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Impact of Cognitive Radio Technology on Spectrum Management Policy

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Abstract
New technology such as cognitive radio will significantly affect spectrum management policy. In addition it will also influence the tradition of spectrum economics, i.e. background theory of spectrum management policy. Spectrum economics treats mainly licensed or exclusive use of spectrum. In this paper, I try to show a theoretical framework and some models to analyze appropriate uses of license-exempted wireless communication systems, making reference to allocation theories of other scare public resources: transport economics, club theory, and theory for local public goods. Finally I will mention my view of cognitive radio.

Keywords
Cognitive radio, Spectrum economics, License-exempted use, Theory of club

1. Introduction
M. Cave [2002] and FCC Spectrum Policy Task Force [2002] categorized a variety of spectrum management policies into three models: the command and control model, the exclusive use model and the commons, open access or license exempted model. Traditionally, spectrum management authorities adopt mainly the command and control model including the exclusive use model, in that they deliver licenses to spectrum users to protect the users from harmful interference and allow them the exclusive use of spectrum. New technology in wireless communications, however, challenges to introduce the commons model. Technology, such as wireless LAN

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(W-LAN), WiMAX and ultra wide band (UWB), does not require assignment of a specific frequency or band, and, instead, shares a wide band of spectrum with other users. These technologies contain the sensor, thus they find a vacant frequency and send signals on it.

Cognitive radio is a typical technology of the sharing spectrum. The equipment recognizes vacant bands of spectrum and adjusts autonomously its transmission to one of the bands by using software defined radio (SDR) technology. Cognitive radio is assumed to be used on the license exempted basis. This new technology is very interesting in its unique characteristic of spectrum use, and has a glorious future in the long run. However, M. Cave et al. [2007] and W. Webb [2007] have a pessimistic view about extensive introduction of cognitive radio in the short run, because of its technological limitation, introduction costs for its own equipment and adaptation in other systems, and cohabitation of two opposite spectrum management systems (licensed and license-exempted systems) in the same bands.

In addition, the diffusion of cognitive radio will affect theoretical discussion of spectrum economists. As I will mention in the next section, the spectrum economics developed on license or exclusive use model basis from R. Coase's works (R. Coase [1959], [1960]; see also P. Marks and K. Yuguchi [2006]). In their discussion, almost every externality problem is solved by negotiations or transactions based on clearly defined spectrum rights, including congestion problems; thus, we should now theoretical framework for the new technology based on license-exempted uses.

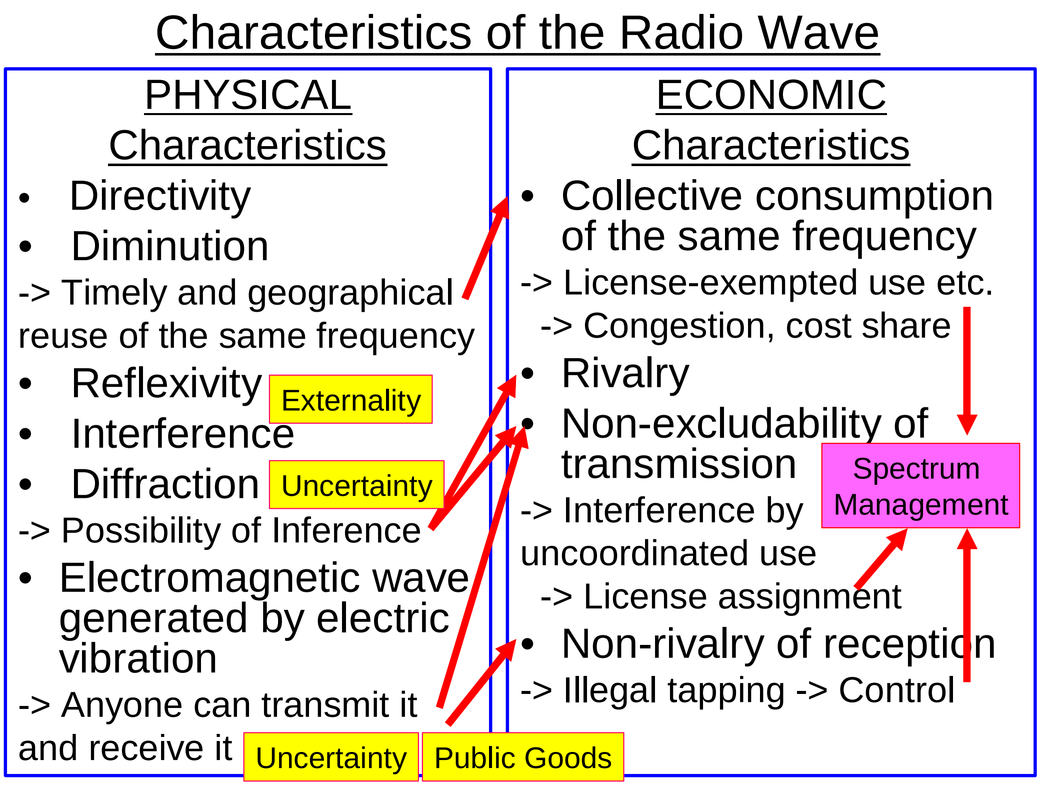
In this paper, I try to show a theoretical framework and some models to analyze appropriate uses of license-exempted wireless communication systems, such as cognitive radio. I make reference to allocation theories of other scare public resources: transport economics, club theory, and theory for local public goods. I refer to these theoretical frameworks along with spectrum economics in section 2, and show some models for seeking conditions of optimum use of spectrum based on the club theory in section 3. Finally I will refer to my view of cognitive radio as the result of the model analysis in section 4.

