

Facilitating adoption of services with positive externalities via subsidies

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ABSTRACT

The paper investigates adoption of network services whose value incorporates three key features, namely, heterogeneity in user service affinity, a positive externality, and a cost. Positive externalities often result in a “chicken and egg” problem where early adopters can see a cost that exceeds the service’s (low) initial value. In this paper we study subsidies as a means to “reach the knee” and push adoption higher (from zero to one). We focus on the simplest of subsidies, namely, a fixed subsidy over a given period of time, and are able to obtain expressions for quantities of natural interest, *e.g.*, the minimum subsidy required, the minimum subsidy duration, and the total subsidy cost. Interestingly, the expressions reveal conditions under which the optimal subsidy is neither the lowest nor applied for the shortest duration. The findings help develop guidelines for effective subsidies to promote the adoption of network services.

Categories and Subject Descriptors

500 [Networks]: Network economics; 300 [Networks]: Public Internet

Keywords

network service adoption; cost subsidization; network externality; Metcalfe’s Law.

1. INTRODUCTION

With the Internet fueling the rise of a “network society” [5], many services and technologies¹ realize their value only after reaching a certain level of adoption. In other words, they exhibit positive externalities, *e.g.*, as captured by Metcalfe’s Law. Externalities are well-known [3, 14] to affect adoption, and in particular create a “chicken-and-egg” problem that can stymie the success of new services. This is because, when a new service is offered, most potential adopters see a cost that exceeds its (low) initial value. This creates a barrier to entry often used to explain the difficulties encountered by various Internet security protocols [17] and new versions of the Internet itself, *i.e.*, IPv6 [11].

A number of possible strategies have been proposed in the past, and in our prior work [9, 10, 20] we investigated

¹For conciseness we use the term services in the paper.

service bundling as a means of overcoming initial adoption inertia. In this work, we turn to another promising alternative, namely, *subsidies*, to achieve the same goal. As with bundling, the models we develop incorporate three key assumptions: *i*) users are heterogeneous, *i.e.*, their affinity for the service varies; *ii*) services exhibit positive network externalities, *i.e.*, the utility perceived by a user is an increasing function of the service adoption level; and *iii*) services have a cost. In particular, a user pays a fixed amount per unit time to participate in the service. We assume there are no costs to initially join or leave the service, nor are there any contractual requirements that prevent a user from leaving the service at any time.

Our focus is on the use of cost subsidization to overcome the adoption problem faced by services with network externalities. Subsidization is a natural solution for such services because it incentivizes adoption among initial adopters (“innovators”), thereby allowing the adoption level to build up to the “knee”, at which point the strength of the externality will incentivize the later adopters (“imitators”), and the subsidy will no longer be needed to sustain the service [2].

Cost subsidization may take many forms; we provide a (necessarily) selective and brief review of this large topic in §1.1. We address the (perhaps) most natural and simple subsidy, namely, the constant level subsidy (CLS), wherein the service provider subsidizes the cost for each adopter at a constant level (per adopter) over a finite duration. Specifically, an (s, T) CLS subsidy starting at time t_0 for a service with cost (per unit time) of c means that any adopter will pay at rate $c - s$ at any time $t \in [t_0, t_0 + T]$, and will pay at rate c for any time $t > t_0 + T$. It is natural that the subsidy duration T be selected so that the subsidized adoption dynamics (AD) reach some target adoption level by the end of the subsidy, and it is intuitive that the required duration be nonincreasing in the subsidy s . A service provider employing a CLS will be interested in minimizing the aggregate cost of the subsidy and the required duration of the subsidy. We identify the dependence of the aggregate subsidy cost and required subsidy duration on s .

