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The tradeoff of the commons under stochastic use☆

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ABSTRACT

We develop a model of scarce renewable resources to study the problem of the commons. Our model formulation differs from the existing literature in that it assumes the use of the commons to be stochastic in nature. One example is microwave spectrum for mobile and wireless communications. We investigate three mechanisms of resource allocation: free usage, the exclusive franchise, and a regulated monopoly. We show that the welfare tradeoff among these three mechanisms depends on the characteristics of the commons and their usage patterns. In particular, we find that property rights are not always the best solution. We then make four extensions that apply to spectrum allocations.

1. Introduction

The problem of allocating exhaustible public resources has been extensively studied in the literature, initiated by Gordon (1954) and Scott (1955). Its organizational form known as the commons is generally considered a tragedy (Hardin, 1968), because it lacks a mechanism to prevent selfish overuse. Instead, assigning property rights is generally believed to offer an efficiency solution. The subject of renewable public resources, however, brings about a different set of perspectives in that the objective of an imaginative welfare-maximizing social planner is to maximize usage, and more precisely to maximize the value of the usage, while at the same time exercising stewardship over the resource by preventing its overuse. Using a scheduling mechanism, McAfee and Miller (2012) first showed that a commons solution can be more efficient than property-rights-based ones, and there exists a tradeoff between the two types of organizational forms. The resources in their model are excludable and indivisible. This means that a fixed number of customers may be accommodated at any one time, but their identities must be fixed during the time of resource use.

In this paper, we extend their conclusions to an alternative situation where a renewable resource is subject to use in a stochastic manner.[1] On the surface, this seemingly small modification may appear trivial, but, in fact, it introduces several important differences that have profound implications when seeking efficient allocation mechanisms. First, in our model the resource is excludable but divisible in that its usage is multiplexed into its designed capacity. The resource is excludable because as its number of users increases its quality can become increasingly degraded. But it is divisible because the actual number of users and, more importantly, the identity of its users can vary from time to time.

In a commons scenario, this suggests that scheduling is neither critical nor practical. It is not critical because, unlike the McAfee and Miller (2012) model which is concerned with loss from coordination

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[1] The type of stochastic use described in our paper refers to stochastic use initiated by end users. In the debate over spectrum policy, there is also the issue of random use by service providers, which usually refers to the issue of spectrum sharing between service providers. However, the original source of random use by service providers is still ultimately initiated by service providers' customers. While we did not touch on the mechanisms and protocols for spectrum sharing among service providers, Section 3.3 later in the paper regarding mixed services does indeed point to the benefit of spectrum sharing.

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failure, here the downside of a service denial in the absence of scheduling does not incur much cost. This is because each demand is treated equally by the resource capacity regardless of the current status of the demand, and it will have equal access probability in the future. Scheduling is not practical, since usage is stochastically session-based such that the overhead cost for establishing every single session would be too great. Without scheduling, the commons essentially becomes a self-regulating system where equilibrium can be automatically reached among users when the resource gets too crowded. Some people may prefer leaving the resource, while others choose to stay and continue to use it while accepting the current (low) quality of service. The social welfare of this equilibrium varies randomly over time, however, and in particular is certainly not maximized. In other words that the resource is allocated to those who value it most is clearly a zero probability event. On the contrary, allocative efficiency is certainly assured under property-rights solutions, albeit at an additional cost. It is precisely this tradeoff that lies at the heart of our analysis.

Our second difference from McAfee and Miller (2012) is that we assume that service quality is expected to be better under property-rights solutions than under the commons form. Technically our model allows for more people accessing the resource capacity, which is also called overbooking in network engineering.[2] In general, overbooking can be accommodated provided the probability of service denial, or in technical terms the blocking probability, is managed within an acceptable level. For example, at public Wi-Fi hotspots a short delay for free Internet access usually causes no concern.[3] Since we endogenize pricing in our model, one would expect that paying customers naturally would have a lower level of tolerance of blocking than those who have free use of the Internet.

Our model description probably applies most appropriately to the case of wireless spectrum. Rapid growth in wireless communications has increased the pressure for more spectrums to support more users, more uses and more capacity. To alleviate that pressure, some countries introduced major regulatory changes regarding spectrum allocation. Today some radio spectrums are indeed offered free of charge in many countries, for example for Wi-Fi applications, but others are still allocated by defined property rights, such as via spectrum auctions.[4] In this paper, we develop an analytical framework to provide a likely theoretical explanation as to why that might be the case by looking at the usage pattern and the network characteristics of spectrum bands.

