri and Gamardella call "the changing technology of technical change [44:112]." The technological revolution altered the information environment to make distributed solutions more feasible, fostering the uniquely user-focused character of the communications-intensive Internet solution. von Hippel argues that "the primary irreversible factor that we speculate is making user-based design an increasingly attractive option is technological advance [45:642]." Technical change transfers the locus of control – "the recent evolution of technology and knowledge bases… has created greater opportunities for task portioning [44:112]," which allows greater local autonomy in decision-making: "Specifically, the main force behind the changing technology of technical change is the complementarity between increased computational power and greater scientific and technological understanding of problems [44:113]."

The ability to embody knowledge in tools and software lowers the cost of transfer dramatically.[8] This also has the effect of promoting a much more fine-grained division of labor.[9] The "changing technology of technical change" allows technological innovation to move outside traditional economic organizations (firms and corporations) and changes the form of organization as well:

> [M]odularity in product design brings about modular organizations… the standard interfaces of a modular design provide a sort of "embedded coordination" among independent firms and innovators, which can coordinate their activities independently of a superior managerial authority. … [M]odular systems that are also open (i.e., where the interfaces are not proprietary standards) make market leaders more vulnerable to competition. While modularity can accelerate overall product innovation, because of the contribution of several specialists, the presence of many specialists can also lead to tougher competition and greater entry [44:104-105].

Platforms

The fact that the technologies at the core of this revolution are platforms within networks reinforces the dynamic of change. "A platform is a common arrangement of components and activities, usually unified by a set of technical standards and procedural norms around which users organize their activities. Platforms have a known interface with respect to particular technologies and are usually 'open' in some sense [47:155]." They are important platforms because there are strong complementarities between the layers and each layer sustains broad economic activity in the layer above it [46:9-15].

The power of the digital communications platform stems in part from the fact that information production is inherently nonrivalrous, is subject to network effects and exhibits positive externalities [46:13-17]. The production and distribution of information becomes more valuable as more people gain access to it. Information is a major input to its own output, which creates a feedback effect [48] [49].

Putting information into the world enables subsequent production at lower cost by its original producers or others.

Communications and computer industries have always exhibited network effects and strong economies of scale [46:22-23]. As the installed base of deployed hardware and software grows, learning and training in the dominant technology is more valuable since it can be applied by more users and to more uses. As more consumers use a particular technology, each individual consumer can derive greater benefit from it. In addition to the direct network effects, larger numbers of users seeking specialized applications create a larger library of applications that become available to other users, and secondary markets may be created. Digitization reinforces these economic characteristics because economies of scope reinforce economies of scale.

These are all the positive benefits of network externalities. Where network effects and feedbacks are direct and strong, they create powerful positive feedback loops [50]. The layering of platforms in networks magnifies these effects.

Networks

The architecture of the network in which these technologies have become embedded is at least as important as the technological characteristics. The technologies themselves would not be as powerful nor would the effect on the rest of society be as great if the platform had not evolved as an ultrarobust network.

Networks are built from nodes (or endpoints) connected through communications links. Interconnectivity is a critical feature of networks because "most systems displaying a high degree of tolerance against failures share a common feature: their functionality is guaranteed by a highly interconnected network [51:110]." It "seems that nature strives to achieve robustness through *interconnectivity* [51:110]." Robust networks are typified by the formation of hubs: "the few highly connected nodes that keep these networks together [51:113]." The links between hubs are especially important as bridges that hold the network together.

In robust networks, hubs and links form modules. Modules share strong internal ties and specialize in discrete functions, but have weak ties to the rest of the network through links between hubs. Modularity implies a division of labor. That is, specialization allows modules to provide functions efficiently in the network. The modules in a robust network are hierarchically organized. Successful nodes grow more rapidly through preferential attachment.[10]

Networks grow and establish structures according to rules that foster efficient structures. Hubs form because of preferential attachment, but links are not added randomly because "building and maintaining new ties…leaves individuals less time for production; hence both congestion and ties are costly [52:277]." Networks can be designed in various ways depending on the pattern of the links. The links can be connected in various ways including centralized, decentralized and distributed.

Networks gain robustness by creating links that reduce effort. Watts calls them shortcuts; "[a]n obvious approach is to bypass the overtaxed node by creating a shortcut, thus rechanneling the congestion through an additional network tie [52:277]." The dictionary definition of a shortcut captures the essence of the process: "a method of doing or achieving something more directly and easily than by ordinary procedure… to make the work more simple and easy [53:2102]."

But, which links are most important to forge? The answer that emerges is familiar to anyone who has studied the Internet: distributing communications increases efficiency. The expenditure of time and effort (energy) are critical factors in efficient structures [52:277-279]. Buchanan notes that this is a pervasive principle: "Whatever the setting, computation requires information to be moved about between different places. And since the number of degrees of separation reflects the typical time needed to shuttle information from place to place, the small-world architecture makes for computational power and speed [54:58]."

We might call this the principle of distributed efficiency. There is a tension between preferential affiliation, in which hubs gain links, and distributed efficiency, in which important shortcuts bypass hubs that have become congested or overburdened and allow nodes to communicate. Nevertheless, the value of distributed efficiency can be easily identified. Important shortcuts (bridges) meet the criteria of reducing traffic between neighboring hubs that are already in communication through a third hub. By adding bridges to the decentralized network, it gains the characteristics of a distributed network.

Watts describes a special characteristic of robust networks that result from balancing these architectural principles as <u>multiscale connectivity,</u> and the network architecture that exhibits superior performance as an ultrarobust network. He describes the importance of multiscale connectivity in terms of avoiding or recovering from failure and also in facilitating success:

The hierarchical, modular network that exhibits both decentralized and distributed communications traits allows experimentation at the periphery, without threatening the functionality of the network. Failure is not catastrophic; since it can be isolated and its impact minimized. Success can be pursued independently and exploited because of efficient communications.[11]

Watts goes on to identify searchability as a critical and "generic property of social networks [52:279:280]." Searchability is facilitated by paying attention to one's neighbors (chosen by preferential attachment).[12]

> The equilibrium state of this process is a multiscale network for the simple reason that only when the network is connected across multiple scales is individual congestion – hence the pressure to create new connections – relieved… the process of ties at multiple scales also renders the network highly searchable, so that the multiscale state becomes effectively reinforcing [52:288].

The Heightened Challenge of Transaction Costs

In the digital, networked platform, interfaces become extremely important. Digital technologies can execute physical transactions at increasingly rapid rates. Negotiating the legal transactions becomes a very large problem. Arora, Fosfuri and Gamardella identify two situations in which the exploitation of available technologies and innovative opportunities can be problematic because private actions are not likely to achieve the optimal outcome. These are essentially collective action challenges.

> The key here is that the knowledge has multiple potential applications, so that users do not compete. When knowledge is nonrival, protecting that knowledge through patents creates potential inefficiencies… A number of different potential users may have to get together to invest in creating knowledge. Such contracts are problematic because users will differ in the value they place upon the enterprises and, consequently, are likely to underreport their value [44:263].

Second are transaction costs problems "in cumulative or systemic technologies," because "a commercializable innovation may require many different pieces of knowledge some of which may be patented and owned by people with conflicting interests [44:263]."

> In a Coasian world with no transaction costs, given any initial distribution of property rights over the fragments, agents will bargain to a Pareto optimal solution. More realistically, the required collection of the property rights, although socially efficient, might not occur because of transaction costs and hold-up problems. An agent holding a patent on an important fragment ("blocking patent") may use the patent in an attempt to extract as much of the value of the innovation as possible…
>
> In other words, when several pieces of intellectual property have to be combined, the transaction costs implied could be so high as to prevent otherwise productive combinations [44:263-264].

Tim-Berners-Lee provides a telling example with respect to the Internet. As the Internet moved out of the laboratory and into the commercial market, the specter of a closed interface arose. Tim Berners-Lee describes it as follows:

> It was about this time, spring 1993, that the University of Minnesota decided it would ask for a license fee from certain classes of users who wanted to use gopher. Since the gopher software was being picked up so widely, the university was going to charge an annual fee. The browser, and the act of browsing, would be free, and the server software would remain free to nonprofit and educational institutions. But any other users, notably companies, would have to pay to use gopher software.
>
> This was an act of treason in the academic community and the Internet community. Even if the university never charged anyone a dime, the fact that the school had announced it was reserving the right to charge people for use of the gopher protocols meant it had crossed the line. To use the technology was too risky.
>
> Industry dropped gopher like a hot potato. Developers knew they couldn't do anything that could possibly be said to be related to the gopher protocol without asking all their lawyers first about negotiating rights… It was considered dangerous as an engineer to have even read the specification or seen any of the code, because anything

> that person did in the future could possibly be said to have been in some way inspired by the private gopher technology [56:72-73].

Open architecture is a powerful but fragile design principle. The next section shows that open wireless networks are a good example of these digital, network platforms and that the performance of these networks in the spectrum commons benefits greatly from the technological and network changes of recent decades.

COLLABORATIVE COMMUNICATIONS NETWORKS IN THE SPECTRUM

The debate over situations in which a commons is a preferable approach to governance of the access, use and management of resources long antedates the digital revolution. It would certainly be possible to argue for a commons approach to spectrum without invoking the concept of collaborative production, but the case is much stronger if we start with that observation and claim. Moreover, the terminology used to describe the radio revolution cries out for such an approach. At the core of the analysis is the concept of software-defined radios, adaptive radios, smart radios or computationally intensive radios in open wireless networks or mesh networks.

