11 Switching to digital television: business and public policy issues

NORBERT MAIER AND
MARCO OTTAVIANI

Abstract

This paper investigates the incentives of broadcasters to use subsidies and sunset dates to affect the viewers' decisions to switch from analog to digital television. It is shown that when viewers have identical preferences for digital television, it is never optimal for the broadcaster to subsidize just a fraction of viewers. When instead viewers have different valuations, broadcasters might want to induce viewers to switch gradually. Implications for welfare and effects of universal service requirements on equilibrium outcomes are also discussed.

1 Introduction

Television is currently undergoing a major transformation. The old analog standards are being replaced by new digital standards, widely perceived to be technologically superior. Digital television (DTV) makes possible the delivery of a signal virtually free of interference, with better image and audio quality and improved interactivity. In addition, data compression technologies allow for a more efficient use of bandwidth.[1] Not only does DTV provide the flexibility of increasing the quality and number of channels, but it also frees up bandwidth for alternative uses.[2]

We thank Victor Stango for guidance, Jozsef Molnar for research assistance, and the UK Economic and Social Research Council for financial support (research grant: RES-000-22-0385).

[1] With the same bandwidth required for a single analog channel, the new digital technology is capable of transmitting five to ten digital channels of comparable ("standard") quality. Alternatively, that bandwidth can be used to deliver high definition television with movie-quality picture and sound.

[2] We do not discuss the different standards for digital television. We refer to Farrell and Shapiro (1992) for an early account of the development of the Advanced Television Systems Committee (ATSC) standard in the United States, and to Grimme (2002) for a discussion of the development of the digital video

These benefits can be realized only if broadcasters as well as viewers are willing to invest in the new technology. On the supply side of the market, broadcasters need to invest in digital transmission equipment and make content available on the digital platform. On the demand side, viewers must be able to receive the digital signal either with a decoder (also called a *set top box*) or an integrated DTV set. In addition, costs and benefits are unevenly distributed across viewers and broadcasters and vary depending on the television delivery platform.

Policymakers in the United States and Europe have taken a keen interest in the transition process.[3] In this paper, we explore the main challenges to the transition process to DTV. In particular, we investigate viewers' incentives for switching to DTV, and how these incentives depend on the actions of broadcasters and policymakers.

1.1 Television market

In most industrialized countries, viewers can opt for free-to-air (FTA) television or pay television. Traditionally, FTA television is an analog technology that is transmitted terrestrially by radio waves and can be received through a rooftop aerial. For technical reasons, the part of the radio spectrum used for terrestrial transmission is limited, so only a small number of channels can be broadcast with the analog technology.[4]

In most countries, almost the entire population has access to FTA television, with the exception of those living in very remote areas. In most European countries, FTA public channels are mainly financed by

broadcasting (DVB) standard in Europe. According to Hart (2004) and Galperin (2004), the transition to DTV so far is the result of the interplay of economic and political factors. In this paper, we take the political factors as given and focus mostly on the normative economic implications.

[3] For information on the US policies, see Congressional Budget Office (1999); and for information on the EU policies, see Commission of the European Communities (2002, 2003).

[4] Terrestrial television employs part of the very high frequency (VHF, between 30 and 300 megahertz [MHz]) and ultra high frequency (UHF, between 300 MHz and 3.0 gigahertz [GHz]) bands. In North America, terrestrial television operates on channels 2 through 6, which use the VHF-low band (54–88 MHz); on channels 7 through 13, which use the VHF-high band (174–216 MHz); and on channels 14 through 69, which use the UHF television band (470–806 MHz). In the United Kingdom, terrestrial television operates exclusively on the UHF band, since VHF transmission was discontinued in 1985.

a special tax (the "license fee") on the ownership of a television set. In addition, there are FTA commercial channels, financed mostly through advertising revenues. In the United States, there are no publicly owned channels and no license fee, and local FTA commercial broadcasting stations are typically affiliated to national networks.[5] Although often licensed to broadcasters, the terrestrial spectrum is owned mostly by governments.[6]

Pay television operators mainly broadcast through cable and satellite.[7] Cable operators transmit their signals through a physical network of underground cables, directly connecting to viewers' homes. Satellite broadcasters send the signal to viewers through a satellite. Viewers equipped with a parabolic antenna (or dish) can then receive the signal provided there is a clear line of sight from the dish to the broadcast satellite. Cable and satellite technology can be used to broadcast many more channels than traditional terrestrial technology.

In addition to the FTA channels, pay television platforms typically offer a large number of other channels bundled in a menu of packages sold at different monthly subscription fees.[8] Platforms compete in the

[5] US broadcasting stations use radio spectrum frequencies licensed by the Federal Communications Commission in exchange for the promise to deliver socially valuable content. In addition, there are some public broadcasting stations financed by viewers' contributions and public subsidies. See Owen and Wildman (1992) for an overview of the US television industry and Levy et al. (2002) for a discussion of terrestrial television in the United States.

[6] Since Coase (1959), economists have argued in favor of privatization of the radio spectrum, without restrictions for its use. See Cramton et al. (1998) for how the terrestrial spectrum could be privatized, even if encumbered by terrestrial broadcasters. See Rosston and Hazlett (2001) for the advantages of eliminating barriers to the development of secondary markets for spectrum.

[7] In addition, digital subscriber line technology allows high-bandwidth data transmission on a conventional residential telephone line. Despite its limited penetration to date, this technology has a bright future. Both digital subscriber line technology and fiber optics to the home allow for one-to-one transmission of programs and therefore the delivery of video on demand. See Hazlett (2001) for a discussion of the superiority of wired to wireless television in the long term. We refer to Katz (2003) for a discussion of the likely impact of Internet television on the broadcasting industry.

[8] Pay television broadcasters typically offer packages of basic programs that must be taken by all subscribers as well as premium programs (such as major sport events and latest Hollywood films) for a supplementary fee. See Cave and Crandall (2001) on the importance of sports rights for television.

market for channels,[9] and channels compete in the market for television content as well as for advertising.[10]

Viewers make long-term decisions of which platform and package to adopt, depending on the corresponding one-off cost of the equipment and the monthly subscription fees. Using their remote control, viewers can then choose to watch a program from the channels to which they subscribe.

The transition to digital technology applies to all three transmission platforms (terrestrial, cable, and satellite).[11] In this paper, we focus on the viewers' long-term decisions of which platform to adopt, and in particular on their incentives to migrate from the analog to the corresponding digital version of any given platform.