2. Theoretical Framework

2-1 Physical and Economic Characteristics of Radio Wave

Radio wave or electro-magnetic wave has physical characteristics such as directivity, diminution, reflexivity, interference and diffraction. The extent of such characteristics depends on frequency bands and other natural conditions, i.e. geography, weather etc. Therefore, plural spectrum users can share timely or geographically the same frequency (or frequency bands) in some time, and can not in other time. Once equipment is prepared, one can easily emit radio wave. However, it is difficult to emit the wave only to a specific target by a specific frequency. It is often that a part of signals from an emitter spill out from a targeted receiver to adjacent spectrum users. To prevent users from interference spectrum management is required, and normally a governmental institution takes charge of this work by the way of guard bands or guard areas and by technical conditions of emitters and receivers. These physical characteristics can be translated into economic characteristics (**Figure 1**). Spill over effects along with unexpected emission can be recognized as externality problems in economic terms.

Figure 1: Physical and Economic Characteristics of Radio Wave

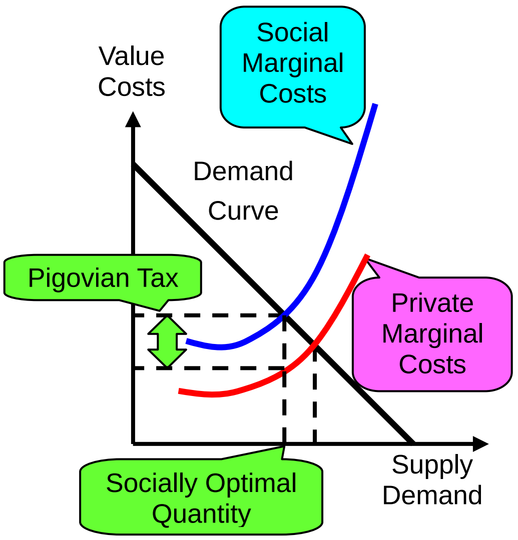


2-2 Pigovian Method and Coasian Method

Two methods are known in economics to solve the externality problems.

The first one is the Pigovian method (A.C. Pigou [1920]) which pays attention to a difference between private marginal costs and social marginal costs. Levying a tax or a charge (often called as the 'Pigovian tax') by the difference, the government makes users know existence of the externality. The marginal costs curve is upward shifted by the difference, i.e. the tax or the charge, so the socially optimal demand or supply becomes less than privately optimal level (**Figure 2**). This method is typically applied to the congestion tax and charge and the emission tax.

