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Policy options for the diffusion orbit of competitive innovations—an application of Lotka–Volterra equations to Japan's transition from analog to digital TV broadcasting

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Abstract

Timely introduction of emerging new technologies that substitute for existing technologies is essential for enhancing a nation's international competitiveness in a globalizing economy. However, such substitution is generally slow because of a lack of information about new technologies, fear of substitution and a reluctance to pay the cost of switching to new technologies. While hasty substitution sometimes accomplishes nothing, delayed substitution can result in a loss of national competitiveness. Thus, policy options for the diffusion orbits of competitive innovations are crucial. This is particularly the case with respect to Japan's transition from analog to digital TV broadcasting, as the Japanese government, in order to minimize the impact of a transition delay, is urging a rapid shift from analog to digital TV broadcasting.

In an ecosystem, in order to maintain sustainable development, predator–prey systems demonstrate a sophisticated balance. Given that an ecosystem can be used as a masterpiece system, this sophisticated balance provides suggestive ideas in deciding an optimal orbit of competitive innovations.

This paper analyzes the optimal orbit for Japan's transition from analog to digital TV broadcasting, and on the basis of an application of Lotka–Volterra equations that analyze the sophisticated balance of predator-prey systems, it demonstrates the optimality of the Japanese government's scenario for shifting from analog to digital TV broadcasting.

Keywords: Analog to digital TV broadcasting; Diffusion orbit; Predator-prey systems; Lotka–Volterra equations

1. Introduction

Facing a paradigm shift from an industrial society to an information society that emerged in the 1990s and given the global acceleration of this shift, maximization of the multiplier effects of integrating communications and broadcasting will be decisive for international competitiveness (MPHPT, 2001a). This is particularly the case with respect to Japan, which has been losing institutional elasticity as it moves toward an information society (Watanabe and Kondo, 2001) while boasting advanced terrestrial TV broadcasting networks nationwide with high popularity (MPHPT, 2001b).

While Japan's broadcasters and manufactures have been world pioneers in the development of high-definition TV and digital production technologies, these advancements resulted in the delay in corresponding to the global waves to transfer from analog to digital TV broadcasting (Seel, 1999). This is something similar to " a dilemma of innovation" (Christensen, 1997). Since delayed transfer can result in a loss of national competitiveness, in order to minimize the impact of this transition delay, the Japanese government is urging a rapid shift from analog to digital TV broadcasting. While this is expected to help pave the way toward the integration of communications and broadcasting, it also contains trade off issues typical to innovation in transition. Under such circumstances, optimal control of the diffusion and substitution orbit is crucial as while hasty substitution sometimes accomplishes nothing, delayed substitution can result in a loss of the invaluable opportunity to

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emerge advanced technologies that substitute for old technologies essential for enhancing a nation's international competitiveness (Gruebler, 1998).

Masterpiece of optimal control of the diffusion and substitution orbit can be observed in an ecosystem (Scudo and Ziegler, 1978). In an ecosystem, in order to maintain sustainable development, predator–prey systems demonstrate a sophisticated balance (Hofbander and Sigmund, 1988), and a dynamism leading to this balance provides suggestive ideas in deciding an optimal orbit of competitive innovations.

In the analysis of an ecosystem, the analysis of the dynamic equilibrium of predator–prey systems is one of the fundamental subjects and Lotka–Volterra equations (Scudo and Ziegler, 1978) are popularly used for this dynamic equilibrium (Hofbander and Sigmund, 1988). With the foregoing understanding that predator–prey systems demonstrate a sophisticated balance between competing species thereby maintaining sustainable development, this paper attempts to apply Lotka–Volterra equations for identifying the optimal diffusion orbit of competitive innovations focusing on an assessment of the Japanese government's scenario for shifting from analog to digital TV broadcasting.

Section 2 reviews transition from analog to digital TV system. Section 3 outlines model synthesis for two-dimensional Lotka–Volterra equations under substitution orbit. Section 4 attempts an assessment of the Japanese government's scenario for shifting from analog to digital TV broadcasting. Section 5 briefly summarizes implications for the diffusion orbit of competitive innovations.

2. Transition from analog to digital TV system

Since its inauguration in February 1953, with its conspicuous features such as providing people with real-time scenes that are going on in distant places and allowing viewers in different places to enjoy the same programs, TV broadcasting service rapidly gained its popularity in Japan. The penetration of color TV sets for households in Japan is now about 100 percent, and TV broadcasting has been contributing to the development of Japanese economy and society as a whole (MPHPT, 2001).