1.2 Digital transition

The costs and benefits of DTV are unevenly distributed among the different market participants. This makes the transition process difficult, especially in the absence of transfers among the parties involved. The transition to DTV is further complicated by the interplay of two peculiar features of television, one economic and the other political.

First, television is "nonrival" in consumption, that is, a viewer receiving the television signal on either platform (be it terrestrial, cable, or satellite) does not preclude other viewers from receiving the same signal. The nonrival nature of broadcasting means that broadcasting has only a fixed cost component, and, as a result, serving only one viewer or all the viewers imposes the same costs on the broadcaster for each specific technology (analog and digital). This means that operating both analog and digital technology at the same time

[9] Some platform operators (e.g., the UK satellite operator BSkyB) are vertically integrated and act as producers as well as distributors of some television channels, especially those with premium programs. Competition among platforms and broadcasters then takes place in a number of stages. First, the content is obtained and the channels are produced in the upstream market. Second, access to the channels is resold to competing platform operators. Third, platform operators compete for viewers' subscriptions. See Armstrong (1999) and Harbord and Ottaviani (2001).

[10] See Anderson and Coate (2005) for the two-sided nature of the television market, and, more generally, Rochet and Tirole (2003) and Armstrong (2004) for the economics of two-sided markets.

[11] Adda and Ottaviani's (2005) Table 2 reports the progress of digitization by platform across EU countries.

duplicates the costs of broadcasting. To implement the smoothest transition to digital, platform operators must address the following business policy question: *Given the nonrival nature of broadcasting, which technology should be operated at any period and which subsidy system can most effectively support this choice*?

Second, governments consider access to information through television the right of every citizen. This universal access requirement represents a constraint, especially for terrestrial television used for FTA broadcasting.[12] Due to this constraint, the terrestrial analog signal cannot be switched off unilaterally. In particular, the US and the UK governments have announced that they do not intend to switch off the analog terrestrial signal until a sufficiently high (respectively, 85% and 95%) fraction of viewers have already switched to digital. Therefore, the government, as a platform operator, is facing the following public policy question: *Given the nonrival nature of broadcasting technology, as well as the universal service requirement, which technology should be operated at any period and which subsidy system can most effectively support this choice*?

The paper proceeds as follows. In the remainder of this section, we describe our approach to analyzing the effects of the nonrival nature of broadcasting technology and the universal access requirement for the transition to digital television. Next, in Section 2, we introduce the basic static model and present our results. We investigate viewers' optimal choice of platforms as a function of their preference parameters for digital service and derive our main insights for business policy. In Section 3, we present the dynamic extension of our model and discuss the timing issue. In Section 4, we conclude by identifying the main challenge imposed by the universal service obligation.

1.3 Our approach

To illustrate the simple economics of the effects of the nonrival nature of broadcasting technology and the universal access requirement for the transition to digital television, we consider the case of a *single*

[12] Serving residents of remote areas is often not commercially viable for private operators. Governments have indirectly subsidized terrestrial broadcasters in a number of ways, such as the license fee and the allocation of spectrum at subsidized rates. In the telephone sector, governments have instead used incentive schemes to create competition among universal service providers (see Laffont and Tirole 2000 and Riordan 2002).

platform in isolation. In our stylized model, the platform can broadcast a given content by analog and/or by digital technology, while the viewers can choose which standard to adopt among those available. Within the model, we analyze the viewers' responses to different policies chosen by the platform.

As was previously explained, in reality, many platforms compete with each other and face different costs and benefits of switching to digital broadcasting. Nevertheless, our model ignores the interaction between different platforms. This simplification allows us to concentrate on each platform's decision of which standards and subsidies to offer and consequently on their effect on viewers' incentives to migrate to digital.[13]

Due to the nonrival nature of broadcasting technology, transmission of each technology involves only a fixed cost. This cost is lower for the digital than for the analog technology, because of the reduced bandwidth requirement for digital transmission. We assume that the platform collects revenues from advertisers only and that the amount of these revenues is proportional to the number of viewers.[14] For a given number of viewers, the platform's only concern is to minimize the cost of transmission. The platform operator has the following choices at any period: (1) operate the analog signal only, (2) launch the digital signal without switching off the analog, and (3) launch the digital while switching off the analog.

We are interested in analyzing the incentives for viewers to migrate from analog to digital. Viewers derive a positive utility from the analog service and obtain an additional utility from DTV. To capture the heterogeneity of viewers' preferences, we allow for two types of viewers, depending on how much they value the benefits of DTV. *High-type viewers* have a higher valuation of the benefits of DTV than *low-type viewers*.

Viewers initially have access to the analog signal and must decide whether to stay with analog, migrate to digital, or opt out of television altogether. To switch to the digital service, both types of viewers must incur the same switching cost, which is comprised of the cost of the digital set top box and the inconvenience of installing it. The choice of each viewer clearly depends on the switching cost, as well as his or her preferences for the different options available.

[13] We refer to Adda and Ottaviani (2005) for an empirical analysis of viewers' adoption choices in the presence of coexisting platforms.

[14] Our model mainly captures the features of FTA terrestrial broadcasting, but can be extended to cover the case of pay television.

1.4 Our findings

We use a static version of the model both to analyze the platform operator's decision regarding which technology to use and to derive the basic features of the optimal subsidies used to induce the viewers to switch.

Subsidies

Since viewers derive a higher utility from analog than from no television, they need to be offered a higher subsidy to switch to digital if analog is also available. Therefore, it is always optimal for the platform operator to switch off the analog when it launches the digital signal, as this reduces the size of the subsidies that must be offered to the viewers.

To encourage the viewers to switch to digital, the platform operator may decide to offer subsidies to the viewers. The platform operator may decide to offer a subsidy to a group of viewers only. In this case, however, subsidized viewers would switch to digital, while unsubsidized viewers would stay with analog (if it is not switched off) or opt out of television altogether.

If the unsubsidized viewers stay with analog, the two technologies are operated simultaneously, and the platform operator would be better off by not giving a subsidy to anyone at all in order to save on both the cost of transmission and the amount spent on subsidies.

If, instead, unsubsidized viewers opt out of television, the net profit per viewer switched to digital (advertising revenue minus the amount of subsidy paid) is positive, so it is profitable to induce all the viewers to switch to digital by the same subsidy. As a result, it is never optimal to offer a subsidy to a group of viewers only.

Welfare

We compare the switching pattern resulting under laissez faire with the first best and find that both excess and insufficient switching can occur in equilibrium. On the one hand, excess switching results from the fact that the platform operator cannot charge viewers for the television services but can subsidize the switch to digital. Note that the platform operator cannot extract all the viewers' surplus under analog broadcasting, but it can extract their entire surplus by switching off the analog signal and subsidizing their switch to digital. As a result, in some cases the platform operator might induce a forced migration to digital more often than would be socially efficient.