Figure 2: Pigovian Tax



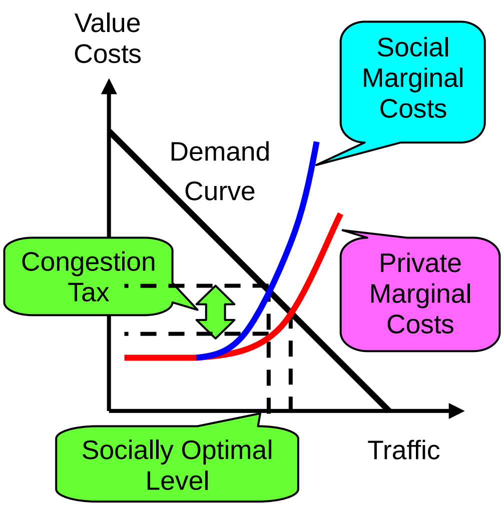
The second one is the Coasian method. R. Coase [1959], [1960], [1988] criticized (welfare) economists for thoughtless application of Pigovian tax to almost every externality problem. He argued alternative methods from the social costs consideration. Each allocation method (system) requires operational costs including opportunity costs generated as the result of introduction of a specific method. He called these costs 'transaction costs.' Compared the command and control system with the spectrum trading system (actually positioned as the 'exclusive use model'), he insisted on introduction of the auction system for spectrum assignment to broadcasters, based on his estimation of the transaction costs. A part of his idea is unfortunately penetrated into many economists as the 'Coase Theorem,' but it is only the case of no transaction costs. He wanted to insist on considering the transaction costs among the social systems.

R. Coase's idea is following. The government defines the property rights on use of resources (ex. spectrum) and allocates them to related parties in advance. If the parties negotiate and trade the rights between them, they will finally attain the socially optimal level of provision and then the externality problems will be solved at the socially optimal level. In the case of no transaction cost, whatever the government allocates the rights between the parties, the same result will be attained in provision level (but will not in the distribution view point). He suggested reciprocity of the result between parties in his argument.

2-3 Pigovian Tax in Transport Economics

In transport economics, the road congestion problem has been one of the most important subjects and the demand control methods have been pursued. One of the significant characteristics of the road congestion is reciprocity. A driver in a long queue of cars is both a victim and an assailant at the same time. It is not necessary to separate victims from assailants; all drivers should be charged the same level of tax. Another characteristic is that the congestion starts when the total number of cars exceeds at a threshold. **Figure 3** shows the congestion tax and the socially optimal level of cars. Note that the congestion tax relax the congestion level, however it does not leave the congestion completely. The other important characteristic is that cars pass through the congestion or the bottleneck in the order of arrival.

Figure 3: An Example of Simple Congestion Model in Transport Economics



In transport economics, it is said that A. Walters [1961] firstly described the road pricing model and W. Vickrey [1969] firstly described the bottleneck congestion. The simple model of traffic congestion, the relationship between speed and traffic is converted into the relationship between traffic density or the time required and traffic, then into marginal cost function. There exists the backward bending problem in the shape of the cost curve, i.e. two different levels of cost correspond to traffic due to two different situations (in no congestion and in hyper congestion). In the bottleneck congestion theory which treats congestion dynamic, more sophisticated departure-time choice models developed (see R. Arnott et al [1998]).

2-4 Pigovian Method in Spectrum Economics

In spectrum economics, if we challenge the tradition after R. Coase, we would face a lot of difficulties. The cost level of the harmful interference depends on the usage of adjacent areas or bands of frequency. Signals do not always pass through the congested networks in the order of arrival. We can only say that 'your message will transmit in the near future.' Almost every license-exempted services such as W-LAN or cognitive radio are operated stochastically on the best-effort basis.

As the result, it is difficult to construct well formalized model of congestion in spectrum economics, unlike in transport economics. So I try to construct some congestion models based on the theory of club or the local public goods. Here, the relationship between the total users of a service and their costs is most important. The users share a band of spectrum, and in some time the research and development costs of equipment operated in this band. We can regard the spectrum as a club good or a local public good, because we can prepare another band for the same service or technology.

3. Models

3-1 Structure of Models

In this paper I will construct several models of sharing a frequency band with license-exempted users. This situation reflects W-LAN, WiMAX etc. if the band has relatively narrow width such as 100MHz, and cognitive radio or UWB if the band has very large width. When each user emits radio wave, it takes him/her transmission costs. These costs are composed of operational costs and delay costs. The latter depends on the number of users; the more users share the same band, the more it takes time and thus extra costs.

3-2 Simplest Model of Usage Congestion

The simplest model of usage congestion would be following formula. The total costs of use of the band equal the sum of each user's costs;

$$TC(q) = qC(q) \quad (1),$$

where TC(q), q and C(q) represent the total costs levied on the society from wireless communication in a band of spectrum (ex. 2.4GHz band), the number of users of the band and their private usage costs, respectively. Here homogeneous users are assumed. The private costs include the equipment cost, operating cost, and in some cases their private (i.e. own recognized) congestion cost. $dC(q)/dq > 0$ and $d^2C(q)/dq^2 > 0$ are assumed.