With the recent development of digital technology, that enabled effective error correcting, efficient data compression, and manageability of data, the TV broadcasting industry is now facing a radical transitional phase—from analogue to digital system (Noll, 1999).

The digital TV broadcasting is highly expected to realize such advanced services as a variety of information services by data casting, interactive services which allows viewers to participate in TV programs, less deterioration in the quality of screen images, and manageable closed captions (Parker, 1999; MPHPT, 2001b).

Realizing the potential of digital TV broadcasting, the transition from an analog broadcast system to a digital broadcast system has been proceeding worldwide as illustrated in Fig. 1. Fig. 1 demonstrates that in the US, the digital satellite broadcast started in 1994, digital cable broadcast in 1997, and digital terrestrial broadcast in 1998. As for Japan, digital broadcasting by Communications Satellite (CS) started in 1996, Broadcasting Satellite (BS) in 2000, and cable TV in 1999. However, the shift to digital terrestrial broadcasting is lagging behind other countries in the figure and is scheduled to be started in 2003 while Western Europe was somewhat quicker than Japan to move away from its previous arrangements (Hart, 1999).

Though the delay can be partly excused by the existence of excellent analog HDTV technology developed by NHK (the Japan Broadcasting Corporation), it is actually of great concern because the digital terrestrial broadcasting is expected to have a significant positive impact both on society and economy as TV broadcasting is one of the most familiar media with almost a 100 percent penetration rate to Japanese households.

According to the report by the Advisory Committee on Digital Terrestrial Broadcasting issued in October 1998, introduction of the digital terrestrial broadcast is forecasted to create about 212 trillion yen economic effect and about 7 million employment in ten years, expecting the emergence of new services using the digital broadcast characteristics.

However, the transition from analog to digital broadcasting involves huge efforts in Japan. First of all, frequency usage is fairly congested in Japan and changes in channels are inevitable for existing analog broadcasting stations in order to allot frequencies to the digital terrestrial broadcasting. This *analog channel change* considerably affects viewers and broadcasters because the channel change requires adjustments of both receivers and transmitters. MPHPT reports that about 2460 thousand households are estimated to be affected by the channel change.

In addition, a lack of information about new technologies, fear of substitution and a reluctance to pay the cost of switching to new technologies generally result in disturbing smooth transition. This is particularly the case with respect to Japan's switch from analog TV to digital TV because of the high popularity of TV broadcasting to daily life of the majority of Japanese.

Under the dramatic advancement of IT, while hasty transfer sometimes accomplishes nothing, delayed transfer can result in a loss of national competitiveness. Thus, policy options for the optimal shift from the analog to digital TV broadcasting have become a crucial issue for Japan.