1.1 Related work

There is a long-standing awareness of the role of subsidies in realizing more efficient outcomes in “markets” that exhibit positive externalities *i.e.*, by demonstrating the benefits of Pigouvian subsidies. For example, [6] examines the impact of early investments on a firm’s growth rate in the telecommunication industry. It identifies that early investments can facilitate the creation of an initial user base, and

lead to greater overall market share. Similar examples highlighting the benefits of subsidies in the presence of positive externalities arise in many other markets, *e.g.*, education [12], healthcare [1, 7], retail stores [8], security [17, 18], etc. This awareness notwithstanding, most of the focus to date has been on case studies, which have helped identify effective strategies, *e.g.*, see [16] for a recent review.

There have been some recent efforts on the modeling front, stemming in part from interest in viral marketing in online (social) networks [4, 13]. As discussed in [13], those works are closely related to studies of adoption dynamics in social networks [15, Chapter 24], but with a focus on maximizing revenue rather than adoption. The optimal marketing strategy in a symmetric network, *i.e.*, a product utility grows in proportion to its number of adopters, is investigated in [13] by formulating it as the solution of a dynamic program. A general network setting is considered in [4] with the important difference of considering a *divisible* good, so that consumption maximization is now the target.

Our work, like [2], has a focus on product adoption among heterogeneous users in the presence of an externality, but differs in that [2] focuses on two classes with no adoption costs, and no subsidization. Furthermore, our approach is similar to [14] in the focus on subsidies (“sponsorship” in their paper) with network externalities, but differs in that [14] focuses on equilibrium pricing, whereas our interest is more in adoption dynamics. Finally our focus is similar to [13] in the focus on optimizing over subsidies, but differs in that [13] considers the combinatorial optimization problem of sequential buyer-specific subsidies under buyer-specific externalities, whereas we consider uniform subsidies and externalities.

1.2 Summary of contributions

We investigate services with positive externalities, restricting our model to uniformly distributed service affinities to explicitly characterize the AD and key performance metrics.

Prop. 1 identifies the four different equilibria sets (as well as their (in)stability) as a function of the key model parameters, and the AD in each of these four settings. The most relevant setting for subsidies is when the two stable equilibria are zero and full adoption, and the final adoption level depends upon which domain of attraction holds the adoption level when subsidies end. The goal of the subsidy is to drive adoption to the “edge” of the domain of attraction for the full adoption equilibrium.

After a simple but not particularly insightful characterization of the AD under CLS in Prop. 2, Prop. 3 give the paper’s main result for a subsidy duration T chosen to guide the AD to the domain of attraction of the full adoption equilibrium. We give the minimum subsidy required to actually change the equilibrium from zero to full, the AD as a function of the subsidy, and both the required subsidy duration and the aggregate cost of the subsidy as a function of the subsidy level. As expected, the required subsidy duration is nonincreasing in the subsidy amount, but more interestingly, while the aggregate subsidy cost is initially decreasing in the subsidy amount, it eventually (for large enough subsidies) increases in the subsidy amount. In other words, there exists a “sweet spot”, when it comes to jointly minimizing overall subsidy costs and duration.

The rest of this paper is organized as follows. We address related work in §1.1, and then introduce the mathematical

model in §2. AD for services with network externalities are analyzed in §3 (no cost subsidization) and §4 (with cost subsidization). A brief conclusion is given in §5.

2. MATHEMATICAL MODEL

2.1 Without cost subsidization

The basic mathematical model captures AD in a large population of potential users of a network service exhibiting the three assumptions in §1. Let $x(t) = x(t|t_0, x_0) \in [0, 1]$ denote the fraction of the population that has adopted the service at each time $t \geq t_0$ subject to the initial condition $x(t_0) = x_0$. The net utility, $V = V(x)$, perceived by a randomly selected user when the adoption level is x , is the random variable $V(x) \equiv U + ex - c$. The net utility, and each of the three terms comprising it, should be thought of as values or costs per unit time. Each of the three terms reflect one of the key assumptions in §1. First, user service affinity heterogeneity is captured by the random variable U with cumulative distribution function (CDF) F_U , denoted $U \sim F_U$. User affinities are assumed to be independent and identically distributed (iid). We further assume F_U to be continuous. Second, the network service externality is captured by a linear utility term ex , where $e \geq 0$ is the externality parameter. Third, the cost of adoption is captured by the constant $c \geq 0$ in the net utility.