On the other hand, private information about viewer's types might lead to insufficient switching. Assume that in the first-best setting both the low and the high-type viewers switch to digital. In a world of incomplete information, however, the high subsidy offered to low-type viewers must also be given to the high-type viewers. This raises the platform operator's costs of switching to digital so much that the platform operator may decide to stick to analog broadcasting, even if switching to digital would be socially efficient.

Sunset date

To address the optimal timing of the switch to digital, we extend the model to a simple dynamic framework with two periods. We allow the platform operator to commit *ex ante* to any policy. A late subsidy seems undesirable since it might induce some viewers who otherwise would have adopted early to delay adoption and cash in on the subsidy.

We show that the platform operator may find it optimal to offer a late subsidy that will be taken only by the low-type viewers. High-type viewers will switch earlier without waiting for a subsidy. This extension provides some discrimination among viewers and might alleviate the problem of insufficient switching described in the static model. The equilibrium outcome explains why analog and digital technologies are sometimes operated jointly during the transition phase, with viewers choosing to switch to digital at different times. Although the operator prefers a swift transition to digital if viewers are homogeneous, delays in the transition can be optimal for the operator if viewers have heterogeneous preferences for DTV.

Universal access

Returning to the static version of the model, we then investigate the implications for public policy of the universal access requirement. As the analog signal can be switched off only if a sufficiently high fraction of viewers migrate, viewers' expectations about the actions of the other viewers become relevant for the equilibrium outcome. Depending on these expectations, multiple equilibria can arise.

Consider the case in which each individual viewer thinks that only a few of the others intend to switch so that the criterion for switching off will not be met. With such pessimistic expectations about the others' switching behavior, it is indeed optimal for the individual viewer not to switch. As a result, the viewers will not switch, the criterion will not be met, and the platform operator will not switch off the analog service, thereby confirming the initial expectations. A similar logic applies for the case when each viewer has optimistic expectations about the others' switching. In this second equilibrium, all viewers switch to digital and the platform operator can successfully switch off the analog service. We give conditions for multiple equilibria to arise.

2 Business policy

In this section, we build a simple static model to analyze viewers' incentives to switch to digital service. We derive the policy adopted by the platform operator and evaluate the resulting switching patterns from the social point of view.

2.1 Static model

There is one platform operator and N viewers. The platform can broadcast a given content by analog and/or digital technology. The viewers can choose to adopt either standard or opt out of television.

Broadcasting involves a fixed transmission cost, equal to C_A for analog and C_D for digital signal. Due to the nonrival nature of broadcasting, this cost is independent of the number of viewers reached by a particular technology. Because of the smaller spectrum requirement of digital broadcasting, we assume that $C_D < C_A$.

The platform derives revenues only from advertising, in proportion to the number of viewers. In particular, r units of advertising revenue are collected for each viewer. For a given number of viewers, the platform then aims at minimizing the transmission cost.

The preferences of a given viewer are described as follows: The utility of no television is normalized to zero. The utility of viewing analog television is equal to $a > 0$. The utility of viewing DTV is $a + b$, so the incremental utility derived from DTV is equal to b.[15] To switch to digital, the viewer must pay the switching cost s.

Initially, viewers receive the analog signal and the platform operator has the following choices: (1) operate the analog signal only, (2) launch

[15] In the case of pay television, b would instead denote the valuation net of the subscription fee.

the digital signal without switching off the analog, and (3) launch the digital while switching off the analog.

In the rest of the section, we shortly review the viewers' decisions when the analog signal is and is not switched off. We then analyze the platform operator's optimal policy and evaluate it from the welfare perspective.

2.2 Viewers' switching decisions

Suppose that analog, digital, and no television are made available. Since utility from analog television is positive, it is never optimal for the viewer to opt for no television. Staying with analog results in payoff $u_A = a$, while migrating to digital yields $u_D = a + b - s$. Viewers prefer to switch to digital whenever the benefit from digital exceeds the switching cost, that is, when $b \geq s$.

If, instead, the platform operator switches off the analog signal when launching the digital, the viewer can choose only between digital service and no television. Not migrating to digital television gives a payoff equal to 0, instead of a, while migrating to digital gives the same payoff. Therefore, viewers will switch to digital broadcasting whenever $a + b - s \geq 0$, or equivalently, when $b \geq s - a$. Clearly, the threshold for switching to digital is lower in this second case.

Next, what is the impact of a subsidy equal to S on the viewers who switch to digital? Such a subsidy makes viewers more willing to switch by increasing the utility from switching to digital to $u_D = a + b - s + S$. The condition for switching then becomes $a + b - s + S \geq a$, or $b \geq s - S$.

2.3 Operator's policy

We now address the problem of the platform operator's technology choice and the business policy supporting that choice. As was previously discussed, the platform operator must decide which technology to operate and which subsidization policy to adopt. The optimal business policy then includes a pricing and a subsidy strategy.[16]

Assume that the viewers differ in their incremental valuation of the digital service. In particular, a fraction ρ of the population has a low valuation, b^L, while the remaining fraction $(1 - \rho)$ has a high valuation, $b^H > b^L$.

[16] While we focus on FTA broadcasting, subsidies alter the viewers' valuations. This suggests that our analysis can be extended to the case of pay television.

//FS2/CUP/3-PAGINATION/SAPP/2-PROOFS/3B2/052186450XC11.3D 355 [345–371] 31.7.2006 4:25PM

The platform operator knows the distribution of viewers' preferences in the population, but cannot observe the type of each particular viewer. (Alternatively, if the platform operator can observe each individual viewer's type, then it cannot discriminate directly among the viewers.) Note that in this incomplete information environment, the platform operator cannot use subsidies to discriminate even indirectly among the different types of viewers.[17]

The objective of the platform operator is to select which technologies to operate and to design a subsidy scheme to support this choice when necessary. Observe that the lower operating costs make digital broadcasting more attractive for the platform operator. Therefore, the platform operator may want to offer subsidies to encourage the viewers to switch to DTV.

In two extreme cases, subsidies are irrelevant. First, viewers are willing to switch to digital even without a subsidy when they have a strong preference for digital (i.e., the value of b is relatively large compared to the value of s), so that the platform operator can switch off the analog signal without subsidies. Second, when viewers' preferences for digital are extremely weak and the costs of switching are very high, the platform operator must stay with the analog signal because the subsidies inducing viewers to switch would be too expensive.