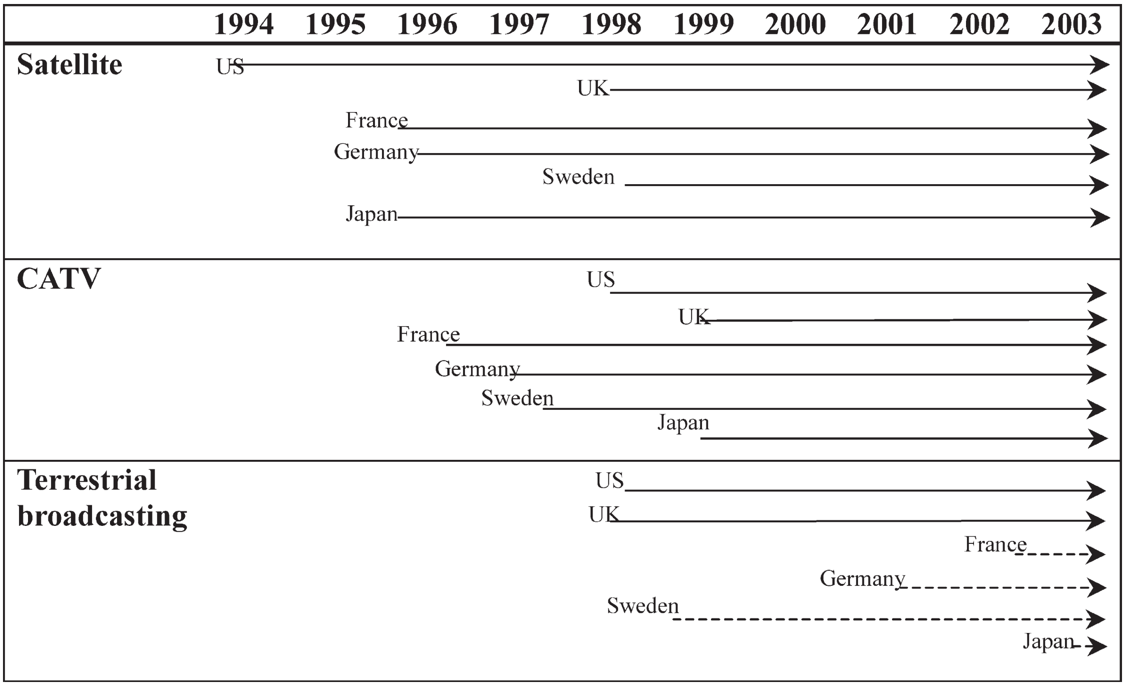

Fig. 1. Trends in digital broadcasting worldwide.

3. Lotka–Volterra equations for predator–prey systems

3.1. The diffusion orbit

Given the rate of growth of species decreases linearly as a function of the density of species, interaction of two competing species x and y can be expressed by the following Lotka–Volterra equations:

$$\dot{x} = x(a-bx-cy) = ax\left(1-\frac{x}{a/b}-\frac{cd}{af}\cdot\frac{y}{d/f}\right) \equiv ax\left(1-\frac{x}{k_x}-\alpha_{xy}\cdot\frac{y}{k_y}\right)$$

$$\dot{y} = y(d-ex-fy) = dy\left(1-\frac{ae}{bd}\cdot\frac{x}{a/b}-\frac{y}{d/f}\right) \equiv dy\left(1-\alpha_{yx}\cdot\frac{x}{k_x}-\frac{y}{k_y}\right) \quad (1)$$

where kx ($= a/b$) and ky ($= d/f$) are carrying capacities, $\alpha_{xy}\left(=\frac{cd}{af}\right)$and $\alpha_{yx}\left(=\frac{ae}{bd}\right)$ are interaction coefficients, and a, b, c, d, e, f are positive coefficients.

Given that the orbit of x and y can be depicted by vector $V(x, y)$, and

$$V(x,y) = eH(x) + cG(y) \quad (2)$$

$$H(x) = \bar{x}\log x-x, G(y) = \bar{y}\log y-y \quad (3)$$

$$\frac{1}{t_n}\int_0^{t_n} x(t)dt = \bar{x}, \frac{1}{t_n}\int_0^{t_n} y(t)dt = \bar{y} \quad (4)$$

where $\bar{x}$ and $\bar{y}$: time average of x and y; and tn: the period of the solution.

From

$$\frac{d}{dt}(\log x) = \frac{\dot{x}}{x} = a-bx-cy$$

It follows by integration that

$$\int_0^{t_n}\frac{d}{dt}\log x(t)dt = \int_0^{t_n}(a-bx(t)-cy(t))dt$$

i.e.

$$\log x(t_n)-\log x(0) = at_n-b\int_0^{t_n}x(t)dt-c\int_0^{t_n}y(t)dt$$

Since $x\ (t_n) = x\ (0)$,

$$a = b\frac{1}{t_n}\int_0^{t_n}x(t)dt + c\frac{1}{t_n}\int_0^{t_n}y(t)dt = b\bar{x} + c\bar{y} \quad (5a)$$

Similarly,

$$d = e\bar{x} + f\bar{y} \quad (5b)$$

while

$$\bar{x} = \frac{af-cd}{bf-ce}$$

and

$$\bar{y} = \frac{bd-ae}{bf-ce}$$

Thus, orbit of x and y can be represented by Eqs. (2), (3), (5a) and (5b).

The derivative of the function $V(x(t),y(t))$ by time t yields

$$\dot{V}(x,y) = \frac{\partial V}{\partial x}\dot{x} + \frac{\partial V}{\partial y}\dot{y} = e\dot{H}(x)\dot{x} + c\dot{G}(y)\dot{y} = e\left(\frac{\bar{x}}{x}-1\right)\{x(a-bx-cy)\} + C\left(\frac{\bar{y}}{y}-1\right)\{y(d-ex-fy)\} \tag{6}$$

From Eqs. (5a) and (5b) we may replace a and d by $b\bar{x} + c\bar{y}$ and $e\bar{x} + f\bar{y}$, respectively. This yields

$$\dot{V}(x,y) = e(\bar{x}-x)(b\bar{x} + c\bar{y}-bx-cy) + c(\bar{y}-y)(e\bar{x} + f\bar{y}-ex-fy) = be(x-\bar{x})^2 + 2ce(x-\bar{x})(y-\bar{y}) + cf(y-\bar{y})^2 \tag{7}$$