We establish three base models to analyze the welfare implications of these mechanisms in terms of regulating spectrum usage: a commons model, a model of an unregulated monopoly and a model of regulation. The welfare comparison between regulation and monopoly hinges upon which of the quality effect and the quantity effect dominates. By quality effect, we mean the improved utility from better service quality resulting from a small number of customers. By quantity effect, we mean the positive effect caused by the larger number of customers in the social welfare summation. We derive a sufficient condition under which the quantity effect dominates the quality effect, imparting regulation having a larger social welfare than monopoly. This sufficient condition essentially boils down to requiring the growth rate of the supported customers with respect to the blocking probability to be large enough. We show this condition can be met with individual's network usage intensity being small and the variable cost of serving each customer being small. Intuitively both factors imply that adding customers pays towards enhancing social welfare.

The welfare comparison between free use and regulation hinges upon several factors among other things. First, if the cost of implementing a pricing mechanism is large, then free use dominates the regulation model. Second, if the maximum acceptable blocking probability is large, free use dominates the regulation model when the quantity effect dominates the quality effect. In other words, property-rights solutions only matter when people care a lot about the service quality or when the costs of implementing such solutions are relatively low.

We also make four extensions to the base models. We analyze the tradeoff between the commons and the regulation models as a function of the cell-site coverage size. We find that the tradeoff condition that favors free use under a macro-cell architecture must also hold under a micro-cell architecture. This means that free use generally favors spectrum bands of shorter reach, such as Wi-Fi and Bluetooth. The second extension concerns channel bonding, which is another important technology feature of the cognitive radio that is currently under development. We investigate whether social welfare is enhanced when spectrum bands are combined together to deliver services as opposed to being used separately under the current regulatory regime. We show that this is always the case as channel bonding exhibits a kind of economy of scale property. This is because the efficiency gain from statistical multiplexing is likely to increase as the spectrum width increases. The third extension concerns a mixed service where the free-use traffic is mixed with the traffic of paying customers who enjoy priority with guaranteed quality of service. This scenario may be viewed as a primitive version of the cognitive or the software-defined radio that is currently being actively developed. We find that the mixed-service model, wherein a certain amount of free use is accommodated, when optimized, always dominates the case where only paying customers have access. The final extension builds a competition model vis-á-vis regulation, where we find the former generates less total social welfare than the later, when the quantity effect dominates the quality effect. This is because competition means spectrum division and, thus, a loss of economy of scale in spectrum usage. Also resource allocation costs are duplicated due to the introduction of multiple competitors.

These results point to some important implications for the spectrum policy debate. Our results generally support a phased approach to opening up more spectrum bands, perhaps starting with those with shorter-range coverage, such as Wi-Fi and Bluetooth. Our results also support tiered services where prioritized paying traffic and free-use traffic can be multiplexed. This is essentially the most important feature currently being developed under cognitive or software-defined radio technologies.

The spectrum policy literature is quickly expanding, especially tangential to the economics profession. Noam (2012) provides a historical review of the evolution of economists' views on radio spectrum. Starting with Coase (1959), economists have favored property-rights solutions to spectrum allocation. In more recent years, a significant debate has emerged over whether the government should make the spectrum open and free. Minervini (2014) analyzes spectrum management deregulation reforms within the theoretical framework of transition economics. He shows how Anglo-Saxon and European countries have been implementing gradual reforms while Central America has opted for a fast transition to market mechanisms.

Brennan (1998), Hazlett (1998), and Cave and Webb (2004) argue that spectrum is still scarce, and they believe that a regime of open but priced access would impose prohibitive transaction costs. Hazlett (2008) advocates for abolishing the control of the Federal Communications Commission, thus permitting any wireless

[2] McAfee and Miller (2012) are concerned about the loss incurred from not using the resources. This problem does not exist in our model as we consider the case of overbooking. Telecommunication networks are usually designed for peak-time usage, and overbooking is commonly used when congestion is expected.

[3] When bits are transmitted in sessions under the TCP/IP protocol, blocking manifests in the form of longer delays.

[4] For a comprehensive review of spectrum auctions, see McAfee and McMillan (1996).