The AD are assumed to be governed by

$$\dot{x}(t) = \gamma(\mathbb{P}(V(x(t)) > 0) - x(t)), \quad (1)$$

where $\gamma > 0$ is a time-scale parameter, state the rate of adoption (whether positive or negative) is proportional to the difference between the fraction of the population that *would* adopt at adoption level $x(t)$, and the fraction of the population that *has* adopted, *i.e.*, $x(t)$. The service is assumed to have an initial adoption level $x(t_0) = x_0$. A level of adoption $\bar{x} \in [0, 1]$ is an equilibrium if $\dot{x}(t)|_{x=\bar{x}} = 0$, *i.e.*, $\mathbb{P}(V(\bar{x}) > 0) = \bar{x}$. The set of equilibria is denoted by \mathcal{X} . An equilibrium may be stable or unstable. An equilibrium \bar{x} is stable if $\frac{d}{d\bar{x}}\mathbb{P}(V(\bar{x}) > 0) \leq 1$. The set of stable equilibria is denoted by $\bar{\mathcal{X}} \subseteq \mathcal{X}$. The intuition behind the definition of the stability property $\frac{d}{d\bar{x}}\mathbb{P}(V(\bar{x}) > 0) \leq 1$ is that for small $\epsilon > 0$, $\dot{x}(t) \geq 0$ for $x \in (\bar{x} - \epsilon, \bar{x})$ and $\dot{x}(t) \leq 0$ for $x \in (\bar{x}, \bar{x} + \epsilon)$, *i.e.*, $x(t)$ is driven towards \bar{x} when $x(t)$ is within the domain of attraction of \bar{x} . The set of (stable) equilibria is determined by the tuple (F_U, c, e) .

2.2 With cost subsidization

A subsidy is a reduction of the cost c so that the net utility is $V = U + ex - (c - s)$. It is natural to consider subsidies that depend upon time ($s(t)$), the adoption level ($s(x)$), or both ($s(t, x)$). The cost of the subsidy to the service provider (normalized to the population size) is

$$S \equiv \int_{t_0}^{\infty} s(t, x(t))x(t)dt, \quad (2)$$

where it is important to note that AD $x(t)$ are affected by the subsidy $s(t, x(t))$. We restrict our attention to a particularly simple but natural cost subsidy that we call the *constant level subsidy* (CLS). The CLS with parameters $(s, T) \in [0, c] \times \mathbb{R}_+$ is

$$s(t) = \begin{cases} s, & t \in [t_0, t_0 + T] \\ 0, & \text{else} \end{cases}. \quad (3)$$

We denote the AD under CLS by $y(t) = y(t|t_0, y_0)$ to distinguish them from the unsubsidized dynamics, denoted by $x(t)$, or more generally $x(t|t_0, x_0)$. The net utility becomes

$$V(t, y) = \begin{cases} U + ey - (c - s), & t \in [t_0, t_0 + T] \\ U + ey - c, & \text{else} \end{cases}, \quad (4)$$

and the AD (1) become

$$\dot{y}(t) = \begin{cases} \gamma(\bar{F}_U(c - s - ey(t)) - y(t)), & t \in [t_0, t_0 + T] \\ \gamma(\bar{F}_U(c - ey(t)) - y(t)), & \text{else} \end{cases}, \quad (5)$$

with initial condition $y(t_0) = y_0$ for $t_0 \geq 0$ and $y_0 \in [0, 1]$. The subsidy cost (2) under CLS is

$$S = s \int_{t_0}^{t_0+T} y(t|t_0, y_0) dt = s \int_0^T y(t|0, y_0) dt, \quad (6)$$

where $y(t)$ is the solution to (5).