Therefore, it is more interesting to focus on the intermediate case between these two extremes, namely, the one in which viewers would not switch by themselves but can be induced to switch by a subsidy. Will the platform operator offer a subsidy to all the viewers or to only a fraction of them? Should the operator switch off the analog signal once it launches digital broadcasting or not? The following proposition answers these questions:

Proposition 1

The optimal policy adopted by the platform operator has the following features:

a. It is never optimal to subsidize only a fraction of a particular type of viewers.
b. Once digital broadcasting is launched, it is optimal to switch off the analog signal.

[17] In the dynamic framework of Section 3, intertemporal discrimination becomes possible instead.

To present the intuition for Proposition 1a, we consider two cases in turn. In the first case, assume that the platform operator cannot switch off the analog signal when some of the viewers would prefer it to the digital signal. If the platform operator chooses to offer a subsidy to only a part of the viewers, these viewers are induced to switch to digital, so that both digital and analog technologies must be operated at the same time. Compared to using only analog, this choice increases the platform operator's costs by two items, namely, the operating cost of the digital technology and the amount of subsidies paid. As a result, the platform operator will never choose this option.

Second, consider what happens when the platform operator can unilaterally switch off the analog signal once it has launched the digital signal. In particular, the platform operator can implement two subsidization policies: one is to offer subsidies that would induce only the high-type viewers to switch, and another one that would induce low-type viewers to switch as well.[18] For such plans to be profitable, the advertising revenues generated by the number of viewers having chosen digital to no television after being offered a subsidy must be larger than the cost of these subsidies. Because both these revenues and costs are the same for each targeted viewer, if their difference is positive, it is optimal to extend that subsidy to the entire target group. If the difference is negative, offering no subsidies at all becomes optimal. Therefore, offering a subsidy to only a subset of the viewers of a particular type is never optimal.

The optimality of switching off the analog signal once the digital is launched is due to the following two facts. First, if it is in the platform operator's interest to offer a subsidy to viewers, switching off the analog signal allows the operator to induce viewers to switch with a smaller subsidy, as the viewers' threshold for switching is reduced when the analog signal is not available. Second, the platform operator may find it optimal to operate both technologies and not give any subsidy, because, in this case, high-type viewers would switch to digital and low-type viewers would stay with analog. Yet, operating both technologies without any subsidy is more expensive than not launching digital at all.

[18] Depending on the value of viewers' preference parameter, any of these subsidies can be equal to zero.

2.4 Welfare

The most important question from the welfare point of view is whether excessive or insufficient switching occurs in equilibrium.[19] To answer this question, it is enough to look at the case when $b^L > s - a - r$ and $\rho r \geq (C_A - C_D)/N$. As is shown in the appendix, switching everybody to digital is optimal for the platform operator whenever $b^L \geq s - a - (C_A - C_D)/N$.

The efficient allocation can be derived from maximizing the joint surplus of the platform operator and the viewers. It can be shown (see appendix) that everybody switching to digital is efficient whenever $b^L \geq b^H - (1/\rho)(b^H - s + (C_A - C_D)/N)$. The following proposition summarizes our welfare result:

Proposition 2
Both excessive and insufficient switching to digital service can occur in equilibrium.

There are two forces that drive the decentralized outcome away from the first-best outcome. First, there is a tendency toward excessive switching, because the platform operator is unable to extract all the viewers' surplus (equal to a) if they choose the analog service. The operator can, however, extract all the viewers' surplus when inducing a switch to digital, because the optimal subsidy in that case leaves the viewers indifferent between switching and opting out of television (with consumer surplus equal to zero). As a result, switching to digital allows the operator to get closer to full rent extraction, so that switching results in some cases when it would not be optimal from the social point of view. Obviously, the magnitude of this distortion rises as the level of a rises.

Second, the fact that the platform operator does not know each viewer's type points in the direction of socially insufficient switching. The reason is that the operator cannot discriminate among viewers and must pay the same amount of subsidy to the low-type and to the high-type viewers. Hence, the operator can extract only part of the benefits

[19] We assume here that the platform operator has the option to unilaterally switch off the analog signal.

of switching. If the fraction of high-type viewers is large, the subsidies intended for the few low-cost viewers are very costly for the operator, so that less switching results compared to the first best level.

3 Timing

To address the optimal switching time of the platform operator, we need to extend our model to multiple periods. To keep the analysis simple, we extend our model to two periods only and assume that the platform operator cannot announce a switching-off of the analog signal.

3.1 Dynamic model

Consider again a single platform operator that can broadcast a given content by analog and/or digital technology for two periods, $t = 1,2$. In each period, the viewers can choose to adopt either standard or opt out of television altogether.

As in the static version of our model, broadcasting involves only a fixed cost in each period, equal to C_A for the analog and $C_D < C_A$ for the digital signal. The platform collects r units of revenue from advertisers for each viewer in each period. For a given number of viewers, the platform's only concern is to minimize discounted transmission costs.

The preferences of a given viewer can be described as follows. The utility of no television is normalized to zero, whereas the utility of viewing analog television is equal to $a > 0$ in each period. Viewing digital television in period t gives utility $a + b_t$, where b_t represents the incremental utility derived from digital television. To switch to digital in period t, the viewer must pay the one-off switching cost s_t. Second-period payoffs are discounted according to the factor δ.

Initially, viewers receive the analog signal. We assume that the platform operator cannot switch off the analog signal unless all viewers have migrated to digital.[20] The platform operator has three choices: Introduce digital broadcasting in the first period, in the second period, or in neither period.

[20] This is the case when no unilateral termination of the analog signal is possible. Even though a more general version of the model should incorporate the unilateral termination of the analog signal, we ignore this option to keep our analysis simple. The case considered here fits the case of the terrestrial platform well.

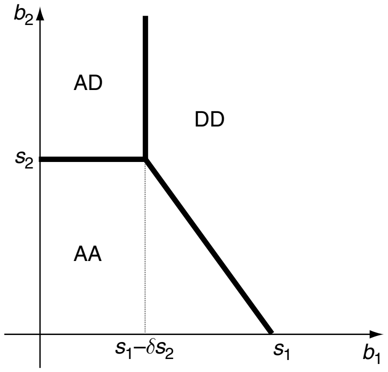

Figure 11.1 Dependence of viewers' choices on preference parameters.

We begin by deriving the viewers' optimal choice of technology, and then turn to the platform operator's dynamic decision.