We differentiate equation (1) by q, and we obtain the following relationship.

$$dTC/dq = q(dC/dq) + C(q) \quad (2)$$

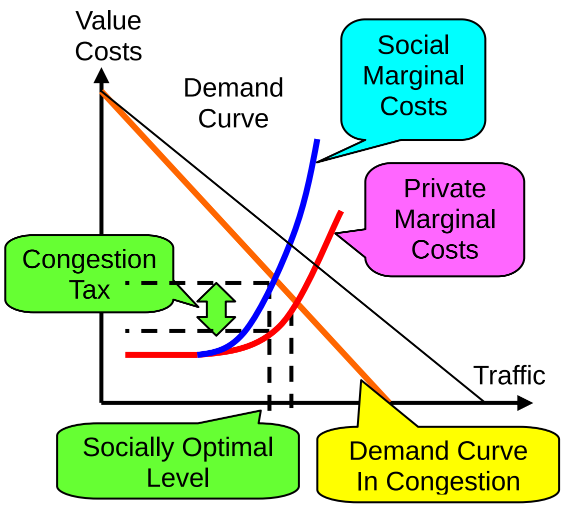
This formula shows most simplistically congestion: as the number of users increases, the access time increases due to congestion. The users recognize the speed-down for own usage. However, they will not recognize that they affect the access time of other users. dTC/dq represents the social marginal cost of wireless communication, whereas C(q) represents the private marginal cost. The Pigovian economists insist that the government or the third party should levy a congestion tax on the difference of the two marginal costs: q(dC/dq). Then the congestion will be internalized and the social optimal equilibrium will realize. Note that in this social optimal equilibrium the congestion will not be completely removed (see **Figure 3**). The users will be received until their individual value does not exceed the social marginal cost.

Modifying the simple formula above, this model can extend the congestion problem between users of the same service or the same band to other external interference problems. For example energy emitted from W-LAN equipment may cause interference with the satellite systems collectively, if the number of equipment exceeds a certain threshold. We add a term on the right hand of equation (1).

$$TC(q) = qC(q) + EC(q) \tag{3},$$

where EC(q) represents other external costs increased by the number of spectrum users. We also assume that $dEC(q)/dq > 0$ and $d^2EC(q)/dq^2 > 0$.

Figure 4: Another Example of Simple Congestion Model in Transport Economics



In the above model, we ignore the influence of congestion on demand for the service. As we often do so, the users tend to choose no-congested or less stress services. As a result, the value of the service will decrease along with the number of users. The demand curve in **Figure 4** reflects this relationship. In this situation, the socially optimal numbers of users will further decrease and the Pigovian tax will be less than the result in the original formula.

3-3 Congestion Models Based on the Theory of Club

Even in the modified model, we ignored somewhat the effect on users from sharing the same service or the same band. If the users are distributed a wider band, congestion will be relaxed. If the number of users increases, they will benefit from the scale merit in research and development in the equipment, although they will suffer from some congestion. These characteristics of spectrum use make us remember the provision of local public goods or club goods. Along with R. Cornes and T. Sandler [1986] (chapter 10), we continue our analysis.

Firstly we consider the simplest model of the club goods, where the users do not directly recognize the congestion in their utility and care only the cost for spectrum and the cost stemmed from congestion. U(y, X) represents an individual's utility function defined by his/her private good, y, and the amount of spectrum X. For the moment, I would not define X exactly; instead, I will say only "the amount of spectrum." C(X, s) refers the collective cost function defined by the amount of spectrum and the total number of users, who share the same spectrum. 'I' represents the individual's income. We assume a standard utility function and a standard cost function for these two functions. We also assume that homogeneous users maximize their own utility subject to their income restriction;

$$\text{Max } \{y, X, s\} \quad U(y, X)$$

$$\text{Subject to} \quad I = y + \{C(X, s)/s\} \qquad (4).$$

This second equation implies that the congestion will make the individual's monetary cost increase. Solving these equations with the Lagrange multiplier and the first-order derivative, the first-order condition for provision is

$$s\,\{(\partial U/\partial x)/(\partial U/\partial y)\} = \partial C/\partial X \qquad (5)$$

which is the same conditions as the Samuelson's optimal public goods provision. The first-order condition for the number of users is

$$\partial C/\partial s = C/s \qquad (6).$$

This result suggests that the marginal cost concerning the users equates with the costs per user (average cost) in the optimal situation. Thinking the standard cost function, the optimal number of users within the spectrum should remain at the level on which the usage costs per person including congestion effects may be minimized.