By converting coordinates from (x,y) to (X,Y) where $X = x-\bar{x}$ and $Y = y-\bar{y}$, and twisting the axis of converted coordinates to (X',Y'), Eq. (7) can be developed to an elliptical orbit (in cases when $bf>ce$) or a hyperbola (in cases when $ce>bf$) as expressed in Eqs. (8) and (9), respectively.[1]

$$\frac{X'^2}{\left(\sqrt{\frac{\dot{V}(x,y)}{\lambda_1}}\right)^2} + \frac{Y'^2}{\left(\sqrt{\frac{\dot{V}(x,y)}{\lambda_2}}\right)^2} = 1 \text{ when } bf > ce \tag{8}$$

$$\frac{X'^2}{\left(\sqrt{\frac{\dot{V}(x,y)}{\lambda_1}}\right)^2} - \frac{Y'^2}{\left(\sqrt{\frac{\dot{V}(x,y)}{-\lambda_2}}\right)^2} = 1 \text{ when } ce > bf \tag{9}$$

where

$$\lambda = \frac{be + cf + \sqrt{(be-cf)^2 + 4c^2e^2}}{2} \tag{10}$$

$$\lambda_2 = \frac{be + cf - \sqrt{(be-cf)^2 + 4c^2e^2}}{2} \tag{11}$$

The angle θ to be twisted from (X,Y) to $(X'Y')$ is expressed by the following equations:

$$\cos\theta = \frac{1}{\sqrt{1 + \frac{\omega^2 + 2c^2e^2 - \omega\sqrt{\omega^2 + 4c^2e^2}}{2c^2e^2}}} \tag{12}$$

$$\sin\theta = \frac{1}{\sqrt{1 + \frac{2c^2e^2}{\omega^2 + 2c^2e^2 - \omega\sqrt{\omega^2 + 4c^2e^2}}}} \tag{13}$$

where $\omega = be-cf$.

The general image of an elliptical orbit under certain $\dot{V}$ condition (in cases of $bf > ce$) can be illustrated as in Fig. 2.

3.2. Orbit for substitution

Provided that a species x is a proceeding species and, later on, a species y appears and steadily succeeds x, and finally substitutes for x, an orbit for y substitute for x can be developed as follows:

A condition of the initial stage just before the substantial emergence of species y can be depicted as

$$\frac{\partial \dot{V}}{\partial y} = 0$$

i.e.

$$\begin{aligned} \frac{\partial \dot{V}}{\partial y} &= 2ce(x-\bar{x}) + 2cf(y-\bar{y}) = 0 \\ e(x-\bar{x}) + f(y-\bar{y}) &= 0 \\ ex + fy &= e\bar{x} + f\bar{y} = d \end{aligned} \tag{14}$$

Eq. (1) suggests that this is equivalent to

$$\frac{\dot{y}}{y} = 0$$

Similarly, a condition of the stage when y totally substitutes for x can be depicted as

$$\frac{\partial \dot{V}}{\partial x} = 0$$

i.e.

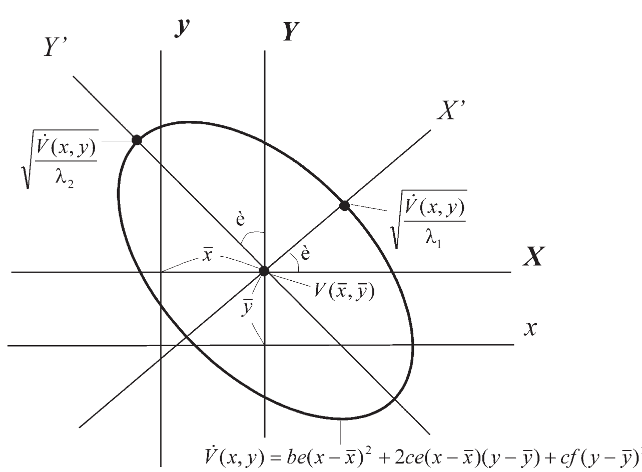

Fig. 2. General image of an elliptical orbit.

[1] See the mathematical details in Hirsch and Smale (1974).

$$bx + cy = b\bar{x} + c\bar{y} = a \qquad (15)$$

This is equivalent to

$$\frac{\dot{x}}{x} = 0$$

The isoclines of the above dynamism can be illustrated as in Fig. 3.