3.2 Viewers' switching

In each period, the viewers decide whether to stay with analog or migrate to digital. Once migrated to digital service, the viewer cannot return to analog service. Staying with analog for both periods (choosing AA, where the capital letters denote the choices in the corresponding period) results in payoff $u_{AA} = a + \delta a$. Migrating to digital in the first period (choosing DD) results in a payoff of $u_{DD} = a + b_1 - s_1 + \delta(a + b_2)$. Finally, staying with analog in the first period and migrating to digital in the second period (choosing AD) results in a payoff of $u_{AD} = a + \delta(a + b_2 - s_2)$.

Figure 11.1 illustrates the dependence of the viewers' choice on their preference parameters for digital in the two periods. In the graph, b_1 is plotted on the horizontal axis and b_2 is plotted on the vertical axis.[21] To understand this graph, we now compare the viewers' utility for each of the three scenarios identified above.

A viewer chooses DD over AA if and only if $a + b_1 - s_1 + \delta(a + b_2)$ $a + \delta a$, or equivalently, when $b_1 + \delta b_2 \geq s_1$. This is the case for the

[21] The preference for analog service can be neglected in the graphical illustration, since the decision depends only on the incremental preference for digital over analog television.

preferences represented by points to the northeast of the diagonal line between areas AA and DD in Figure 11.1. Intuitively, a viewer will choose to switch to digital in the first period rather than remain with analog technology forever, whenever the present value of the benefits from switching is greater than the switching cost incurred in the first period. Note that an increase in the discount factor increases the present value of the benefits from switching.

A viewer chooses DD over AD if and only if $a + b_1 - s_1 + \delta(a + b_2) \geq a + \delta(a + b_2 - s_2)$. This reduces to $b_1 \geq s_1 - \delta s_2$, which is satisfied in the area to the right of the vertical line in Figure 11.1. Intuitively, the viewer switches in period 1 rather than in period 2, if the benefit from digital in the first period is larger than the rental cost of switching.[22] So, DD is the most preferred option for a particular viewer if the two inequality conditions above are simultaneously satisfied, that is, if the viewer's preference parameters for digital service in both periods are high and can be represented by a point in the DD area.

The boundary between the AA and AD areas can be identified in the same way. In particular, a viewer chooses AD over AA if and only if $a + \delta(a + b_2 - s_2) \geq a + \delta a$, or $b_2 \geq s_2$, which is satisfied for the points above the horizontal line in Figure 11.1. Intuitively, a viewer would choose to switch to digital service in period 2 if the benefit from digital more than offsets the cost of switching. It can be seen that AD is the most preferred option for a particular viewer if $b_1 \leq s_1 - \delta s_2$ and $b_2 \geq s_2$, that is, if the viewer has high preferences for digital service in period 2 and low preferences for digital service in period 1. Similarly, AA is the most preferred option for someone with low preferences for digital in both periods. In addition, note that someone with a high preference in the first period and a low preference in the second period will also switch in the first period.

The impact of subsidies on viewers' optimal choice can easily be analyzed in this framework. If a subsidy is offered in the first period (see Figure 11.2), the switching costs of viewers in period 1 decreases, which shifts to the left the borderlines between both the AA and DD areas (defined by $b_1 + \delta b_2 = s_1$) and the AD and DD areas (defined by

22 The difference of the present values of switching costs in the two periods is $s_1 - \delta s_2$. If s is the price of a digital decoder, this difference is equal to the rental cost of such an equipment, as it is the difference between the price for which the equipment can be bought in period 1 and the present value of the price for which it can be sold in period 2.

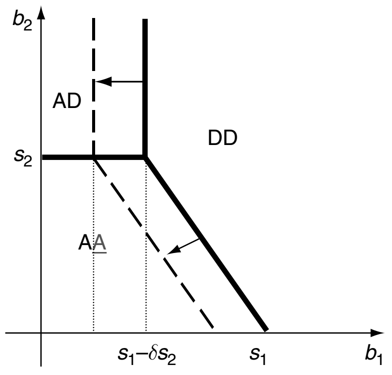

Figure 11.2. Impact of a subsidy in the first period on viewers' choices.

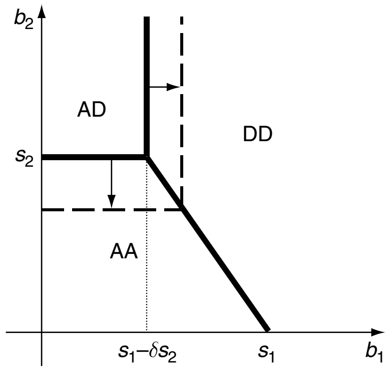

Figure 11.3. Impact of a subsidy in the second period on viewers' choices.

$b_1 = s_1 - \delta s_2$). The impact of a subsidy in period 2 is illustrated in Figure 11.3. As we have already seen in the static model, subsidies can be used to induce users to switch to digital service in cases when they would otherwise prefer to remain with the analog service. In the following section, we analyze the platform operator's choice of when to launch digital broadcasting and the subsidy policy supporting this decision.

3.3 Subsidization policy

We now analyze the platform operator's optimal subsidy policy. Solving for the optimal subsidy policy in general involves deriving the optimal timing for launching the digital signal. In this two-stage game, the viewers take into account the subsidies offered by the platform. In the first period, the platform operator commits to a dynamic subsidization policy. In the second stage, the viewers make their two-period service choice. Since each player moves only once, credibility is not an issue here.

As in the static model, viewers have heterogeneous preferences for digital service. We denote type-i viewer's ($i \in \{L,H\}$) preferences for digital service in period t by b_t^i and assume that $b_t^L < b_t^H$, that is, the high-type viewer has a higher valuation for digital in both periods.

In this dynamic setting, the platform operator may decide to discriminate among viewers, thereby inducing them to switch to digital technology in different periods. Operation costs are higher, however, when viewers do not switch simultaneously, as both technologies must be operated in the same period.[23] Consequently, the platform operator will only choose to discriminate among viewers if the benefits from discrimination more than offset the extra costs imposed by the simultaneous operation of the two technologies.[24] The following proposition formalizes this idea:

Proposition 3
When analog and digital broadcasting technologies can be operated at the same time, the platform operator may induce viewers to switch to the digital service in different periods. In particular, if digital broadcasting is much cheaper to operate than analog, and the surplus of low-type viewers from digital is very low in the first period, the platform operator might offer a subsidy only in the second period. Low-type viewers will take this subsidy and switch in the second period, whereas high-type viewers switch in the first period without benefiting from the subsidy.

The intuition for this "asymmetric" switching pattern is the following: Suppose that the low-type benefit, b_1^L, is much lower than s_1. A subsidy offered to low-type viewers in the first period should be very high. In addition, since the platform operator cannot observe the viewers' type, high-type viewers also would take this high subsidy.