Antirivalry and Inclusiveness: The Physics of Spectrum Meets Technology in a Digital Networked World

The technologies that have been at the heart of the digital revolution are at the heart of the deployment of open wireless networks in the spectrum commons. The potential carrying capacity of the spectrum has been the direct beneficiary of the convergence of progress in digital technology and the institutional development of networks.[13]

In the terms offered in this paper, the communications networks in the spectrum commons in the digital age exhibit elements of antirivalry and inclusiveness by adapting a multiscale, ultrarobust network structure. Adding nodes to the network – repeaters – increases its carrying capacity.[14] Smart nodes get their expanding brainpower from decentralized computational capacity to communicate seamlessly utilizing embedded coordination protocols. Their brainpower is driven by Moore's law. "There exist *networked* architectures whose *utility increases* with the density of independent terminals… Network architectures provide tremendous gain in communications efficiency on a system basis [57:2]."

Antirivalry: Smart technologies in mesh networks push spectrum toward the characteristic of antirivalry. The ability of each node to receive and transmit messages, even when they are neither the origin nor the destination expands the capacity of the network.

Inclusiveness: As a communications network, the spectrum commons exhibits the strong positive externality associated with inclusiveness. The more people on the network the greater the value to users. The denser the nodes in the commons, the greater its communications capacity.

Distributed Intelligence: The availability of intelligence and throughout the network is the key to its immense capacity.

Decentralization: Investment necessary for using the commons to build communication networks is decentralized. Virtually all of the investment inheres in the individual devices. This cuts down or eliminates the free rider problem. With low investment and transaction costs, the recruitment of contributors is facilitated. With mass-market devices as the central investment, this creates an interested community of appliance developers who can profit from the preservation and expansion of the commons.

Reed describes two characteristics of the adaptive network architectures in the spectrum that parallel the concepts of antirivalry and inclusiveness. The characteristic Reed calls cooperation gain is the focal point of his analysis. This is the antirivalry principle identified earlier.

> What is clear for analyzing networked architecture is that as the demand for capacity increases, and as the density of terminals increases, adaptive network architectures that involve cooperation among all of the communicating entities create radio systems whose capacity can scale as demand increases.
>
> Compared to systems of dedicated, isolated links, networks provide much more transport capacity at much greater transport efficiency. This phenomenon, which I have begun to call *cooperation gain,* creates major economic benefits. [57:10]

The second characteristic Reed calls network optionality. It is a form of the inclusiveness principle identified earlier.

> The system-wide option value of flexibility in a network scales proportionally to the square of the number of nodes, according to the law popularly known as Metcalfe's Law. Similarly, the option value that accrues due to the ability to dynamically assign capacity depending on shifting demand can increase superlinearly as the number of cooperating nodes in a network. I call these network externalities *network optionality* [57:10].

The network efficiency principle identified earlier has a specific physical expression in open wireless networks. "If nodes repeat each other's traffic then transmitted power can be lower, and many stations can be carrying traffic [2:12]." The efficiency principle is the same because "there is a tradeoff between optimality and responsiveness to demand that involves deciding how much communications capacity should be allocated to the overhead of capacity management [57:8]."

The combination of digital technology and network organization has turned the old logic of interference on its head. Adding users improves performance.

> Technologies like smart antennas, spread spectrum modulation, and cognitive (software) radios make it feasible for transceivers to dynamically change their frequency, modulation, or power levels to enable more efficient and intelligent spectrum sharing. The traditional logic that exclusive frequency licenses are needed to manage "interference," has been significantly undermined by technical progress and the evolution of wireless markets. For example, advances in signal processing technology (e.g. multi-user detection theory) and cooperative networking (e.g. ad hoc networking or grid computing) can exploit the fact that there are multiple signal sources sharing the same frequency bands to improve reception gain. [62:8]

Reed identifies a series of findings about the functioning of cooperative radio networks that he labels as "counterintuitive." Having outlined the technology and network revolutions and examined network principles and collaborative production, they are not counterintuitive at all, but the consistent performance characteristics of a set of coherent economic organizations and social institutions – "Mutlipath increases capacity; Repeating increases capacity and reduces energy, Mobility increases capacity, Distributed computation increases battery life. Channel sharing decreases latency and jitter [58]."

An Economic Model of Collaborative models

I have stressed in the analytic framework that technology is only one of the conditions that determines performance. The physics of spectrum and the principles of networks create the opportunity, but economic organizations and social institutions must answer critical institutional challenges.

Since cooperation is the key to the capacity gain, the challenge becomes the classic hurdle of institutional organization. The core transition is to "embed coordination" in technology. The technology of technical change provides the solution.

> Digital signal processing is the use of extremely inexpensive and rapidly improving digital technology to handle all aspects of processing signals, including tuning, modulation, coding, and compression, among other functions. Since digital technology enables complex and adaptive algorithms we are able to approach closer and closer to the theoretical limits involved in manipulating and perceiving aspects of the physical world – in the case of radio, directly manipulating and sensing the electromagnetic fields that can be manipulated to carry information [57:5].

The physics of spectrum which lays the foundation for economic organization and institution formation that exploits cooperative gain is reinforced by another important characteristic of the techno-economic environment. As noted above, the investment necessary to create the growth of capacity is decentralized, financed by users.[15] End-user purchase of devices that carry the embedded coordination replicates the Internet phenomenon where intelligence was distributed widely.

> What the Internet has taught us is that…carrying all kinds of traffic over whatever links are available, we can achieve a high degree of efficiency, both technically and economically. Interoperation between networks removes unnecessary transaction costs, enabling new applications to reach economically viable scale without the overhead of purpose-built networks for each application, and enabling existing applications to be improved in an upward compatible way while allowing legacy version to coexist [57:5].

As a consequence of the shift in the nature of the devices and the network, and the focal point of investment, competition and innovation is shifted.[16] The network and technology discussions argued that decentralizing decision-making and shifting problem solving to the local level has inherent benefits.[17]

Reed presents a graphical demonstration of the fundamental characteristics of collaborative production in the network commons. The analysis is essentially the difference between a centralized network and a decentralized network. This is the supply-side of the analysis (see Figure 3). In the traditional network, communications distances are much longer, therefore requiring more energy/resources. When devices do not help, the capacity of the network is set by the bandwidth available back to some central switch or server. Therefore, it is fixed at a given level. As more devices are added, the capacity per station declines.

In contrast, when devices help and act as repeaters, sharing and supporting communications between neighboring points, the total capacity of the system increases as devices are added. Depending on how well devices share, the per device capacity may decline, but at a slower rate than in the non-helping case.

Cooperative gain means that in a repeater network a given number of transmitters will have a higher carrying capacity (Figure 4). The total capacity will be higher and the average capacity per repeater will be greater. If we were to calculate a cost curve (not shown), we would find that the cost per unit of capacity is lower for both total capacity and on a per station basis in the repeater network.

Figure 5 presents the basic concepts of the demand side of Reed's network analysis. I call this the demand side since the size of the network – the number of the members of the network that can be reached – and the pattern of interactions dictates the value of the networks to the members. The value of the network inheres in the number of connections that can be made and the possibilities for communications (and therefore commerce) that they open up.

Reed identifies three types of networks.

In the one-way broadcast network – the Sarnoff push network – the value is equal to the number of receivers that a single transmitter can reach. Reed uses a wire service as an example. In the Metcalfe network the center acts as an intermediary, linking nodes. Reed uses classified advertising as an example.

In the Reed Community, collateral communications can take place. The nodes can communicate with one another. Reed uses a chat group as an example. The possible connections expand dramatically. Network optionality, when realized in group-formation, generates much greater value than traditional models.

Figure 6 shows how the value of being part of the network scales as the number of members increases. The Sarnoff value is N. The Metcalfe value is N^2. The Reed community value is 2^N.

Figure 7 combines the supply side and the demand side of the collaborative network analyses. The bold lines in the figure represent the collaborative model in the spectrum. The non-bold represent the traditional spectrum model. The dashed lines represent the supply-side of the model in the sense that they show the relationship between the number of users and the capacity of the system. The solid lines represent the demand-side of the model in the sense that they show the relationship between the number of users and the value of the network (and therefore the presumed willingness to pay to be part of it). The collaborative model produces a much higher level of capacity, use and value. These key elements of the collaborative model are defined in contrast to the basics of the traditional model.

Traditional v. Collaborative Economics

Recent discussions of that traditional model, by one of the first people to suggest that unlicensed spectrum might make sense [64], underscores how easy it is to misunderstand the collaborative model. Noam offers an explanation with respect to Figure 8 that describes a progression that starts with community-based activity, but does not end with it. The economic picture is the traditional neoclassical analysis with economies of scale of network operators on the supply side and Metcalfe's law on the benefit side, or the willingness to pay side. This is the "father's saying" we must get behind. The cost curves reflect high fixed costs and low marginal costs. The competitive case is defined as a Metcalfe network, similar to Reed. [72:3]

For Noam the economic problem is that one must reach critical mass in order to get costs low enough to justify investment. "This activity will not take place, unless there is someone to support and subsidize the activity until it reaches the size of a critical mass and becomes self sustaining. How then does one get to the take off point?" [72:4]

Noam identifies traditional examples of government subsidies, regulated cross-subsidies and penetration pricing of complements to expand demand. He sees community-based activity as a fourth way to prime the pump. "The fourth alternative, and the one most overlooked, is te community approach. This means that the early users form a community with the aim of increasing benefits and externalities, and reduces costs." [72: 6]

What Noam is describing are shifts in the demand curve (see Figure 9). "In some cases, the community take-off will not lead to size that will reach a commercially viable point. They will remain community-based rather than commercial… But in other cases, the externalities and cost structure are such that the community take-off leads to a community size that reaches the commercial take-off point. At that point, business firms will enter." [72:7] Figure 9presents the more familiar supply-demand equilibria. Note also that in Figure 9, oligopoly pricing takes place not where the supply and demand curve intersect, but where the supply and marginal revenue curve intersect, since "the solution, evident in most media industries, is to a market structure that maintains prices above marginal costs." [72:9]

Thus, Noam hypothesizes a progression from community-based systems that are driven by an "intense spirit of community, volunteerism and piracy [65:4)." But he assumes that the economics of the traditional model will overtake the community-based mode.