3. AD AND EQUILIBRIA W/O COST SUB.

In this section, we characterize *i)* the set of equilibria \mathcal{X} and stable equilibria ($\bar{\mathcal{X}}$), and *ii)* the AD $x(t)$ in (1) in the absence of subsidies. In the interest of providing explicit expressions for AD and equilibria, we *hereafter assume the affinity distribution to be uniform, i.e., $U \sim \text{Uni}[u_m, u_M]$ for $u_m < u_M$.* The following notation will be employed. Let

$$x^\circ(c) \equiv \frac{u_M - c}{u_M - (u_m + e)} \quad (7)$$

denote the unique equilibrium in $(0, 1)$ of (1) under uniform affinities. Then (see [19])

$$\begin{aligned} \hat{x}(t|t_0, x_0, c) &\equiv x^\circ(c) + (x_0 - x^\circ(c)) e^{\frac{e+u_M-u_m}{u_M-u_m} \gamma(t-t_0)} \quad (8) \\ \hat{t}(x|t_0, x_0, c) &\equiv t_0 + \frac{1}{\gamma} \frac{u_M - u_m}{e + u_m - u_M} \log \left(\frac{x - x^\circ(c)}{x_0 - x^\circ(c)} \right) \quad (9) \end{aligned}$$

are the solution of (1) under uniform affinities, for $(c - u_M)/e \leq x \leq (c - u_m)/e$, and initial condition $x(t_0) = x_0$.

PROPOSITION 1. *Suppose $U \sim \text{Uni}[u_m, u_M]$ for $u_m < u_M$. The possible equilibria sets \mathcal{X} are:*

$$\mathcal{X} = \begin{cases} \{0\}, & \max\{u_M, u_m + e\} \leq c \\ \{x^\circ(c)\}, & u_m + e \leq c \leq u_M \\ \{0, x^\circ(c), 1\}, & u_M \leq c \leq u_m + e \\ \{1\}, & c \leq \min\{u_M, u_m + e\} \end{cases} \quad (10)$$

All equilibria are stable, aside from $x^\circ(c)$ when $u_M \leq c \leq u_m + e$. The AD, denoted $x(t|t_0, x_0)$ are given in the technical report [19] in terms of $\hat{x}(t)$ (8) and $\hat{t}(x)$ (9). For case 3) ($u_M \leq c \leq u_m + e$), if $x_0 < (>)x^\circ(c)$ then $x(t) \rightarrow 0(1)$, respectively.

4. AD AND EQUILIBRIA WITH COST SUB.

We study the impact of cost subsidization on the AD when the service affinity distribution is uniform, and focus on the specific case when the parameters (u_m, u_M, c, e) are such that the possible equilibria are $\mathcal{X} = \{0, x^\circ(c), 1\}$ (case 3 in Prop. 1), *i.e., $u_M \leq c \leq u_m + e$.* We further assume the stable equilibrium without subsidization is $x^* = 0$, *i.e., $0 \leq x_0 \leq x^\circ(c) \leq 1$,* so that under CLS and uniformly distributed affinities, (5) specializes to

PROPOSITION 2. *Under CLS with $U \sim \text{Uni}(u_m, u_M)$*

$$y(t|t_0, y_0) = \begin{cases} x(t|t_0, y_0)_{c-s}, & t - t_0 \leq T \\ x(t|t_0 + T, y(t_0 + T)), & t - t_0 > T \end{cases} \quad (11)$$

where $x(t|t_0, y_0)_{c-s}$ denotes substitution of the cost c with the subsidized cost $c - s$ in the unsubsidized dynamics from Prop. 1, and the initial value at the end of the subsidy is $y(t_0 + T) = x(t_0 + T|t_0, x_0)_{c-s}$.