[23] We assumed that there is no unilateral switch-off of the analog signal.
[24] Note that we cannot have both technologies operated at the same time in the static version of our model, as that scenario would be dominated by operating the digital signal only (see Section 2).

//FS2/CUP/3-PAGINATION/SAPP/2-PROOFS/3B2/052186450XC11.3D 363 [345–371] 31.7.2006 4:25PM

Therefore, such a high first-period subsidy would be costly for the platform operator and would not necessarily be offset by the savings incurred by switching off the analog signal in the first period.

With low-type viewers having a higher benefit from digital in the second period (or equivalently when the evolution of technology lowers switching costs), their subsidization may become cheaper in the second period. High-type viewers would switch to digital early on in the first period and would not wait for a moderate subsidy in the second period. Therefore, the costs imposed by the second-period subsidies on the platform operator will be of moderate magnitude and will be more than offset by the savings generated by switching off the analog signal in the second period. As a result, it would be profitable for the platform operator to offer a second period subsidy of a moderate amount targeting low-type viewers.

Even though the operator can now intertemporally discriminate among viewers, the full benefits of screening cannot be realized because of two reasons. First, since we are considering FTA television, viewers do not pay for either type of the service. As a result, the platform operator has no means to extract all the viewers' surplus, which weakens its incentives to discriminate. Second, as broadcasting is an excludable public good, the cost of providing it is constant and does not depend on the number of viewers served. This necessarily leads to a duplication of costs if the platform operator discriminates among viewers – and, therefore, it discourages discrimination.

4 Public policy

In this section, we analyze the problems raised by the universal service requirement. The universal service obligation requires that all viewers be assured access to some kind of broadcasting. Therefore, the platform operator cannot unilaterally switch off the analog signal. The analog signal can only be switched off if a sufficiently high fraction of viewers has already migrated to the digital service.

To keep the analysis simple, we return to the static version of our model. We also assume that viewers are identical. Because of the universal service requirement, the platform operator has the option to switch off the analog signal only if a sufficiently high fraction of viewers has already migrated to digital. The effects of a conditional switch-off are summarized below:

Proposition 4
Suppose that it is announced that analog broadcasting is to be switched off, conditional on a given and arbitrary fraction of the population of viewers taking up digital. If $s - a \leq b \leq s$, there are two equilibrium outcomes, one in which the entire population of viewers switches to digital and the other in which the entire population stays with analog.

Condition $b \geq s - a$ implies that viewers prefer switching to digital if the choice is between digital television and no television. Condition $b \leq s$ implies that viewers prefer staying with analog television if both analog and digital are available.

In the first equilibrium, individual viewers expect all the other viewers to switch to digital, so the critical mass required by the "take-up criterion" will be achieved. The analog service will then be switched off, so it is in the interest of individual viewers to switch to digital as $s \leq a + b$, and the initial expectation is fulfilled.

In the second equilibrium, each individual viewer expects that no other viewer will switch to digital service. Given this expectation, it is in the best interest of each viewer not to switch to digital, as $b \leq s$. All viewers will then remain with analog service, so the critical mass for switching is not achieved, and the analog signal is not switched off, which confirms the original expectation.

Note that if viewers' preferences are different from those described in the proposition, there are no multiple equilibria. Nevertheless, this result can be generalized to the case with heterogeneous viewers, and it can be shown that it is reasonable to expect multiple equilibria in empirically plausible scenarios (see Adda and Ottaviani 2005). Expectation management then becomes important.

In future research, it would be interesting to extend the model to allow for competition among platforms, which has proven essential in the UK experience. In particular, we believe that governments should seriously consider market solutions to the universal service obligations.[25]

[25] Governments could create competition among different platform operators to obtain subsidies to provide television in remote areas. These areas are often less costly to serve by satellite than terrestrial technology.

References

Adda, J., and M. Ottaviani 2005. "The transition to digital television," *Economic Policy* 41: 160–209.

Anderson, S., and S. Coate 2005. "Market provision of broadcasting: A welfare analysis," *Review of Economic Studies* 72: 947–72.

Armstrong, M. 1999. "Competition in the pay-TV market," *Journal of the Japanese and International Economies* 13: 257–80.

2004. "*Competition in two-sided markets*," mimeo, London: University College London.

Cave, M., and R. Crandall 2001. "Sports rights and the broadcast industry," *Economic Journal* 111: F4–26.

Coase, R. 1959. "The Federal Communications Commission," *Journal of Law & Economics* 2: 1–40.

Commission of the European Communities 2002. "eEurope 2005: An information society for all," COM (2002) 263 final, Brussels.

2003. "Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions on the transition from analogue to digital broadcasting (from digital 'switchover' to analogue 'switch-off')," COM (2003) 541 final, Brussels.

Congressional Budget Office of the United States 1999. "Completing the transition to digital television," Washington, DC: Government Printing Office.

Cramton, P., E. Kwerel, and J. Williams 1998. "Efficient relocation of spectrum incumbents," *Journal of Law & Economics* 41: 647–75.

Farrell, J., and C. Shapiro 1992. "Standard setting in high-definition television," *Brookings Papers on Economic Activity: Microeconomics* 1–77.

Galperin, H. 2004. *New television, old politics: The transition to digital TV in the United States and Britain*. Cambridge: Cambridge University Press.

Grimme, K. 2002. *Digital television: Standardization and strategies*. Norwood, MA: Artech House.

Harbord, D., and M. Ottaviani 2001. "Contracts and competition in the UK pay-TV market," Discussion Paper 01–5, London Business School.

Hart, J. 2004. *Technology, television and competition: The politics of digital TV*. Cambridge: Cambridge University Press.

Hazlett, T. 2001. "The US digital TV transition: Time to toss the Negroponte Switch," Working Paper 01–15, Washington, DC: AEI-Brookings Joint Centre for Regulatory Studies.

Katz, M. 2003. "Television over the Internet: Industry structure and competition absent distribution bottlenecks," in *Internet television*, E. Noam,

J. Groebel, and D. Gerbarg (eds.), Mawah, NJ: Lawrence Erlbaum Associates, 31–59.

Laffont, J. J., and J. Tirole 2000. *Competition in telecommunications*. Cambridge, MA: MIT Press.

Levy, J., M. Ford-Levy, and A. Levine 2002. "Broadcast television: Survivor in a sea of competition," OPP Working Paper Series 37, Washington, DC: Federal Communications Commission.