> when the commercial entry takes place, it pushes aside the community that made it possible. The community-based system is transitional, not permanent. Within the commercial alternatives, the center of gravity moves from
>
> — P_4, (the take-off point of complementarity),
>
> — to P_1 (the take-off point of competition),
>
> — to P_2 (the take-off point in an oligopoly) [65:5].

Noam argues that "when commercial entry takes place, it quickly and unavoidably and unsentimentally pushes aside the community that made it all possible in the first place" because

> the big firms are able to provide the investment to create organized innovation and user friendly and reliable products that appeal to users beyond the original savvy community. Their familiar brands reassure users who value their time. Their decision mechanism is speedier than that of a self-governing community of volunteers. And

> their persistence is much longer-lived than that of voluntarism whose flame burns brighter in the beginning than when gray daily routines set in. [72:6]

For Noam, community-based activity is a precursor, not a sustainable permanent institution at economic scale. If the community-based activity is successful in creating a large economic base, it will be supplanted. Noam's narrow role for community-based production as an enabling or catalyst bears little relationship to the collaborative production argument presented in this paper. The examples he uses, like CB radio, are simply a different phenomenon. Figure 10 makes this point by superimposing Reed's discussion of collaborative economics on Noam's traditional spectrum model. I have already noted that Reed has argued that the Metcalfe network is replaced by community formation. The benefits scale much more rapidly in a community. Moreover, the capacity of the system scales as well. Production expands dramatically because there is greater value and more capacity. The impact of these two characteristics has a dramatic effect on the economics. Benefits that can only be captured in the collaborative approach are substantial. Figure 10 assumes that output expands to the point where total capacity and value are equal because individuals are making the decentralized decisions, facing only the community-created cost curve.

Translating the capacity/value analysis into the supply and demand analysis pinpoints the difference (see Figure 11). There are two factors at work, as depicted. The costs are lower. But the shift to the collaborative demand curve is the key factor that results in a much higher level of output. This seems to be a better fit for the empirical phenomenon depicted in the quotations from the *Wired* article presented in the Introduction to this paper.

There remain uncertainties about the range over which these characteristics of open wireless networks in the spectrum commons will operate. Physical limits can be reached and congestion (rivalry and subtractability) could again become a more prominent feature of the environment. Given where we are at present, however, that should not be the focal point of concern.

> In wireless, it is likely that the declining price of computation and the growing market in wireless communications devices will, for any useful time horizon (say 20 years), make it cheaper to increase supply by improving end user devices than to introduce a pricing system to allocate slower growing capacity [7:40].

Exactly how rapidly the value curve rises and how strongly capacity grows are open to debate, but there is a very high probability that the collaborative result is superior to the traditional economic results. There is certainly enough evidence to support the proposition that open wireless networks should be given at least an equal opportunity to thrive in the spectrum commons. As they prove their superiority, they should be allowed to expand.

POLICY IMPLICATIONS FOR GOVERNANCE RULES

For millennia, the spectrum was locked in a rudimentary technological prison, used everyday by human beings to communicate with their natural physical transmitters, vocal cords and musical instruments and their natural receivers (ears). Once technology amplified the use of the spectrum, the determination of governance rules became a political decision of extreme importance.

For about a quarter of century, spectrum in the U.S. was unlicensed and Americans took to it with a passion. But, given the technology of the day, spectrum quickly became congested, or so the story goes. A deal was struck to control congestion by controlling broadcasting (communications and speech). The choice of governance rules based on exclusive dedicated licenses (i.e. license given to a single entity to provide a single service) blended economic logic (or illogic) and political power, as governance regimes inevitably do.

Whether the initial choice was correct or how long ago it outlived its usefulness are historical questions of little relevance to the current set of possibilities. Technology has now made it possible to solve the problem of congestion without exclusion based either on property or licensing.

The current approach to dedicated, licensed spectrum has been rightly criticized, capturing neither the efficiency of the market not the efficiency of a commons. The choice of governance rules can be seen as falling on a continuum of exclusion and access in which the fit between the benefits of private incentives and public goods and externalities maximizes social welfare and the adaptive efficiency of the economic and institutional system. Coase's [22] critique of licensed spectrum (which is the launching pad for the claims to propertize the spectrum [64]) was made almost half a century ago, before the digital revolution. Without abandoning the critique of the system of exclusive licenses, a careful consideration of the transformation of the technical, economic and institutional landscape argues for a different approach.

Transactions and Transaction costs in the spectrum commons

Even without the claim of cooperation gain, the governance rules should still be progressive in the sense introduced at the beginning of the market structure discussion. That is, the preferred regime should exploit the opportunities made possible by the advance of science and technology.

If spectrum in a digital environment did not have the clear characteristics of a collaborative good, it would still be a good candidate for treatment as a commons based on its other characteristics. At a minimum, it has the attributes of a common pool resource that is non-depletable, but congestible under certain circumstances.

As technology advances, more transmissions may be accommodated, since smart technologies allow them to be closer together in frequency, time and space, without interfering. The moment the spectrum is vacated by one transmitter, it can be re-occupied by other transmitters. This is independent of whether or not the transmitters act as repeaters, as in the earlier discussion of collaborative production.

The resource is not depleted when it is used. Put another way, the replenishment costs are zero [71]. In the context of a traditional analysis of such a common-pool resource the analysis focuses on the transaction costs and external benefits of different rules to govern access to and use of the resources. Since the resource is non-depletable, the only costs that are relevant in the allocations of access to the resource are congestion costs. Any set of governance rules that create an incentive for or possibility of restriction of capacity should be suspect. Those that promote increases in available capacity should be preferred.

Assuming that governance regimes are equal with respect to incentives to supply capacity, the analysis turns to traditional transaction cost issues. Here the nature of congestion influences the number, frequency, timing and duration of transactions. In the digital age, congestion is likely to be local, intermittent and short lived. The instant a transmission is completed, the spectrum becomes available for another transmission. It is only the desire of two or more parties to transmit at exactly the same frequency in exactly the same place at exactly the same time that results in congestion. By exactly, we mean close enough in frequency, time and space that the two transmissions would interfere with one another. Of course, that interference is a function of the transmitting and receiving technologies.

In evaluating the governance rules for these transactions, the distinction between the physical and legal transaction introduced earlier becomes important. Seamlessness is a matter of a technical protocol, essentially built into devices. If the carrying capacity is to be fully developed, the full set of physical transactions must take place in all cases, but what do the legal transactions costs – bargaining – add? The answer is little, given the nature of the resource. Dynamic reallocation in a property environment is difficult if not impossible with uses and users changing in milliseconds. The challenge of negotiating, clearing, billing and enforcing rights means that "the more dynamic the system, the costlier it is to do transactions [65:4]."

> The geographically local nature of wireless communications network capacity, the high variability in the pattern of human communications, and the experience of wired networks suggests, however, that if pricing will prove to be useful at all, it will be useful only occasionally, at peak utilization moment, and the cost benefit analysis of setting up a system to provide for pricing must consider the value of occasional efficiency gains versus the cost of the drag on communications capacity at all other times [7:7-8].

Because of the variable, local and short duration of congestion, the transaction costs associated with negotiating clearance rights to transmit are high. The challenge becomes even greater when transmitters and receivers are mobile. Solving the transaction problem at the physical level and avoiding haggling is an attractive solution.

> Coase's Theorem says that commons can be allocated Pareto-efficiently by market mechanisms if the externality can be internalized by assigning property rights. However, such assignment is efficient only if the cost or exclusion is lower than its benefits. In the case of spectrum, the cost of narrowing bandwidth and the difficulty of spectrum management is far more serious than the benefits of direct trading [70:10].

If exploitation of the opportunities made available by technology and science is a key measure of performance, then the opportunity to expand capacity through dynamic allocation of spectrum must be captured. Given the current technological environment, Benkler's observation that "property rights in bandwidth inefficiently fence a sub-optimal resource boundary" has basic validity.

The Macoecxonomics of the Sepctrum Commons

Demonstrating that allowing communications networks to develop in the spectrum commons has superior transaction cost characteristics is sufficient to establish a public policy basis for supporting policies to promote open (unlicensed) spectrum. However, the concept of performance introduced at the outset of the paper was broader than mere transactional efficiency. Several other desirable characteristics of the economic and institutional structure of society were identified. There are additional, macroeconomic reasons that promoting open wireless networks in the spectrum commons merits public policy support, at least in parts of the spectrum.

Future allocative and adaptive efficiency will depend upon a pervasive computing environment in which the end points are mobile. Open wireless networks in the spectrum commons are better able to support such activity.

Incentives and Infrastructure: In a repeater system with embedded coordination, decentralized investment and cooperation gain, Reed strongly doubts the value of selling rights to spectrum.

> [I]f my technical argument about how value is created in radio networks by user financed investment is correct, then by selling spectrum rights to private holders for all time at *any* price, the government is not encouraging capital investment in the economic development of a resource (the usual argument for privatization). Instead, it is selling out the future value of a resource best developed by individual citizen/ users to a group of arbitrageurs – whose best payoff is achieved by making no investment at all, while waiting until the public has to buy it back at a guaranteed substantial premium [57:19]

As I noted in the discussion of industrial organization, the incentive of property owners to increase their profits is not synonymous with the maximization of social welfare. Reed ties this to cooperation gain.