PROOF. For $t \in [t_0, t_0 + T]$ the AD follow the unsubsidized dynamics in Prop. 1, with subsidized cost $c - s$, and for $t > t_0 + T$, they follow the unsubsidized dynamics with the unsubsidized cost c . \square

We focus next on the case of a general subsidy level s and a subsidy duration $\hat{T}(s)$ chosen to ensure that adoption at the end of the subsidy is at the minimum required for the (then) unsubsidized dynamics to converge to 1, *i.e., $y(t_0 + T(s)) = x^\circ(c)$.* The dynamics under CLS with subsidy s and duration $\hat{T}(s)$ can be characterized as follows

PROPOSITION 3. *Suppose $u_M \leq c \leq u_m + e$ so that the unsubsidized dynamics in Prop. 1 follow case 3) (with stable equilibria $\bar{\mathcal{X}} = \{0, 1\}$), and suppose $y_0 = x_0 < x^\circ(c)$ so that the unsubsidized adoption level will converge to $x^* = 0$. It is convenient in what follows to normalize the subsidy level s by the externality e , as s/e . Under CLS with subsidy level s and duration $\hat{T}(s)$ the following facts hold:*

1. *The minimum normalized subsidy s/e required to change the equilibrium from 0 to 1 is*

$$\frac{\hat{s}}{e} \equiv \left(1 - \frac{u_M - u_m}{e}\right) (x^\circ(c) - y_0), \quad (12)$$

meaning for $\frac{s}{e} \leq \frac{\hat{s}}{e}$ the subsidized AD still converges to 0, but if $\frac{s}{e} > \frac{\hat{s}}{e}$ it converges to 1, provided $T > \hat{T}(s)$, below.

2. *The required subsidy duration, $\hat{T}(s)$ is*

$$\hat{T}(s) = \begin{cases} \hat{t}(x^\circ(c)|0, y_0, c - s) & 0 \leq \frac{s}{e} \leq \frac{c - u_m}{e} - x^\circ(c) \\ \hat{T}_m(s) + \frac{1}{\gamma} \log \left(\frac{1 - \frac{c - s - u_m}{e}}{1 - x^\circ(c)} \right) & \frac{c - u_m}{e} - x^\circ(c) \leq \frac{s}{e} \leq \frac{c - u_m}{e} - y_0 \\ \frac{1}{\gamma} \log \left(\frac{1 - y_0}{1 - x^\circ(c)} \right) & \frac{c - u_m}{e} - y_0 \leq \frac{s}{e} \leq \frac{c}{e} \end{cases} \quad (13)$$

Moreover, $\hat{T}(s)$ is nonincreasing in the subsidy amount s .

3. *For $\frac{\hat{s}}{e} \leq \frac{s}{e} \leq \frac{c - u_m}{e} - x^\circ(c)$, the cost of subsidization $S(s)$ of (2) is given by*

$$\frac{s(u_M - u_m)}{\gamma(e + u_m - u_M)} \left(x^\circ(c - s) \log \left(\frac{x^\circ(c) - x^\circ(c - s)}{y_0 - x^\circ(c - s)} \right) + x^\circ(c) - y_0 \right). \quad (14)$$

For $\frac{c - u_m}{e} - y_0 \leq \frac{s}{e} \leq \frac{c}{e}$ the cost of subsidization is given by:

$$S(s) = \frac{s}{\gamma} \left(\log \left(\frac{1 - y_0}{1 - x^\circ(c)} \right) - (x^\circ(c) - y_0) \right)^2. \quad (15)$$

4. *The cost of the subsidy $S(s)$ is decreasing in the subsidy level s for $\frac{\hat{s}}{e} \leq \frac{s}{e} \leq \frac{c - u_m}{e} - x^\circ(c)$, and increasing in s for $\frac{c - u_m}{e} - y_0 \leq \frac{s}{e} \leq \frac{c}{e}$, *i.e.,**

$$\frac{d}{ds} S(s) \begin{cases} < 0 & \frac{\hat{s}}{e} \leq \frac{s}{e} \leq \frac{c - u_m}{e} - x^\circ(c) \\ > 0 & \frac{c - u_m}{e} - y_0 \leq \frac{s}{e} \leq \frac{c}{e} \end{cases} \quad (16)$$

²The cost of subsidization for the remaining case $\frac{c - u_m}{e} - x^\circ(c) \leq \frac{s}{e} \leq \frac{c - u_m}{e} - y_0$ remains to be studied.