Under the condition that $x,y>0$ (hence $\bar{x},\bar{y} > 0$) and given the case when y succeeds x, $d/e>a/b$ as well as $a/c>d/f$ and hence $b/e>a/d>c/f$ conditions should be satisfied which lead to bf/ce.

These conditions imply the followings with respect to an orbit of two-dimensional Lotka–Volterra equations for y substitutes for x:

(i) The orbit follows an elliptical orbit,
(ii) Relationship between x and y is the case of stable coexistence, and
(iii) Equilibrium point of this coexistence $V(x,y) = V(\bar{x},\bar{y})$.

Under the above dynamism, given the situation when y totally substitutes for x at the final substitution stage, $\bar{x} = 0$ and hence $a/c=d/c$ should be satisfied which imply the followings with respect to an orbit in the period starting from the initial stage when y first invades into x ($\partial\dot{V}/\partial y = 0$) and ending final substitution stage when y totally substitutes for x ($\partial\dot{V}/\partial x = 0$):

(i) The orbit $V(x,y)$ moves from $V(d/e,0)$ to $V(0,a/c)$, and
(ii) The interaction coefficient α_{xy}=1 (see eq. (1)) while α_{yx}=ae/bd)<1.

(This implies y's invasion power into x territory is stronger than that of x into y.)

Thus, isoclines for two-dimensional Lotka–Volterra equations under substitution orbit can be illustrated as in Fig. 4.

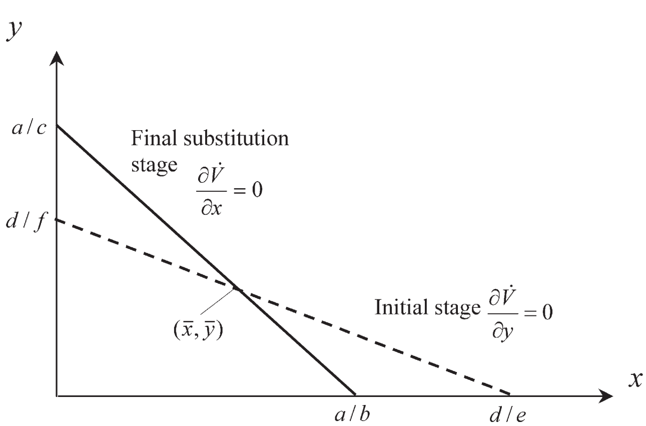

Fig. 3. Isoclines for two-dimensional Lotka-Volterra equations.

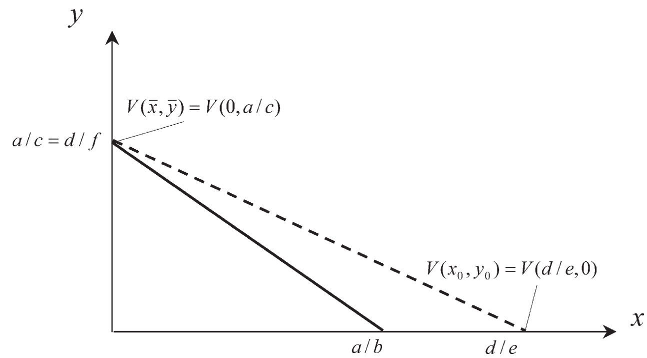

Fig. 4. Isoclines for two-dimensional Lotka–Volterra equations under substitution orbit.

As the general two-dimensional game suggests, after a certain game, $\dot{V}$ stagnates steadily and reaching $\dot{V} = 0$,[2] by synchronizing Figs. 1 and 3, a general image of an elliptical orbit for substitution can be illustrated as in Fig. 5.

Under the condition when $V(x,y)$ shifts to the state of equilibrium with respect to y substitution for x with certain constant pace,[3] an orbit of Fig. 5 can be projected to respective time trends of x and y as illustrated in Fig. 6.

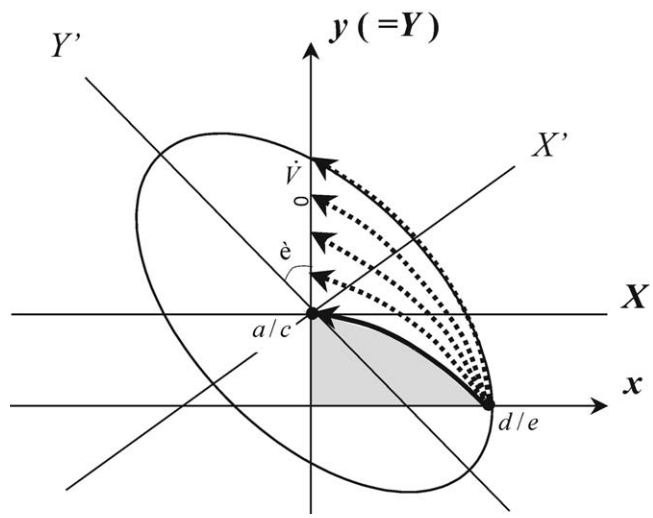

Fig. 5. General image of an elliptical orbit for substitution.