Owen, B., and S. Wildman 1992. *Video economics*. Cambridge, MA: Harvard University Press.

Riordan, M. 2002. "Universal residential telephone service," in *Handbook of telecommunications economics*, M. Cave (ed.), Amsterdam: Elsevier Science, 423–73.

Rochet, J. C., and J. Tirole 2003. "Platform competition in two-sided markets," *Journal of the European Economic Association* 1: 990–1029.

Rosston, G. L., and T. W. Hazlett 2001. "Comments of 37 concerned economists [on] promoting efficient use of spectrum through elimination of barriers to the development of secondary markets," WT Docket No. 00–230, Federal Communications Commission, Washington, DC: AEI-Brookings Joint Center for Regulatory Studies.

Appendix: *Proofs*

Proof of Proposition 1

There are six cases to be considered separately depending on the magnitude of b^L and b^H, relative to $s-a$ and s:

(i) $b^L < b^H < s-a$;
(ii) $b^L < s-a < b^H < s$;
(iii) $b^L < s-a < s < b^H$;
(iv) $s-a < b^L < b^H < s$;
(v) $s-a < b^L < s < b^H$;
(vi) $s-b^L < b^H$.

We present the proof only for case (i), which is the one that best illustrates the logic of the result. In this case, the level of the subsidy required to make either type of viewer switch depends on whether or not analog is available in addition to digital. If only digital is available, the platform operator can design two types of subsidies, a "high subsidy" equal to $s-a-b^L$ with an impact on the choice of all viewers, and a "low subsidy" equal to $s-a-b^H$, which affects only the choice of high-type viewers. Note that the low subsidy is not enough to induce

//FS2/CUP/3-PAGINATION/SAPP/2-PROOFS/3B2/052186450XC11.3D 367 [345–371] 31.7.2006 4:25PM

the low-type viewers to switch, and so is paid only to the high-type viewers. Similarly, if both analog and digital are available, the high subsidy is equal to $s - b^L$ and the low subsidy is equal to $s - b^H$.

The surplus of the platform operator for each option is:

(1) Offer analog only and no subsidy: $Nr - C_A$;
(2) Offer digital only and a number $K \leq (1-\rho)N$ of low subsidies: $Kr - K(s - a - b^H) - C_D$;
(3) Offer digital only and a number $K \leq N$ of high subsidies: $Kr - K(s - a - b^L) - C_D$;
(4) Offer digital only and no subsidy: $-C_D$;
(5) Offer analog and digital and a number K of low subsidies: $Nr - K(s - b^H) - C_A - C_D$;
(6) Offer analog and digital and a number K of high subsidies: $Nr - K(s - b^L) - C_A - C_D$;
(7) Offer analog and digital and no subsidy: $Nr - C_A - C_D$;
(8) Offer neither analog nor digital and no subsidy: 0.

It can be seen that option (1) dominates option (7). Since $b^L < b^H$, option (5) dominates option (6). Option (5) is dominated by option (1) because of its extra second and fourth term. Also, option (8) dominates option (4). In turn, option (1) dominates option (8) if analog is profitable in the first place. The only remaining options are (1), (2), and (3), which proves claim (ii), namely, that it is not optimal to simulcast analog and digital signal.

In option (3), it is in the platform operator's interest to set the value of K equal to N whenever $r - (s - a - b^L) > 0$, and $K = 0$ (the case of no subsidies at all) otherwise. Similarly, in option (2) the platform operator should set $K = (1-\rho)N$ if $r - (s - a - b^H) > 0$, and $K = 0$ otherwise. This shows that it is never optimal to subsidize a fraction of the viewers targeted by a subsidy, the first claim of the proposition. This completes the proof of Proposition 1 for case (i), with $b^L < b^H < s - a$.

Cases (ii) through (vi) can be analyzed in a similar way. For the second part of the proposition, note that in cases (i), (ii), and (iii) the platform operator can reach the low-type viewer with the analog signal and save the cost of the subsidy needed to induce the low-type viewer to switch to digital by simulcasting the analog and digital signal. This cannot be optimal for the operator, however, because transmitting the analog signal only would save the digital transmission cost and the eventual subsidy to the high-type viewer.

Proof of Proposition 2

We first derive the platform operator's optimal choice for the case presented in the proof of Proposition 1. Assume that $r-(s-a-b^L)>0$, or equivalently, that $b^L>s-a-r$. This implies that $r-(s-a-b^H)>0$; therefore, only the following options must be compared (see proof of Proposition 1):

(1) Offer analog only and no subsidy: $Nr-C_A$;
(2) Offer digital only and low subsidy: $(1-\rho)N[r-(s-a-b^H)]-C_D$;
(3) Offer digital only and high subsidy: $N[r-(s-a-b^L)]-C_D$.

It can be seen that whenever $b^H<s-a+\frac{\rho}{1-\rho}r-\frac{1}{1-\rho}\frac{C_A-C_D}{N}$, option (1) dominates option (2). If we assume $\rho r\geq(C_A-C_D)/N$, then condition $b^H<s-a+\frac{\rho}{1-\rho}r-\frac{1}{1-\rho}\frac{C_A-C_D}{N}$ is satisfied automatically if $b^H<s-a$.

The platform operator chooses option (3) over option (1) whenever $b^L>s-a-(C_A-C_D)/N$. Note that $\rho r\geq(C_A-C_D)/N$ also implies $r\geq(C_A-C_D)/N$, which in turn implies $s-a-(C_A-C_D)/N\geq s-a-r$, or equivalently, that it is sometimes optimal to choose analog. In particular, the platform operator chooses analog whenever $s-a-r<b^L<s-a-(C_A-C_D)/N$ and chooses digital whenever $s-a-(C_A-C_D)/N<b^L<s-a$.

We now turn to the first-best outcomes. The joint surplus of the viewers and the platform operator for the four possible allocations are:

(I) All view analog: $Na+Nr-C_A$;
(II) High-type viewers use digital and low-type viewers use analog: $N[a+(1-\rho)(b^H-s)]+Nr-C_A-C_D$;
(III) All viewers use digital: $N[a+\rho b^L+(1-\rho)b^H-s]+Nr-C_D$;
(IV) High-type viewers use digital and low-type viewers use no television: $(1-\rho)N(a+b^H-s)+(1-\rho)Nr-C_D$.

Since we are considering the case with $b^L<b^H<s-a$, we also have $b^H<s+\frac{1}{1-\rho}\frac{C_D}{N}$, so that outcome (II) is dominated by outcome (I). In addition, outcome (IV) is dominated by outcome (III), since $b^L\geq s-a-r$.