The proof is found in the technical report [19].

EXAMPLE 1. We illustrate the results in Prop. 3 with the following example. Fix $u_m = 1$, $u_M = 2$, $e = 3$, $c = 5/2$, $\gamma = 1$, $t_0 = 0$ and $y_0 = 0$. First note $u_M \leq c \leq u_m + e$, so the unsubsidized dynamics $x(t|t_0, x_0)$ will follow case 3) in Prop. 1, and furthermore $x^\circ(c) = 1/4$, and thus $y_0 \leq x^\circ(c)$, so the unsubsidized dynamics will converge to $x^* = 0$. The minimum normalized subsidy to change the equilibrium from 0 to 1 is $\hat{s}/e = 1/6$. The thresholds on the normalized subsidy are $(c - u_m)/e - x^\circ(c) = 1/4$, $(c - u_m)/e - y_0 = 1/2$, and $c/e = 5/6$. The performance metrics $S(s), T(s)$ are shown in Fig. 1. On the plot of $T(s)$ and $S(s)$ vs. s the vertical lines show the critical subsidy levels. Observe $T(s)$ is strictly decreasing for $s/e \leq (c - u_m)/e - y_0$, and then $T(s)$ is independent of s for $s > 3/2$. Further, observe $T(s)$ grows without bound as s decreases towards the minimum subsidy threshold \hat{s} . Next, observe the aggregate subsidy cost $S(s)$ is strictly decreasing for $\hat{s}/e \leq s/e \leq (c - u_m)/e - x^\circ(c)$, and then increases linearly for $s/e \geq (c - u_m)/e - y_0$. The cost $S(s)$ for $s/e \in [(c - u_m)/e - x^\circ(c), (c - u_m)/e - y_0]$ are computed numerically. For large s the cost increases without decreasing the duration, hence these points are inefficient, while for small s the cost again increases as does the cost, and thus such points are also inefficient. There is a critical interval for the subsidy s within which $S(s)$ is decreasing while $T(s)$ is increasing; this interval represents the efficient frontier for the subsidy.

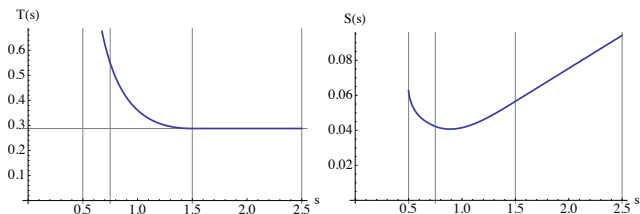


Figure 1: Example 1: Required subsidy duration $\hat{T}(s)$ vs. s (top), and aggregate subsidy cost to provider $S(s)$ vs. s (bottom)

5. CONCLUSION

This paper has investigated the use of cost subsidization as a means of increasing the adoption level of services exhibiting network externalities. Specializing the problem to the simple CLS subsidy and uniform user service affinities, we obtain concrete expressions for the AD, and the two key performance indicators, namely, the aggregate cost of the subsidy to the service provider and the duration of the subsidy. For both small subsidies and large subsidies these two metrics are not in tension in that both are increased by an increase/decrease in the subsidy, while for intermediate subsidies there is a tradeoff between them.

It is obvious that a sufficiently large and long subsidy will serve to drive the AD sufficiently high so as to “cross the knee”, such that the externality can thereafter sustain the AD towards full adoption. The contribution of this paper is in illuminating precisely how the model parameters (u_m, u_M, c, e, γ , and (t_0, y_0)) determine quantities of interest such as the minimum subsidy size, the aggregate cost of the subsidy, or the required duration of the subsidy.

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