> The… bulk of the value created by adaptive networks and cooperation gain comes from the voluntary actions of users (deploying new devices, protocols, and systems.) That value already paid for by the users, devolves to those users directly in the form of useful applications of the communications system. There is little or no value that is retainable by "spectrum owners" when the capacity of the spectrum increases by adding more users who pay for their physical and software capital.
>
> The only way for a spectrum owner to create a return, when capacity grows as the user participation grows, would be to create an unnecessary scarcity of communications capacity; that is, artificially raising prices by blocking users from using their own investment in hardware and software capital freely [57:318-19].

Others see this as a more pervasive problem. The history of spectrum owner behavior suggests that there would be an inclination to exercise market power in a variety of ways.

> The key distinguishing feature of unlicensed spectrum is that there is *no* grant of such a right. In an exclusive regime it is possible for the licensee to exclude other users for reasons beyond those related to interference management…
>
> The Licensee has an incentive to maximize the value of its exclusive license, which includes potentially restricting future access to the spectrum, even when such access could be shared at zero cost. If there is either monopoly or monopsony power, prices may deviate from optimal levels… incumbents have an incentive to protect and exploit their market power. By restricting the availability of spectrum, they may be able to inflate prices to capture artificial scarcity rents. Even more perversely, they may selectively restrict spectrum access to new technologies that are expected to pose a competitive threat to their market power, thereby influencing not only end-user prices but the direction of technical change and slowing the progress of competition. [62:16, 22, 23]

Accommodating uncertainty: The commons approach with its decentralized user driven focus has clear advantages in flexibility. It is less dependent on small numbers of network owners guessing what will be demanded. It avoids large lumpy investment and should lower the cost of updating and versioning. Flexibility and uncertainty combine to enhance the ability of the structure to accommodate uncertainty.

Innovation: Decentralized end-user driven innovation is likely to accommodate far more experimentation and innovation. The experience of unlicensed spectrum in the age of digital, networked platforms exhibits the fundamental characteristics of user-driven innovation, aggressive atomistic competition because of its decentralized nature.

> In addition many end-users are using WiFi to extend the reach of their fixed broadband Internet access and providing opportunities for new types of consumer networked appliances. In many cases these home WLANs and sponsored hot spots are supporting open access to the general public through "freenets."
>
> Five years ago, WLANs and 3G services were viewed as addressing very different needs. Now it is clear that these services can be both complements *and* substitutes. Equipment makers and service providers are now busily trying to integrate 3G and WiFi services….
>
> While current development efforts are focusing on the use of UWB [ultrawideband] as a short-distance wireless-cable substitute (*e.g.*, to provide wireless connectivity for home entertainment systems, UWB also could be used to support wide-area broadband communications [62:9].

Democracy: Although this paper has focused on economic issues, there is no doubt that the decentralized open wireless network has desirable political characteristics [59] [60]. Because of the one-way broadcast nature of the electronic mass media in the twentieth century, First Amendment rights were defined as listeners' rights – the ability to hear diverse points of view. The licensing regime that excluded people from using the spectrum to project their voices far and wide limited their right to speak. Open wireless networks that allow each repeater to be a speaker expands speakers' rights and holds the promise of invigorating First Amendment rights. It returns them more closely to their original formulation.

Lessig [64] observes that

> The "press" in 1791 was not the *New York Times* or the *Wall Street Journal.* It did not comprise large organization or private interests, with millions of readers associated with each organization. Rather, the press then was mush like the Internet today. The cost of a printing press was low, the readership was slight, and anyone (within reason) could become a publisher – and in fact an extraordinary number did. When the Constitution speaks of the rights of the "press," the architecture it has in mind is the architecture of the Internet.

Specific Policies

Public policy will influence the extent of the space that collaborative production occupies and the extent to which the commons is created. To expand the space, public policy should change its direction in a number of areas that have been identified as the focal points of economic organization and institutional development.

Structure: The central constraint on the development of open communications networks is the limitation on the space in which these networks are allowed. At present the spectrum commons is ghettoized, restricted to areas of the spectrum that have undesirable propagation characteristics. Given the above analysis, this is unjustified. There will be substantial cost and quality limitations imposed on open wireless networks if they are restricted to higher frequencies, which impose substantial cost on society – raising the cost of communications [61] [62].

The playing field should be leveled between user-driven innovation and investment and network operator driven investment. Small end users and equipment vendors should have the same chance that large network operators have. This means that dedicated unlicensed spectrum should be set aside for open wireless networks at various frequency levels so that the these networks can develop to exploit the diverse propagation characteristics of the spectrum.

Coordination: The central institutional challenge, once spectrum is made available, as a commons is to develop rules of the road. Embedding coordination in devices requires standards and protocols. "Managing vendors of network components that will be formed into networks by users will be the role of any regulatory approach. Obviously it is important to make sure that those networked components work together efficiently, and that joint societal benefits be maximized [57:6]."

Recreating the hourglass shape of the Internet in the spectrum commons is the goal. There are a range of choices that should be evaluated with respect to promoting the open architecture that maximizes carrying capacity and allow innovation and competition in devices and applications. This means that open standards should govern the interface at the waist of the hourglass ensuring (for example) that all formats and multiple frequency networks are supported; routing is nondiscriminatory; and end-to-end connectivity is preserved.

It is critically important to recognize how vital rules the achieve cooperation are. An absence of property does not mean an absence of rules of governance. It means a different set of rules. It is also important, however, not to assume that such rules cannot be written, or that the must be written by government (and therefore will be captured by one set of interests at the expense of all others). In fact, the study of common pool resources, of which the spectrum is an interesting example, suggests otherwise.

> Policymakers responsible for the governance and management of small-scale, common-poll resources should *not* presume that the individuals involved are caught in an inexorable tragedy from which there is no escape. Individuals may be able to arrive at joint strategies to manage these resources more efficiently. To accomplish this task, they must have sufficient information to pose and solve the allocation problems they face. They must also have an arena where they can discuss joint strategies and perhaps implement monitoring and sanctioning. In other words, when individuals are given an opportunity to restructure their own situation they frequently, but not always, use this opportunity to make commitments that they sustain, thus achieving higher joint outcomes without recourse to an external enforcer. [71:193-1294]

Communications is the key to cooperation, which is precisely the parameter of collective action that the digital revolution has transformed.

Lower transactions costs: Eliminating or refusing to require a negotiation between spectrum owners and spectrum users will lower transaction costs. One of the most important steps would be to not auction the spectrum. Spectrum auctions are essentially taxes that are passed through to users of the spectrum [62:17-18]. However, there are other ways to reduce the number and complexity of transactions, such as making it easy to join the network; keeping the equipment certification process simple and open; ensuring portability of addresses, designing low maintenance networks that easily isolate faults; relying on best effort networks (to minimize QOS negotiation and disputes) [69].

Incentives: In a capitalist economy tax policy is one of the most powerful instruments for directing investment. Policies that promote centralized investment (e.g. investment tax credits for large corporate investments but not small individual investments) may be driving economic activity in the wrong direction. This playing field should be levelized too.

Transitions: Considerable attention has been devoted to the transition out of the current dedicated licensed regime. In particular, possibilities for co-existence should be considered. These include both allocating spectrum that is cleared of dedicated licensed uses between flexible licenses and unlicensed approaches. This also includes allowing non-interfering underlays where incumbents have previously had exclusive rights. It also should include regimes to expand dedicated unlicensed spectrum. This can be an evolving approach in which the exclusive license holders, who are "overly sensitive to interference," are required to accommodate progressively more sharing [65:3].

Another transition should be considered. A world of pervasive mobile computing might become congestible (i.e. where cooperation gain has been exhausted). Under these conditions, it is not clear that abandoning the spectrum commons in favor of privatized spectrum would be the correct answer. Some have argued that collective actions to expand the communications infrastructure would be preferable as a general proposition [63] and with respect to spectrum in particular [62]. In other words, clearing out dedicated use bandwidth hogs to make space for open wireless networks may be the better policy. The spectacle of the over-the-air broadcasters holding a huge swath of exclusive spectrum and simultaneously demanding that cable operators distribute all their digital signals (digital must carry) suggests that something is very wrong with the dedications of that much very attractive spectrum to that particular use.

CONCLUSION

The surprise of *Wired* magazine at the strength of collaborative production underscores the challenge to conventional thinking that the new economic paradigm constitutes. Many analyses that extrapolate from traditional paradigms, like CB radio, miss the point [66][67][68], just as an executive from ABC did, when he opined in 1989 that the Internet would be 'the CB radio of the 1990s [4:132]."

Perhaps the ultimate irony of *Wired* magazine's cover story is that now that it "gets" the essential dynamic of "collaborative action," the future is *wireless*, not *wired*. The Internet principle propagates well in open wireless networks in the spectrum commons because the physics of spectrum interacts in a powerful, positive feedback loop with the economics and institutional fundamentals of digital, networked platforms. Preserving and expanding the spectrum commons is critically important to ensuring the adaptive efficiency of the collaborative production that the Internet revolution has triggered because it provides and thrives on mobile, distributed computational capacity. Dedicated licensed spectrum is quickly becoming one of the walls that has outlived its usefulness and should come down.