What does X represent in this formula? In the original model of the club theory (R. Cornes and T. Sandler [1986]), X represents the amount of a single club good or a local public good. Here we defined X simply as the amount of spectrum. In our formula X has two characteristics. As X increases, the provision cost of the spectrum increases. As s increases, the monetary cost of the spectrum also increases. These aspects imply that X refers to the bandwidth distributed to one or several services operated on license-exempted basis. What is the provision cost? If the spectrum is assigned on the license basis, this cost would reflect to the spectrum use fee or the bid of the auction. On the license-exempted basis, however, the direct cost for spectrum would not exist. Instead, we could regard this monetary cost as equipment costs. This cost would perhaps include not only manufacturing costs but also research and development costs. The physical characteristics of radio frequency differ from a band to a band; as the equipment adapts to more bands or bandwidth, these costs will increase due to high level of technical requirements. However, the costs per user may decrease if the number of users increases along with the adaptable bandwidth. The cost formula assumed here represents a situation that once the technology and the equipments are developed, the users get benefit from sharing the same technology.

In the above formula, the number of users, i.e. congestion and sharing, affected only on the monetary costs. However, the congestion also affects user's utility function. Here we count the number of use, v. This additional element contains the user's own use and the total uses of all users, sv. We modify equation (4) and define the new utility function and cost function.

$$\text{Max } \{y, X, v, s\} \quad U(y, X, v, sv)$$
$$\text{Subject to} \quad I = y + \{C(sv, X)/s\} \qquad (7)$$

We still assume that homogeneous users maximize their own utility subject to their income restriction. Here, the user's utility will increase along with his/her private good, the amount of spectrum distributed to the service and the number of own uses, and will decrease along with the total number of uses by all users there ($\partial U/\partial(sv) < 0$). The first order conditions are the Samuelson provision condition,

$$s\{(\partial U/\partial x)/(\partial U/\partial y)\} = \partial C/\partial X$$
$$(\partial U/\partial v)/(\partial U/\partial y) = C/(sv)$$
$$\{\partial C/\partial(sv)\} - s\{(\partial U/\partial(sv))/(\partial U/\partial y)\} = C/(sv) \qquad (8).$$

The first equation shows the Samuelson provision condition. The second equation reveals that the user's relative value of unit use equals unit costs of use. The third equation suggests that the marginal costs of unit use does not equal the average costs in the optimal use level if the users' disutility of congestion contains of the utility function. Note that the second term of the third equation is positive; thus in the optimal use level the marginal costs would be less than the average costs. This means that the optimal provision/demand level should be prepared within the downward sloping quantity (of the average costs).

4. Concluding Remarks

In this paper, I tried to construct analytical models for the license exempted use of spectrum such as WiLAN and cognitive radio. I should further consider the shape or definition of the utility function and the cost function. Especially I should clearly separate the monetary costs from the social costs in the cost function. These models are still under construction in this sense. In my further study (including my presentation in the ITS in Montreal) I will ameliorate these weakness and develop the models to analyze comparison of methods of spectrum use i.e. whether a wider band should be distributed to various services on license exempted basis or narrower fragmented bands should be distributed to each service.

In my analysis above, comparing the results of equation (6) (replica of the C. Tiebout [1956]'s 'voting with the feet' model by M. Mc Guire [1974]) and (8), I have an impression that instead of a wider band for various services such as cognitive radio, a system composed of narrower fragmented bands for one service might obtain higher efficiency. This subject remains in the discussion in the biennial conference.

Spectrum economics develops from the R. Coase's great works. So we have a lot of works in the license system and the exclusive use models. However we do not have much works on license exempted use of spectrum. Following the famous E. Noam [1998]'s suggestion, C. Ting, Carol S. Wildman, and J. Bauer [2005] analyzed the comparison of two opposite spectrum use models in a specific service. Along with the technological evolution, we have to deepen our analysis for the license exempted use.

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