[2] This implies the state of equilibrium with respect to y substitution for x, and does not imply the termination of y or x increase.

[3] By differentiating $\dot{V}(x,y)$ in Eq. (7) by time t we obtain

$$\frac{d\dot{V}(x,y)}{dt} = -2\{ex(a-bx-cy)^2 + cy(d-ex-fy)^2\} \leq 0$$

$$\frac{d\dot{V}(x,y)}{dt} = 0 \text{ when } V(x,y) = V(\bar{x},\bar{y})$$

This suggests that an orbit $V(x,y)$ shifts towards the equilibrium point $V(\bar{x},\bar{y})$ with a pace of $g(\equiv -2\{ex(a-bx-cy)^2 + cy(d-ex-fy)^2\})$. Given a constant g, $\dot{V}(x,y)$ can be depicted as $\dot{V}(x,y) = \dot{V}_0(x,y)e^{gt}$ where $\dot{V}_0(x,y)$ indicates initial change.

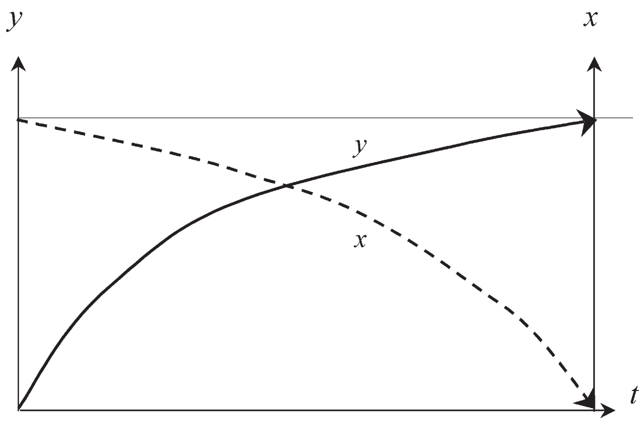

Fig. 6. Trend in x and y under y substitutes for x condition.

Fig. 7 compares orbits between exponential function, logistic (epidemic) function and Lotka–Volterra function.

Looking at Fig. 7 we note that the Lotka–Volterra orbit displays concave and higher growth rate at the initial stage. This is considered due to the maturity of growth condition, because the substitution proceeds for existing competitive species (x) under pure competition without any institutional constraints.

4. Assessment of the scenario for shifting from analog to digital TV broadcasting

Considering the huge impact of the transition from digital to analog terrestrial broadcasting, the Ministry of Public Management, Home Affairs, Posts and Telecommunications (MPHPT), together with broadcasters, has been making efforts towards introducing the digital terrestrial TV broadcasting while gradually solving issues around the transition.

In November 1997, MPHPT set up the Advisory Committee on Digital Terrestrial Broadcasting involving members from a broad range of industries and academy as well as nonprofit organizations in order to build a vision of the digital terrestrial broadcasting in Japan. The Committee submitted a report in October 1998 (Advisory Committee on Digital Terrestrial Broadcasting (1988)) indicating that the digital terrestrial TV broadcasting is expected to be inaugurated by the year 2003 in Kanto, Chukyo, and Kinki areas (the three largest metropolitan areas), and by the year 2006 in other areas in Japan.

In order to implement the digital terrestrial TV broadcasting based on the vision described in the Report, commercial broadcasters, NHK, and MPHPT established the Joint Study Committee concerning Digital Terrestrial Broadcasting in November 1999. In June 2001, after an intensive nineteen months study, the Committee drafted the digital channel plan and changes in analog channels as well as detailed measures to accomplish the analog channel change with minimum negative effects on both viewers and broadcasters.

Based on these cooperative efforts, MPHPT formally set a target date of the year 2003 for digital terrestrial broadcasting to start in Kanto, Chukyo, as well as Kinki areas, the year 2006 in other areas in Japan, then the year 2011 for the analog terrestrial TV broadcasting to terminate, and enforced revised Radio Law together with necessary ministerial ordinances for the transition in July 2001.