ENDNOTES

[1] See [5] for an earlier, scholarly discussion of this transformation.
[2] On collective action, see [12]. On social relations see [13]. On the breakdown of bundles see [14].
[3] The clashes have become frequent and prominent. Among the more notable exchanges see [15][16]
[4] Both sides of the debate over spectrum governance claim Coase as a forefather, in part because of his critique of the Federal Communications Commission management of spectrum [22].
[5] Heller and Ostrom [25] refine the legal into three rights (alienation, exclusion and management) and the physical into two rights (access and extractions).
[6] The lack of precision in the definition compared to allocative efficiency has been criticized [24: 475-476].
[7] We can track the technological transformation across all dimensions of society [30] including the economy [31], the workforce [32][33], the polity [34] and civic institutions [35].
[8] "Advances in scientific understanding decrease the costs of articulating tacit and context-dependent knowledge and reduce the costs of technology transfer. Further, such knowledge can be embodied in tools, particularly software tools, which make the knowledge available to others cheaply and in a useful form [45:105]."
[9] "Advances in science and the tremendous increase in computational capabilities have greatly contributed to extending the division of innovative labor [45:105]."
[10] Hierarchical modularity has significant design advantages. It permits parts of the network to evolve separately… The impact of genetic mutations [experimentation or innovation], affecting at most a few genes at once, is limited to a few modules. If a mutation is an improvement, the organism with the superior module will flourish. If, however, tinkering with a gene decreases the module's fitness, the organism will fail to survive [51:236].
[11] Multiscale connectivity, therefore, serves not just one but two purposes that are essential to the performance of a firm in uncertain environments. By distributing the information congestion associated with problem solving across many scales of the organization, it minimizes the likelihood of failure [maximizes the chances for success]. And *simultaneously* it minimizes the effect of failures [maximizes the impact of successes] if and when they do occur…. Because they exhibit this two-for-the-price-of-one robustness property, we call multiscale networks ultrarobust [52:286].
[12] Searchability implies another characteristic of the network, feedback, as described in neural networks in [55:134].
[13] "There is a 'new frontier' being opened up by the interaction of digital communications technology, internetworking architectures, and distributed, inexpensive general purpose computing devices [57:2]
[14] Berger [65:7] refers to user/relay nodes.
[15] A key aspect of the new demand is that the systems can and will be largely "user-financed" unless regulation bars users from deploying new technology. The bulk of capital expenditure in networked systems, especially systems that need no cables or optical fibers will be borne by users rather than by "network operators." The remarkable success of 802.11b (WiFi) radio systems is clear evidence of the growth of this category of devices and applications. Without any significant marketing expenditure, 802.11b WLAN terminals have grown at a remarkable rate, even during a telecom recession [57:3]
[16] "Like the PC industry, the control of modular interfaces, standards and protocol evolution will be the key areas of competition to define services for users, rather than the current situation where competition focuses on operators because they bear the capital costs of system deployment [57:6]."
[17] Lehr provides a simple example for open wireless networks:

> In the case of a Bluetooth-enabled headset or MP3 player or a USB-enabled home entertainment hub, it is more likely that interference issues – if they arise – can be locally managed (*e.g.*, if a cordless phone is interfering with the use of the home WLAN, then walk a few feet away). In contrast, service providers may be reluctant to invest the millions of dollars that are required to build wide-area carrier networks without the protection against future interference that an exclusive license provides [62:10]

SOURCES

[1] R. Frost, "Mending Wall," in 12 Poets, G. Legget, Ed. New York: Holt, Rinehart and Winston, 1958, p. 253.

[2] D. Reed, "How wireless networks scale: the illusion of spectrum scarcity." Silicon Flatirons Telecommunications Program, Boulder Colorado, March 5, 2002. p.21.

[3] Y. Benkler, Open Spectrum Policy, NYU School of Law, N.D.

[4] Kelly, Kevin, "10 years that changed the world," Wired, August, 2005, p. 132.

[5] Y. Benkler, "From consumers to users: shifting the deeper structure of regulation toward sustainable commons and user access," Fed. Com. L. J. vol. 56, 2000.

[6] K. Werbach, "Open spectrum: the paradise of the commons," Release 1.0, November 2001.

[7] Y. Benkler, "Some economics of wireless communications," Harv. J. L. & Tech., vol. 25, 2002.

[8] M. Olsen, The Logical of Collective Action. Cambridge, MA: Harvard University Press, 1965.

[9] R. D. Putnam, Bowling Alone: The Collapse and Revival of American Community. New York: Simon and Schuster, 2000.

[10] P. Levine, The Internet and Civil Society. University of Maryland, Institute for Philosophy and Public Policy, 2000.

[11] Y. Bakos and E Brynjolfsson, "Bundling and competition on the Internet: aggregation strategies for information goods," Mgmt. Sci., vol. 19, 2000.

[12] A. Lupia and G. Sin, "Which public goods are endangered? How evolving communications technologies affect the *Logic of Collective Action,"* Pub. Choice, vol. 117, 2003.

[13] S. Coleman and J. Gotze, Bowling Together: Online Public Engagement in Policy Deliberation. London: Hansard Society, 2002.

[14] H. Varian, Copying and Copyright, Working Paper, December 2004.

[15] Spectrum Policy: Property or Commons, Stanford Law Scholl, March 1-2, 2003.

[16] Future of Spectrum Management: Private Property or Open Standards, Silicon Flatirons Telecommunications Conference, March 5, 2002.

[17] F.M. Scherer and D. Ross, Industrial Market Structure and Economic Performance, 3rd Ed. Boston: Houghton Mifflin, 1990.

[18] D. Besanko and R.R. Braeutigam, Microeconomics: An Integrated Approach. New York: John Wiley & Sons, 2002.

[19] D. C. North, Institutions, Institutional Change and Economic Performance. Cambridge: Cambridge University Press, 1990.

[20] R. H.Coase, "The nature of the firm," Economica, vol. 4, 1937.

[21] R. H. Coase, The problem of social cost," J. of L. and Econ., vol. 3: 1960.

[22] R.H. Coase, "The Federal Communications Commission, J. of L. and Econ., vol. 2, 1959.

[23] D. C. North, "Institutions and Economic Theory," Am. Economist, Spring, 1992.

[24] E. G. Furubotn and R. Richter, Institutions and Economic Theory: The Contribution of the New Institutional Economics. Ann Arbor: University of Michigan Press, 2000.

[25] C. Hess and E. Ostrom, "Artifacts, facilities, and content: information as a common-pool resource," Conference on the Public Domain, Duke Law Schoool, November 9-11, 2001.

[26] M. A. Heller, "The tragedy of the anticommons: property in the transition for Marx to markets," Harv. L. Rev., vol. 11, 1998.

[27] C. Rose, "The comedy of the commons: commerce, custom and inherently public property, Univ. of Chicago L. Rev., vol. 53, 1986.

[28] S. Weber, The Success of Open Source. Cambridge, MA, Harvard University Press, 2004.

[29] E. von Hippel, Democratizing Innovation. Cambridge, MA. MIT Press, 2005.

[30] M. Cooper, "Inequality in digital society: why the digital divide deserves all the attention it gets," Cardozo Arts & Ent. L. J., vol. 93, 2002.

[31] BRIE-IGCC E-conomy Project, Tracking a Transformation: E-commerce and the Terms of Competition in Industries. Washington, D.C.: Brookings Press, 2001.

[32] I. H. Simpson, "Historical patterns of workplace organization: from mechanical to electronic control and beyond," Current Soc., vol. 47 . 1999.

[33] B. Bluestone & B. Harrison, Growing Prosperity: The Battle for Growth With Equity in the Twenty-First Century. Boston: Houghton Mifflin, 2001.

[34] E. C. Kamarck & J. S. Nye Jr. Eds., Governance.Com: Democracy in the Information Age. Washington, D.C.: Brookings, 2002.

[35] A.L. Shapiro, The Control Revolution: How the Internet is Putting Individuals in Charge and Changing the World We Know. New York: Public Affairs, 1999.

[36] E.Brynjolfsson and B.Kahin, "Introduction," in Understanding the Digital Economy, E. Brynjolfsson and B.Kahin, Eds. Cambridge: MIT press, 2000.

[37] D. B. Audretsch & P.J.J. Welfens, "Introduction," in The New Economy and Economic Growth in Europe and the US, D.B. Audretsch and P. J.J. Welfens, Eds. New York: Springer-Verlag, 2002.

[38] B. Steil, D. G. Victor and R. R. Nelson, Technological Innovation & Economic Performance. Princeton: Princeton University Press, 2002.