Consequently, it is efficient for everyone to switch to digital whenever the joint surplus in outcome (III) is higher than in outcome (I), that is, whenever $b^L\geq b^H-\frac{1}{\rho}\left(b^H-s+\frac{C_A-C_D}{N}\right)$. Since $s-a-r<b^L<$

$b^H < s - a$, we also need condition $\frac{C_A - C_D}{N} > a > \frac{C_A - C_D}{N} - r$ for having both cases in which analog or digital is socially efficient. In particular, analog is socially efficient whenever $s - a - r$ and digital is socially efficient whenever $s - \frac{C_A - C_D}{N} < \rho b^L + (1-\rho) b^H < s - a$.

Excessive switching occurs whenever the threshold for the decentralized outcome is lower than the corresponding threshold for the first-best outcome. In other words, $b^H - \frac{1}{\rho}\left(b^H - s + \frac{C_A - C_D}{N}\right) > s - a - \frac{C_A - C_D}{N}$, or equivalently $b^H < s - \frac{C_A - C_D}{N} + \frac{\rho}{1-\rho} a$. By taking into account that $s - a - r < b^H$, we also need to have $\frac{1}{1-\rho} a + r > \frac{C_A - C_D}{N}$. For example, excessive switching occurs when $b^H = \min\left\{ s - \frac{C_A - C_D}{N} + \frac{\rho}{1-\rho} a, s - a \right\} - \varepsilon$ and $b^L = s - a - \frac{1}{N}(C_A - C_D) + \varepsilon$.

Similarly, insufficient switching occurs whenever $b^H > s - \frac{C_A - C_D}{N} + \frac{\rho}{1-\rho} a$. Yet, since $b^H < s - a$, we also need to have $\frac{C_A - C_D}{N} > \frac{1}{1-\rho} a$. For example, insufficient switching occurs when $b^H = \max\left\{ s - \frac{C_A - C_D}{N} + \frac{\rho}{1-\rho} a, s - a - r \right\} + 2\varepsilon$ and $b^L = s - a - r + \varepsilon$.

Proof of Proposition 3

For the purpose of this proof, it is enough to concentrate on the case in which the preference parameters of the low-type viewer are located in area AA of Figure 11.1 and the preferences of the high-type viewer are in DD area. In the absence of subsidies, the low-type viewer would then remain with analog service in both periods, while the high-type viewer would switch to digital in the first period. We also make an additional assumption that $b_1{}^H + \delta b_2{}^L > s_1$. This assumption requires that the high-type viewer prefers DD to AD even when offered a subsidy equal to $s_2 - b_2{}^L$ for switching in the second period.

Providing the two types of viewers with the previous choices presented requires operating both technologies in both periods. The platform operator might find such a solution costly and decide instead to offer a subsidy to the viewers to induce them to change their decision.

Nine final scenarios can be envisaged, as each type of viewer might potentially end up in either one of the three areas AA, AD, and DD. The platform operator's problem aims at the cheapest among these nine scenarios.

We now compute the costs associated with each of these nine scenarios. Let $C_{ij,IJ}$ denote the present value of the costs incurred by the platform operator when the low-type (high-type) viewer chooses technology i (I) in the first period and technology j (J) in the second period, while taking offered subsidies as given. Obviously each cost $C_{ij,IJ}$ has two components: the cost of operating the given technology (coexistence of technologies is allowed) and the cost of subsidies that induce viewers to switch to that technology. For example, $C_{AD,DD}$ is the present value of the cost the platform operator incurs when the subsidies induce the low-type viewer to choose analog in the first period and digital in the second, and the high-type viewer to choose digital technology in both periods.

Depending on the final position taken by the two types of viewers, the platform operator's costs are:

(i) $C_{AA,AA} = C_A + \delta C_A$;
(ii) $C_{AA,AD} = C_A + \delta C_A + \delta C_D$;
(iii) $C_{AA,DD} = C_A + C_D + \delta C_A + \delta C_D$;
(iv) (AD, AA) – not feasible;
(v) $C_{AD,AD} = C_A + \delta C_D + \delta(s_2 - b_2^L)$;
(vi) $C_{AD,DD} = C_A + C_D + \delta C_D + \delta\rho(s_2 - b_2^L)$;
(vii) (DD,AA) – not feasible;
(viii) (DD,AD) – not feasible;
(ix) $C_{AD,DD} = C_D + \delta C_D + (s_1 - b_1^L - \delta b_2^L)$.

In this list, the cost $C_{AD,DD} = C_A + C_D + \delta C_D + \delta\rho(s_2 - b_2^L)$ in (vi) should be read as follows: The first two terms represent the transmission cost for analog and digital in the first period. The third term represents the present value of the cost of operating digital technology only in the second period. The last term denotes the subsidy given to the low-type viewers that induces them to switch to digital in the second period. High-type viewers prefer to switch early and not wait for the late subsidy in this case. The last term of $C_{AD,DD}$ denotes the present value of the costs associated with this subsidy policy. The other costs in the list can be interpreted in a similar manner.

Note that there is no subsidy policy implementing cases (AD,AA), (DD,AA), and (DD,AD) as any subsidy designed for low-type viewers would be taken by high-type viewers too, who would never switch to digital later than low-type viewers, since choices are monotonic in preferences.

In its cost minimization problem, the platform compares the values in (i) to (ix). It can be seen that technology patterns (AA,AD) and (AA,DD) are not profitable, as they are dominated by the pattern (AA,AA). We are interested under which conditions pattern (AD,DD) is optimal. By comparing costs (i), (v), (vi), and (ix), we conclude that pattern (AD,DD) is optimal if the following conditions are satisfied:

$$\frac{C_D}{\delta(1-\rho)} \leq s_2 - b_2^L \leq \frac{\delta C_A - C_D - \delta C_D}{\delta\rho}, \tag{1}$$

and

$$s_2 - b_2^L \leq \frac{s_1 - b_1^L - \delta b_2^L - C_A}{\delta\rho}. \tag{2}$$

The first inequality is only feasible if

$$\frac{C_A}{C_D} \geq 1 + \frac{1}{\delta(1-\rho)}, \tag{3}$$

and inequalities (1) and (2) can be satisfied simultaneously if and only if

$$s_1 - b_1^L - \delta b_2^L \geq C_A + \frac{\rho}{1-\rho} C_D. \tag{4}$$

So, whenever conditions (1) through (4) hold, it is in the platform operator's interest to induce asynchronous switching by viewers. This can be the case when δ and s_1 are large, but ρ, b_1^L, and b_2^L are small.