Fig. 8 illustrates possible orbit for shifting from analog to digital TV in Japan by comparing government's scenario, an orbit projected by two-dimensional Lotka–Volterra equations under substitution as analyzed in Section 3, and general projection by logistic growth. As for the government's scenario, since the exact cover rate is not given at this stage, we assumed that only key stations of each broadcasting area start digital broadcasting in each target year, and used household coverage from NHK Integrated Technology (2001), which indicates about 45% for the year 2003 and about 75% for 2006, respectively.

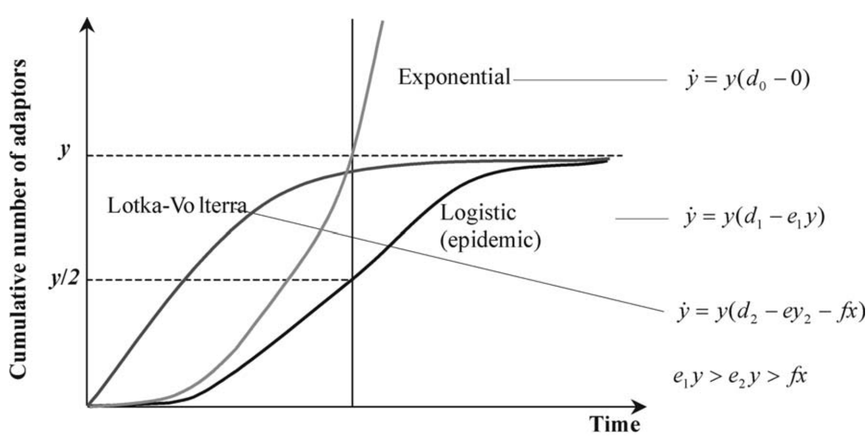

Fig. 7. Comparison between exponential function, logistic function and Lotka–Volterra function.

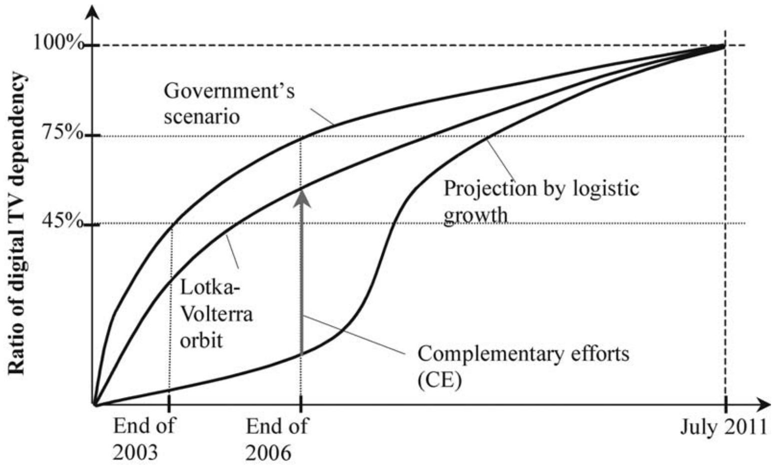

Fig. 8. Japanese government's scenario for shifting from analog to digital TV broadcasting.

It is generally predicted that diffusion and substitution of digital TV broadcasting follows the similar substitution as dissemination orbits of monochrome TV sets and color TV sets as demonstrated in Fig. 9. Looking at Fig. 9 we note that diffusion and substitution orbit of Japan's color TV sets followed a typical logistic growth. The bottom line in Fig. 8 demonstrates a projection given the diffusion and substitution of digital TV following a similar orbit as is generally expected. This is because of a lack of information about new technologies, fear of substitution and a reluctance to pay the cost of switching to new technologies. In addition, the barriers to prompt shift to digital TV within broadcasters and the manufacturing industry cannot be overlooked (Lundgren, 1993). However, given the logistic growth, ratio of digital TV dependently reaches 50% in 2007 which is significant delay than estimated government's scenario: 45% by the end of 2003 and 75% by the end of 2006.

As analyzed in Fig. 7, contrary to the logistic growth orbit, Lotka–Voterra orbit demonstrates a convex orbit with higher dependency on digital TV from the early stage of its introduction. As reviewed in Section 3, Lotka–Volterra orbit represents substitution and diffusion orbit under the conditions of pure competition between competing species just by functions of respective species with fair information, without fear of substitution, a reluctance to pay the cost of switching, and barriers within the manufacturing industry.