[39] Y. Benkler, "Coase's penguin, or Linux and the nature of the firm," Conference on the Public Domain, Duke University Law School, Nov. 9-11, 2001.
[40] M. Castells, The Internet Galaxy – Reflections on the Internet, Business, and Society. Oxford: Oxford University Press, 2001.
[41] L. W. McKnight, "Internet business models: creative destruction as usual," in Creative Destruction: Business Survival Strategies in the Global Internet Economy, L.W. McKnight, P. M. Vaaler, & R. L. Katz, eds. Cambridge: MIT Press, 2001.
[42] National Research Council, Realizing the Information Future: The Internet and Beyond. Washington, D.C.: National Academy Press, 1994.
[43] J. Mokyr, "Innovation in an historical perspective: tales of technology and evolution," in Technological Innovation and Economic Performance, B. Steil, D. G. Victor & R. R. Nelson, Eds. Princeton: Princeton University Press, 2002.
[44] A.Arora, A.Fosfuri and A. Gamardella, Markets for Technology: The Economics of Innovation and Corporate Strategy. Cambridge: MIT Press, 2001.
[45] E. von Hippel, "Economics of product development by users: the impact of 'sticky' local information," Mgmt. Sci.., vol. 44, 1998.
[46] C. Shapiro & H. Varian, Information Rules: A Strategic Guide to the Network Economy. Boston: Harvard Business School Press, 1999.
[47] Shane Greenstein, "The evolving structure of the Internet market," in Understanding the Digital Economy, E. Brynjolfsson and B. Kahin, Eds. Cambridge: MIT press, 2000.
[48] B. R. Gaines, "The learning curve underlying convergence," Tech. Forecasting and Soc. Change, Jan/Feb, 1998.
[49] W. B. Arthur, "Positive feedbacks in the economy", Scientific Am. vol. , 95, 1990.
[50] W. B. Arthur, "Competing technologies, increasing returns and lock-in by historical events," Econ. J. vol. 99 , 1989.
[51] A.L.Barabasi, Linked. New York: Plume, 2002.
[52] D.Watts, Six Degrees: The Science of a Connected Age. New York: Norton, 2003.
[53] Webster's Third New International Dictionary. Springield, MA: 1986.
[54] M. Buchanan, Nexus: Small Worlds and the Groundbreaking Theory of Networks. New York: Norton, 2002.
[55] S. Johnson, Emergence: The Connected Lives of Ants, Brains, Cities and Software. New York, Simon and Schuster, 2001.
[56] T. Berners-Lee, Weaving the Web: The Original Design and Ultimate Destiny of the World Wide Web by Its Inventor. New York: Harper Business, 1999
[57] D. P. Reed, Comment for FCC Spectrum Policy Task Force on Spectrum Policy, ET Docket No. 02-135, July 8, 2002.
[58] D. P. Reed, Bits Aren't Bites! Balkanizing Spectrum Creates Scarcity. MIT Wireless Forum, December 4, 2002.
[59] Y. Benkler, "Free as the Air to Common Use: First Amendment Constraints on Enclosure of the Public Domain," New York U. L. Rev. vol. 74, 1999.
[60] Y. Benkler, Property Commons and the First Amendment: Toward a Core Common Infrastructure. Brennan Center for Justice, New York University Law School, March 2000.
[61] V. Bahl, Openness and the Public Airwaves, Mobihoc 2005, University of Illinois, Champaign Urbana, May 26, 2005.
[62] W. Lehr, The Economic Case for Dedicated Unlicensed Spectrum Below 3 Ghz. Washington, D.C.: New America Foundation, July 2004.
[63] B. M. Frischmann, "An economic theory of infrastructure and commons management," Minn. L. Rev., 4:2005.
[64] L. Lessig, Code and Other Laws of Cyberspace. New York: Basic, 1999.
[65] R. J. Berger, No Time for a Big Bang: Too Early to Permanently Allocate Spectrum to Private Property. Center for Global Communications, January 23, 2003.
[66] C. Ting, J. M. Bauer, and S.S. Wildman, The U.S. Experience With Non-Traditional Approaches To Spectrum Management. Quello Center for Telecommunications Management and Law, Michigan State University.
[67] J.M. Bauer, A Comparative Analysis Of Spectrum Management Regimes. Department of Telecommunications, Michigan State University, N.D.
[68] P. J. Weiser and D. N. Hatfield, Policing the Commons. N.D.
[69] "Charter," The Wireless Commons, December 30, 2002.
[70] N. Ikeda, The Spectrum as Commons: Digital Wireless Technologies and the Radio Policy. Research Institute of Economy, Trade and Industry, March 2002.
[71] E. Ostrom, R. Garnder & J. walker, Rules, Games & Common-Pool Resources. Ann Arbor: University of Michigan Press, 1994.
[72] E. Noam, "P2P as a Market Catalyst," TPRC, September 2005.

FIGURE 1: THE FRAMEWORK FOR ECONOMIC ANALYSIS

STRUCTURE, CONDUCT, PERFORMANCE

BASIC CONDITIONS

Demand
Price
Elasticity
Substitutes
Rate of Growth
Cyclical & Seasonality
Purchase Method
Marketing Type

Supply
Raw Materials
Technology
Unionization
Product Durability
Value/Weight
Business Attitudes
Legal Framework

MARKET STRUCTURE

Number of sellers and Buyers
Product differentiation
Barriers to entry
Cost structures
Vertical integration

Public Policy
Taxes & Subsidies
Trade Rules
Regulation
Price Controls
Antitrust

CONDUCT

Pricing behavior
Product strategy & advertising
Research and innovation
Plant investment
Legal tactics

PERFORMANCE

Production & allocative efficiency
Progress
Full employment
Equity

INSTITUTIONAL ECONOMICS

COOPERATION & COORDINATION

TRANSACTION COSTS

Physical & legal
Information search & asymmetries
Bargaining
Measurement & enforcement

POLITICAL ACTION

Governance property rules
Third-party enforcement

FORMAL CONSTRAINTS

INFORMAL CONSTRAINTS

MOTIVATION

Altruism, Honesty, Integrity, Commitment
Fairness, Justice

ADAPTIVE EFFICIENCY

FIGURE 2: TYPES OF GOODS

	SUBTRACTABIILTY		
	RIVAL	**NON-RIVAL**	**ANTI-RIVAL**
EXCLUSION			
Excessive	Tragedy of the Anti-common		
Exclusive (easy)	Private Good	Toll /Club Good	
Non-Exclusive (difficult)	Common-Pool Resource	Public Good	Private/ Collective Good
Inclusive		Network Good	Collaborative Good

Source: The traditional four-cell typology with the characteristics of subtractability and exclusion is from C. Hess and E. Ostrom, “Artifacts, Facilities and Content: Information as a Common-pool Resource,” Conference on the Public Domain, Duke University School of Law, November 2001, p. 54.

Figure 3: Traditional v. Repeater Networks

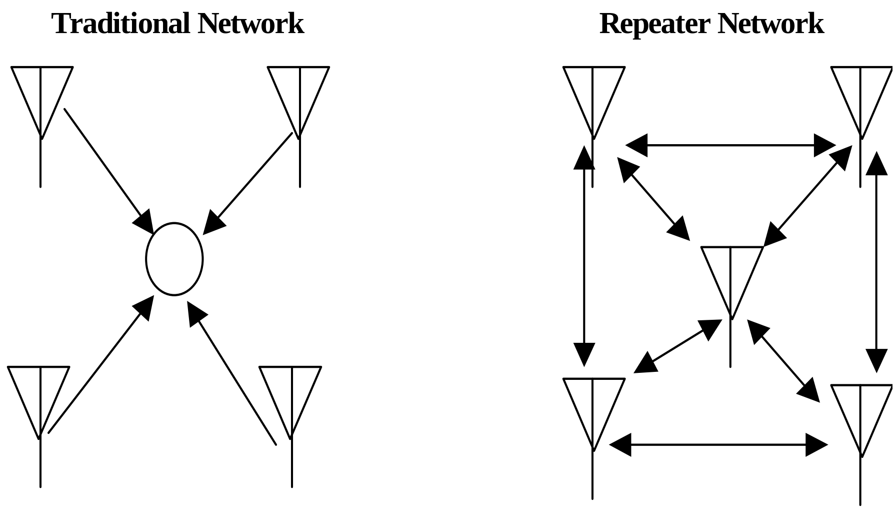
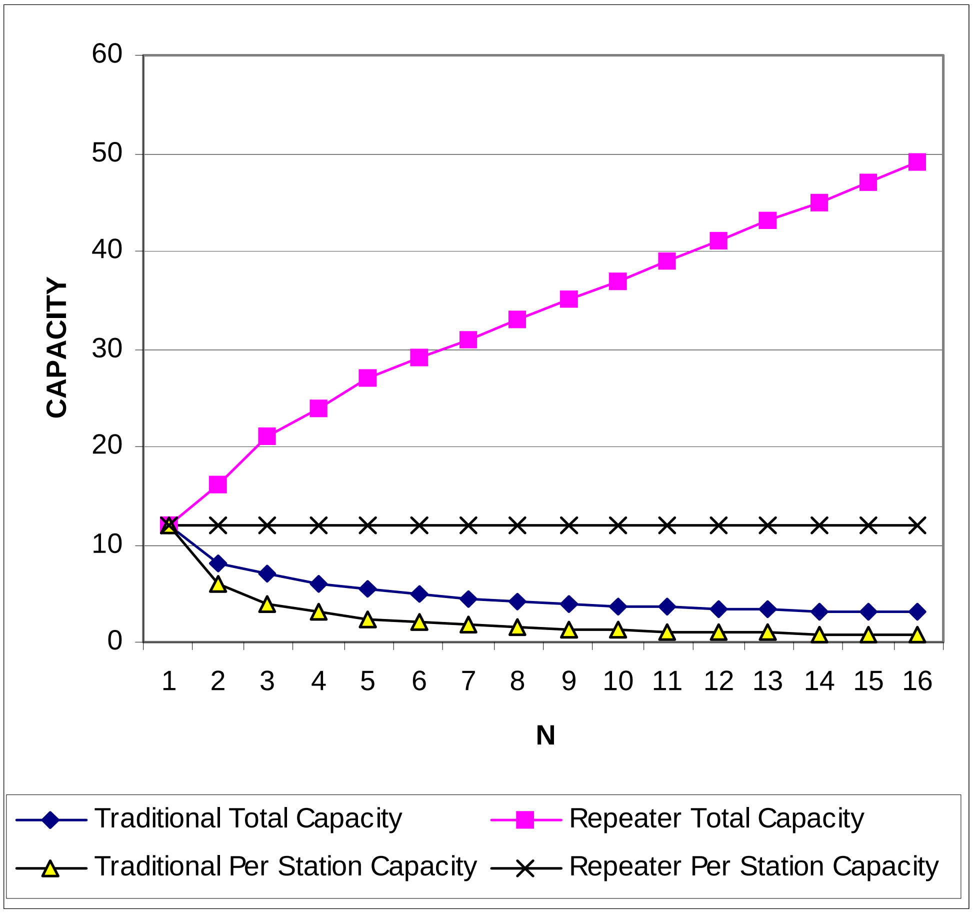


Figure 4: Spectrum Capacity in Traditional and Repeater Networks



Source: D. P. Reed, "How Wireless Networks Scale: The Illusion of Spectrum Scarcity," Silicon Flatirons Telecommunications Program, March 5, 2002, pp. 10, 14.

Figure 5: Network Configurations

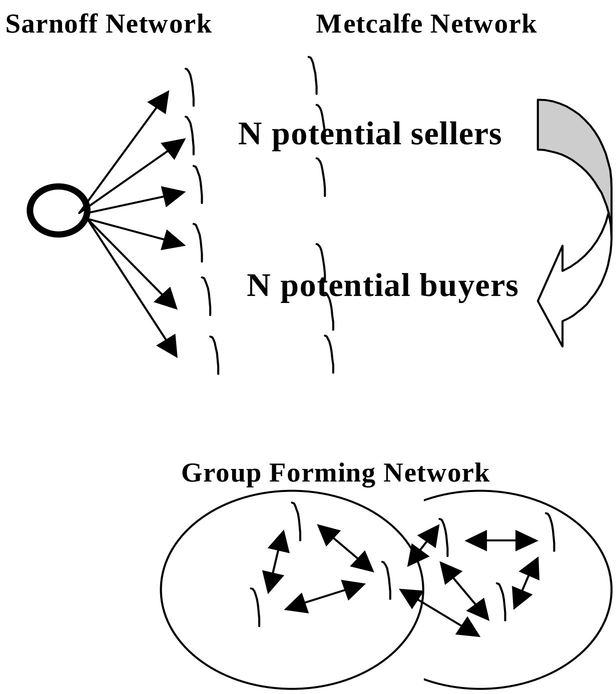


Figure 6: Capacity in Traditional and Repeater Networks

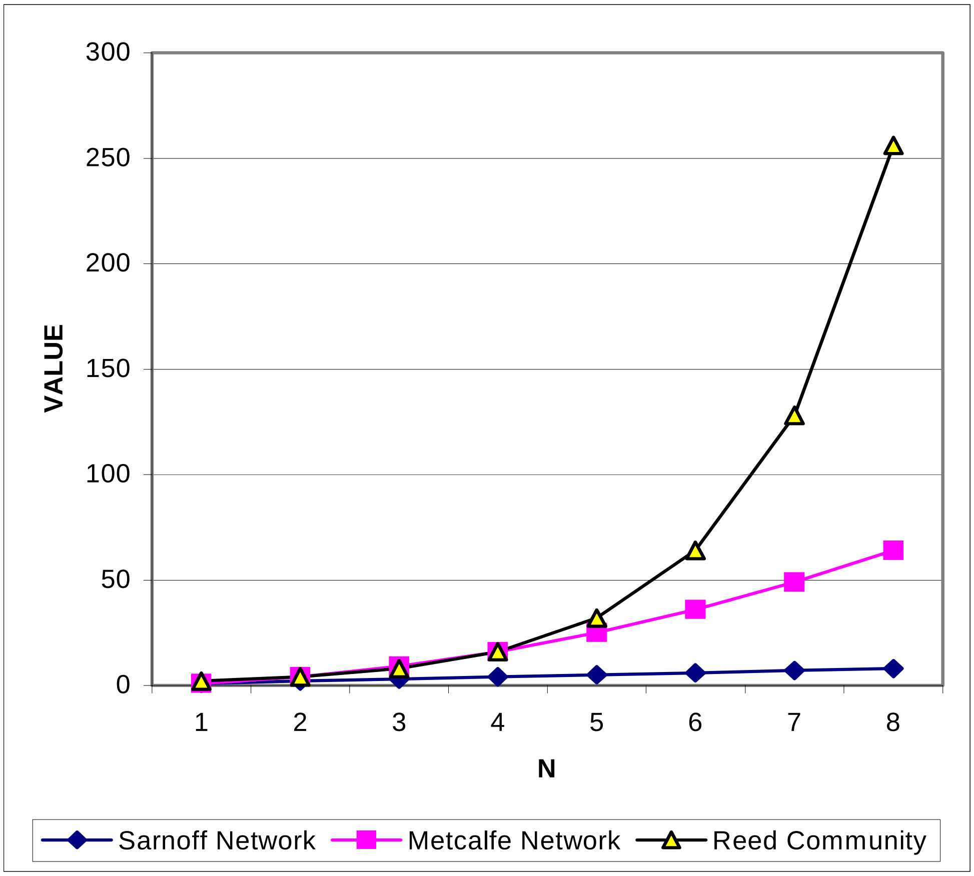


Figure 7: The Intersection of Community Formation and Repeating Networks

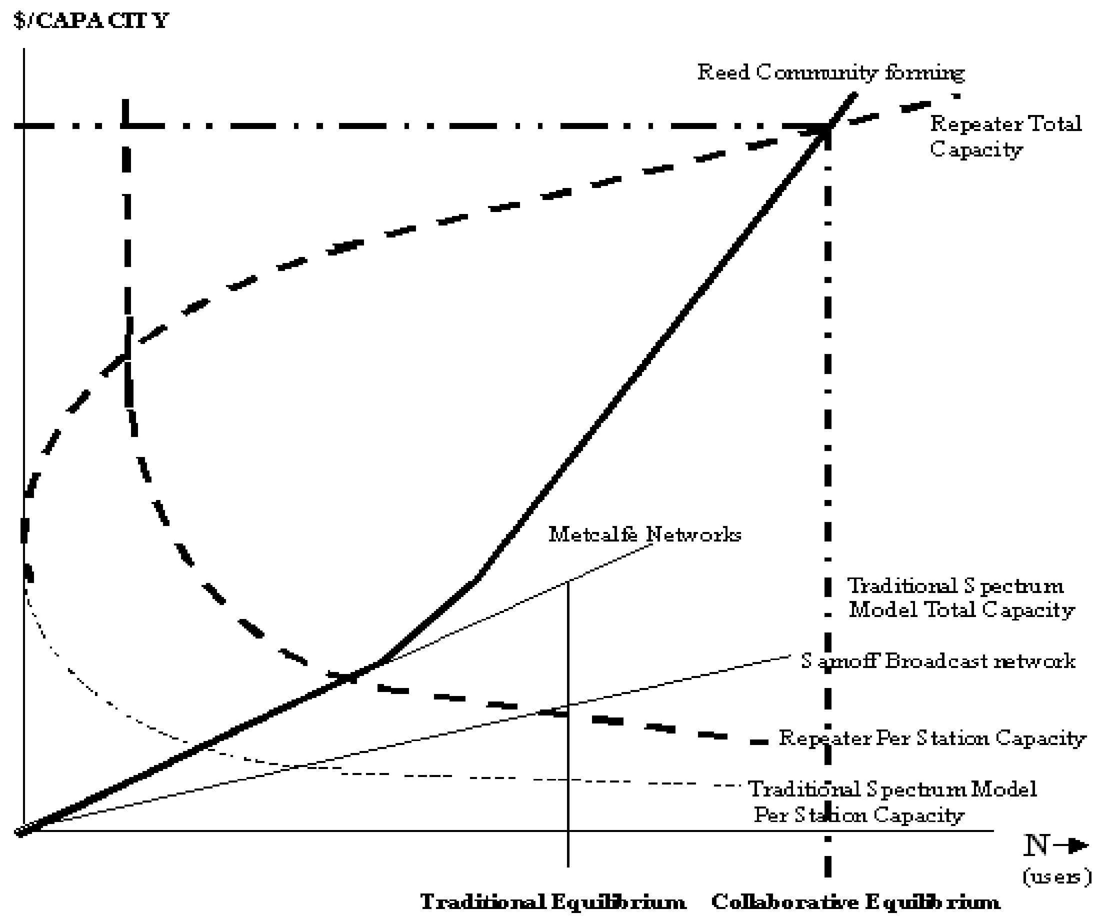
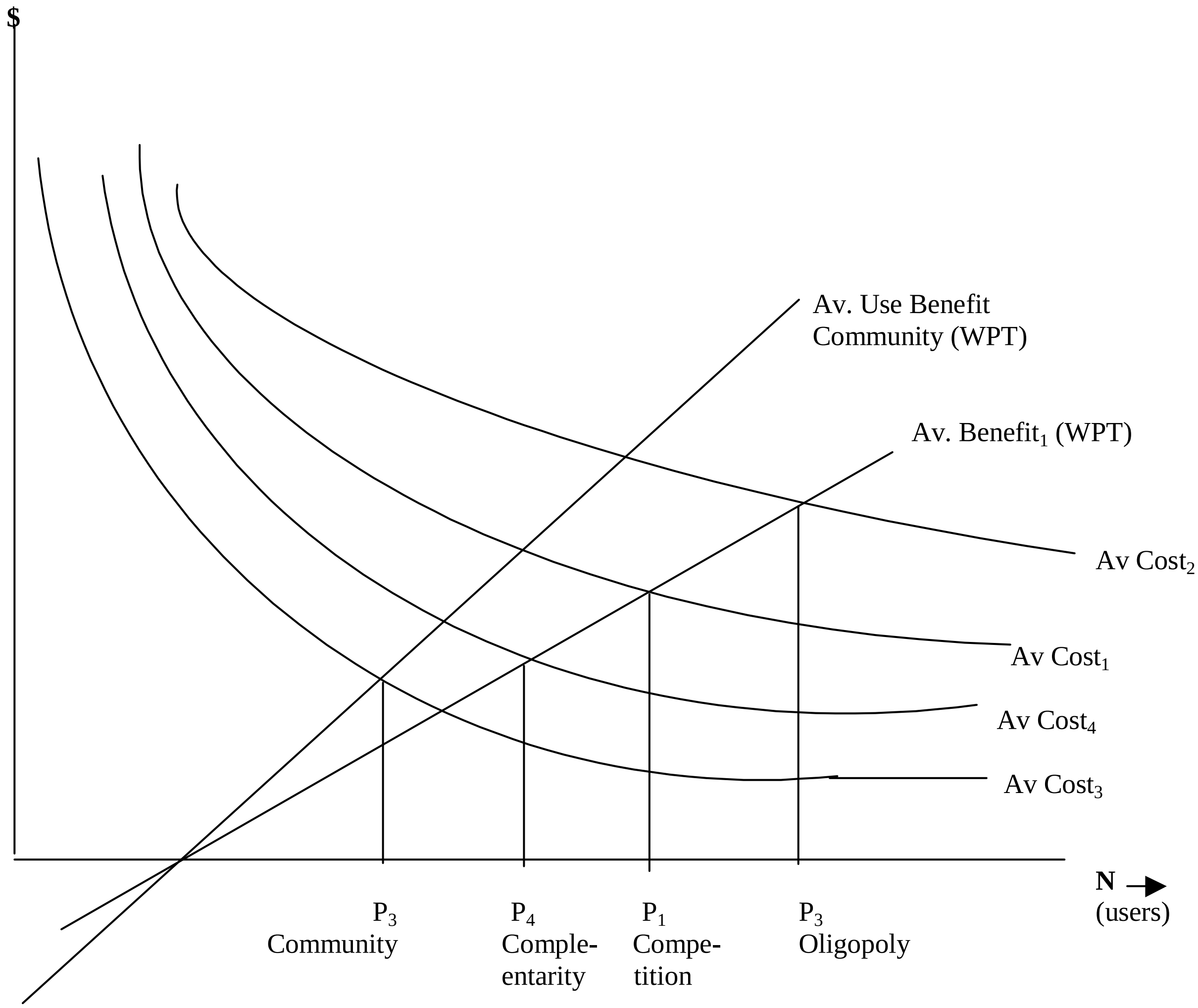
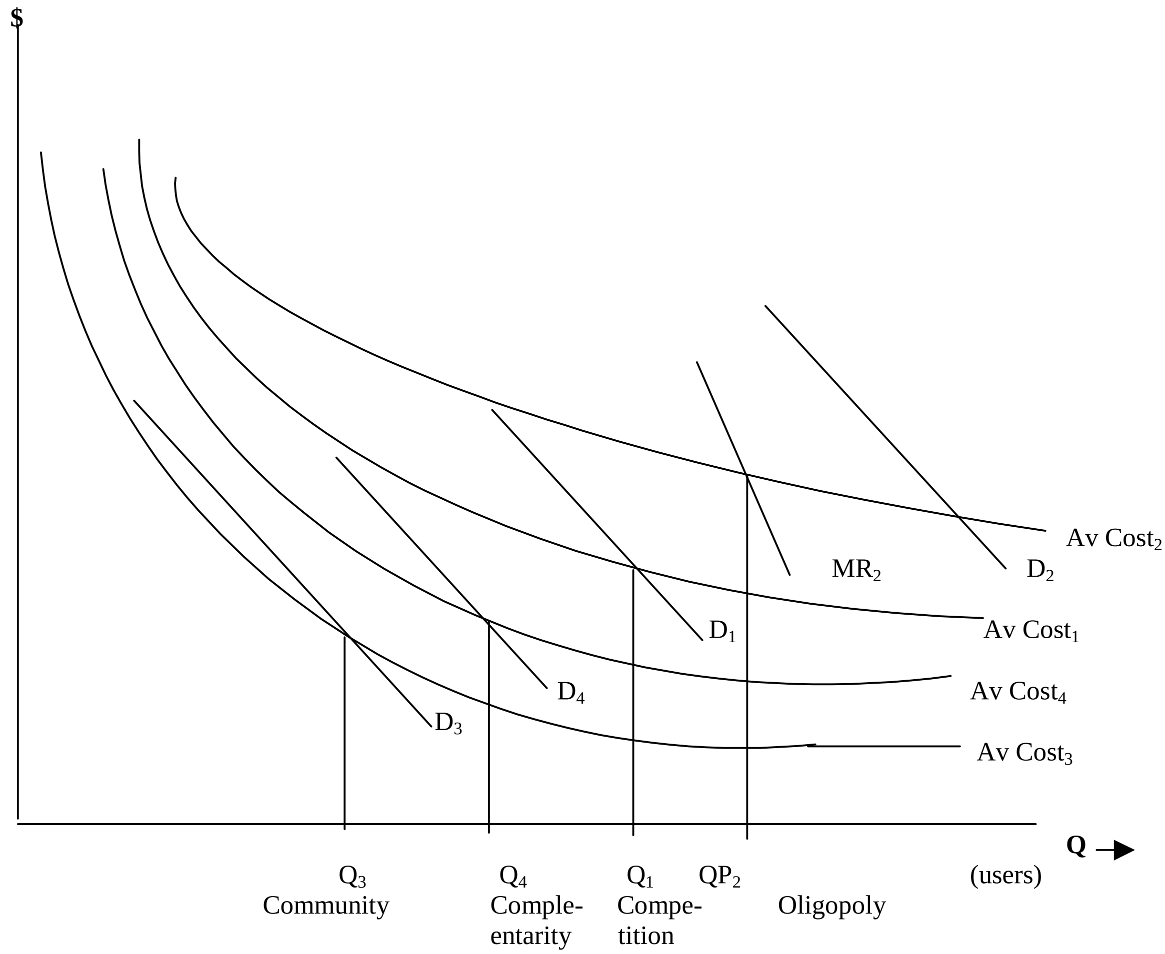