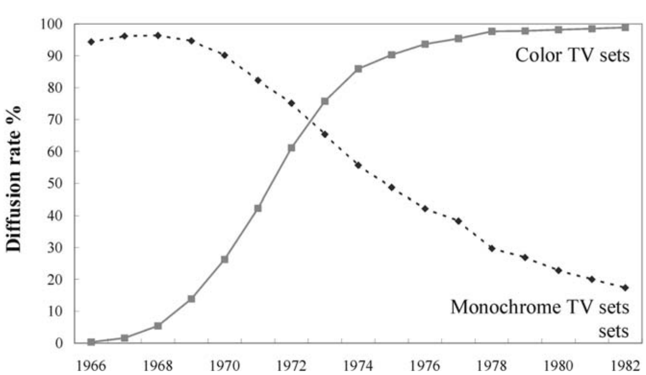

Fig. 9. Dissemination orbit of TV sets in Japan. Source: Consumer confidence survey, Cabinet Office, Government of Japan.

Therefore, in order to accomplish the government targets, factors separating the two orbits, logistic growth orbit and Lotka–Voterra orbit, should be removed. Given the fact that the TV broadcasting can be successful when three factors being arranged, that is, infrastructure for broadcasting, attractive TV programs, and existence of viewers, complementary efforts are necessary to remove the gap. This is equivalent to complementary efforts (CE) in Fig. 8. For example, broadcasters and MPHPT have been cooperatively making efforts to publicize the merits of digital TV broadcasting to mitigate the fear of substitution of the general public. As for financial supports, the Japanese government decided to invest 12.3 billion yen (110 million US $) for the cost of the analog channel change in fiscal 2001.

The level of government's scenario for shifting from analog to digital is slightly higher than the level represented by Lotka–Volterra orbit as illustrated in Fig. 8. This is due to the fact that broadcast stations with larger coverage are often constructed first and broadcast stations with smaller coverage are constructed in later stages, which leads to the target trajectory rising slightly higher than the level of Lotka–Volterra orbit.

Above comparative assessment suggests that given the government target to accomplish a rapid shift from analog to digital TV within a limited period (between 2003 and 2011), shifting scenario should be accelerated in line with a slightly higher level of Lotka–Voterra orbit. For this, every effort should be accelerated in removing factors separating the two orbits between logistic growth orbit and Lotka–Volterra orbit.

5. Conclusion

In light of the increasing significance of timely introduction of emerging new technologies that substitute for existing technology for enhancing a nation's international competitiveness in a globalizing economy, this paper, focusing on Japan's transition from analog to digital TV broadcasting, analyzes policy options for the diffusion orbit of competitive innovations.

With an understanding that predator–prey systems in an ecosystem demonstrate a sophisticated balance between competing species thereby maintaining sustainable development, an application of Lotka–Volterra equations that analyze these sophisticated balance in an ecosystem, is conducted for assessing the Japanese government's scenario for shifting from analog to digital TV broadcasting.

On the basis of the comparative assessment by using synthesized two dimensional Lotka–Volterra equations for substitution and general logistic growth equation, following findings are obtained:

(i) Lotka–Volterra equations for substitution are useful for identifying an optimal orbit of competitive innovations.
(ii) Given the government target to accomplish a rapid shift from analog to digital TV broadcasting within a limited period, shifting scenario should be accelerated in line with a slightly higher level of Lotka–Voterra orbit.
(iii) In order to accomplish this orbit, every effort should be accelerated in removing factors separating the two orbits between logistic growth orbit and Lotka–Volterra orbit including:
a. A lack of information about digital TV technologies,
b. Fear of substitution and a reluctances to pay the cost of switching from analog to digital TV, and
c. Barriers to prompt shift to digital TV broadcasting within broadcasters and the manufacturing industry.
(iv) In addition, in order to accelerate such shift with a higher pace of Lotka–Volterra orbit, with the understanding that IT's specific functionality is formed through dynamic interaction with institutional systems (Antonelli, 1999), efforts should be focused on maximizing IT's self-propagation behavior.

Given the global paradigm shift from an industrial society to an information society, maximization of the multiplier effects of integrating communications and broadcasting will be decisive for international competitiveness. This is particularly the case with respect to Japan, which has been losing institutional elasticity as it moves toward an information society while also depending greatly on TV broadcasting. Shifting to digital broadcasting is thus important.

Considering that while hasty shift sometimes accomplishes nothing, delayed shift can result in a loss of national competitiveness, identification of the optimal diffusion and substitution orbit is essential, thus, the foregoing approach is very useful in identifying policy options for the diffusion orbit of competitive innovations.

Further empirical analyses taking a variety of innovations are expected for broader application of this approach.

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