FIGURE 8: ECONOMICS OF TRADITIONAL SPECTRUM MODELS



Source: E. Noam, "Commons as Enabler of Commerce," Columbia Institute for Tele-Information, May 2005, p. 5.

FIGURE 9: ECONOMICS OF TRADITIONAL SPECTRUM MODELS



Source: E. Noam, "Commons as Enabler of Commerce," Columbia Institute for Tele-Information, May 2005, p. 5; "P2P as a Market Catalyst," TPRC, September 2005.

FIGURE 10: COLLABORATIVE PRODUCTION OF COMMUNICATIONS IN THE SPECTRUM COMMONS OUTPERFORMS THE TRADITIONAL SPECTRUM MODEL

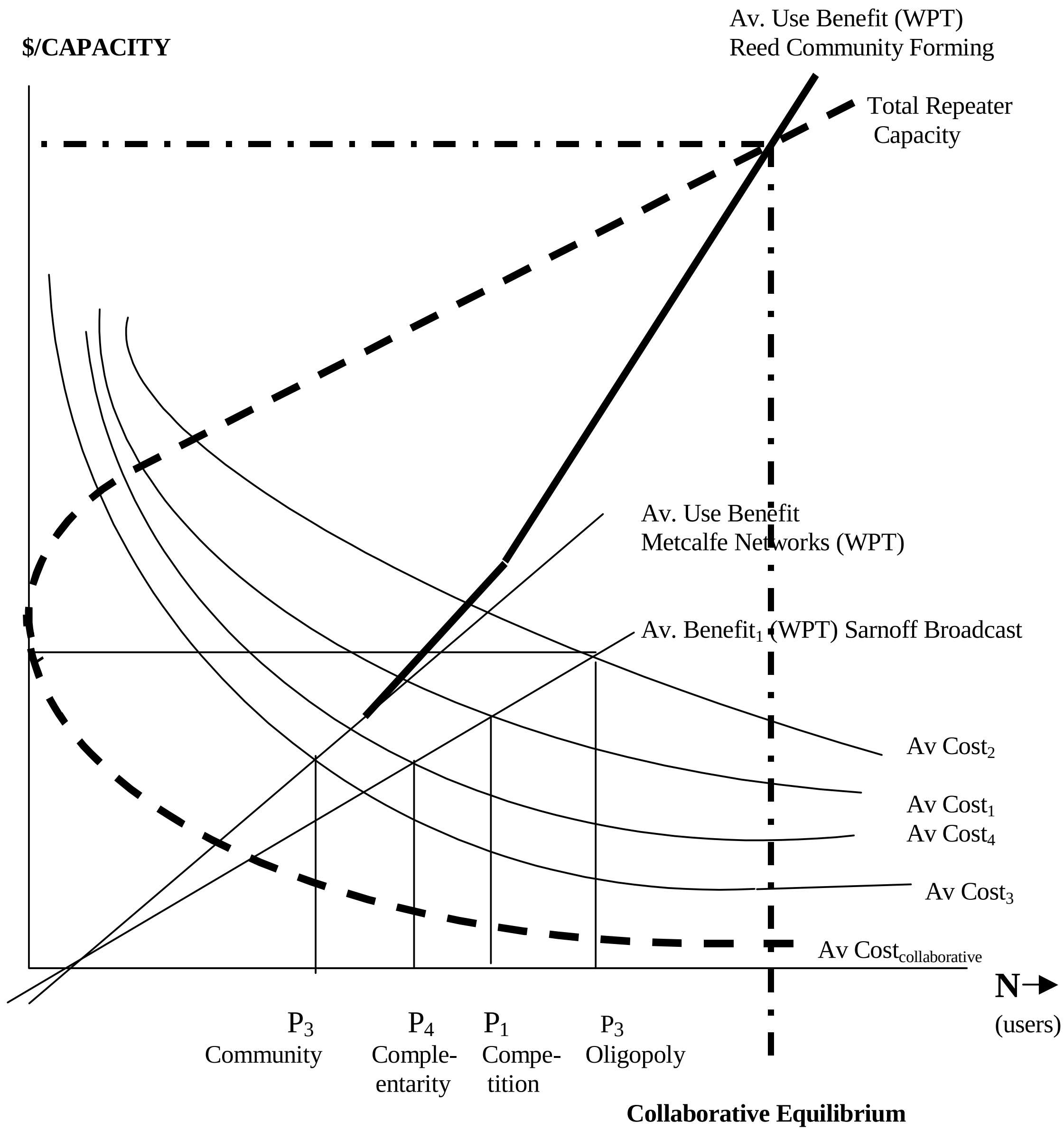


Figure 11: Comparison of Traditional Oligopoly and Collaborative Production