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Network Neutrality and Provider Investment Incentives

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Abstract

This paper develops and analyzes a game theoretic model to study how the network regime (neutral or non-neutral) affects provider investment incentives, network quality and user prices. We formulate the conditions under which a non-neutral network is more favorable for providers and users. Our results indicate that the non-neutral regime is more favorable when the ratio between parameters characterizing advertising rates and user price sensitivity is either low or high. When the ratio is in the intermediate range, the neutral regime can be preferable (in terms of social welfare). The degree by which the neutral regime is preferable increases with the number of transit providers.

1 Introduction

In 2006 there was a considerable divergence of opinions on the subject of net neutrality. Indeed the issue was intensely debated by law and policy makers, and the threat of the imposition of restrictive network regulations on internet service providers (ISPs) in order to achieve network neutrality seemed highly likely. Recently, the situation has begun to change. In June 2007, the Federal Trade Commission (FTC) issued a report, forcefully stating the lack of FTC support for network neutrality regulatory restraints, and warning of "potentially adverse and unintended effects of regulation" (FTC, 2007, p. 159). Similarly, on September, 7, 2007 the Department of Justice issued comments "cautioning against premature regulation of the Internet," (DOJ, 2007). Thus, by the fall of 2007, the imminent threat of new regulation has diminished, and a consensus favoring the current (or unregulated) network regime seems to have emerged. Still, the debate about network neutrality is far from over.

The main aspects of network neutrality are user discrimination and service differentiation. A network is weakly neutral if it prohibits user discrimination (pricing users differently for the same service, see Wu, 2003, 2004), where in this context "user" means any party that uses a transit provider's network, which can either be a content provider or an "end" user.

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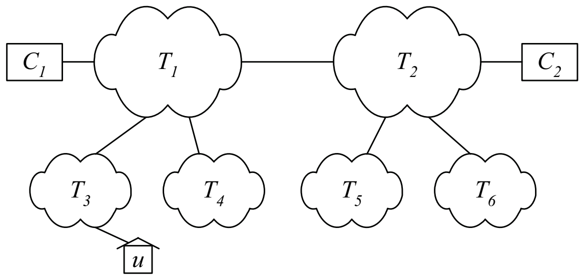

Figure 1: Transport providers $\{T_1, \ldots, T_6\}$, content providers $\{C_1, C_2\}$ and end user u.

It is strongly neutral if it prohibits service differentiation (handling packets differently, see Berners-Lee, 2006). In this paper, we focus on user discrimination. For simplicity, henceforth we use the term neutral to mean weakly neutral and non-neutral to mean that user discrimination is allowed. To introduce the notation and illustrate the arguments for and against network neutrality, consider the network shown in Figure 1.

The figure shows end user u, transport providers $\{T_1, \ldots, T_6\}$, and content providers $\{C_1, C_2\}$. In this network, T_1 and T_2 are transit providers (i.e., transport providers who provide a direct access to a backbone, $T_3 - T_6$ are local internet service providers (ISPs). In the figure, the content providers are attached to a transit provider whereas a typical end user u is attached to an ISP. In a neutral network, end users and content providers pay only for their direct access. The transit providers charge the ISPs for carrying their traffic. The transit providers typically enter in peering agreements under which they agree to carry each other's traffic, usually free of charge. The transit providers charge the content providers for their attachment. Thus, in a neutral network, transport providers are prohibited from charging users not buying access directly from them.

In a non-neutral network, the transit provider T_2 is able to charge C_1 even though that content provider is not attached directly to T_2. Accordingly, T_2 could charge C_1 and not end user u for carrying their traffic, thus allowing transit providers to discriminate between users by charging them differently for the same service. In a non-neutral network, it is also possible for an ISP T_3 to charge C_1 for carrying its traffic.

The arguments pro and against weak neutrality can be summarized as follows. See ACLU (2006), Farber (2007), Felten (2006), Lessig (2006), Owen and Rosston (2003), Sidak (2006), and Yoo (2006) for more elaboration on those points.

Against Neutrality: This line of reasoning is usually expressed by transport (and transit) providers. Say that C_1 is a source of video streams that require a large bandwidth. Transport provider T_2 may argue that to accommodate the traffic needs of C_1, he must make substantial investments, which he cannot recover from the parties who buy access directly from him. For instance, if T_3 faces Bertrand competition from T_4, their access fees are set at marginal costs, which are much smaller than average costs due to the presence of substantial fixed costs. The content providers make additional advertising revenues when end users consume new high-bandwidth services, which justify their investments. If the transport providers cannot get a share of these additional revenues, they will not invest to increase the network capacity. The situation causes poor network quality, which reduces end user demand, which in turn leads to further reduction of incentives to invest for both provider types, transport and content. Said another way, the extra traffic of content providers imposes a negative externality on transit providers. This reduces network quality, which depresses end user demand, and through that investment incentives of all providers. The reduced network investments eventually make all parties worse off.

For Neutrality: This line of reasoning is usually expressed by content providers. If every transport provider can charge the content provider C_i, and not just the transport provider with which C_i is directly connected, the market power of the transport providers would increase dramatically. This would enable the transport providers to charge content providers more, and in turn, this would reduce the investment incentives for content providers thus lowering content quality. Another argument made by some neutrality advocates is that a small startup may be unable to afford the increased network fees before its popularity justifies sufficient advertising revenues, i.e., new content providers will face a higher barrier to entry, which facilitates more concentrated market structure for content providers.

To sum up, both lines of reasoning (of content and transport providers) argue that their preferred regime makes everyone better of, i.e., creates a Pareto improvement. Clearly both sides cannot be right; a more detailed analysis is required to clarify the trade-off. This paper explores how provider investments and revenues differ with network regime. We assume that the number of transport and content providers is fixed. That is, we do not consider the longer term impact of neutrality regulations on the structure of the industry.

In section 2, we propose an economic model that relates the investments and prices to revenue for content and transport providers. We analyze the non-neutral regime in section 3 and the neutral regime in section 4. Section 5 is devoted to a comparison of the two regimes. In section 6 we summarize our findings. The details of the analysis can be found in the appendix.

1.1 Related Work

There is a large literature on two-sided markets, and our model can be viewed in the two-sided market framework. For a survey of two-sided markets see for example Rochet and Tirole 2006 and Armstrong (2006). The two-sided market literature studies markets in which a platform provider needs to attract two types of participants, and the presence of more of the one type makes the platform more valuable to the other type. Rochet and Tirole (2006) define the market as two-sided, when the volume of realized transactions depends not on the aggregate price level, but on the specifics of prices that the parties are charged. Using the two-sided market parlance, the transit providers of our model provide the platform, while end users are one type of participant and content providers are the other type. As will become clear when we describe the details of our model, the end users "single-home" or connect to one transit provider. In a non-neutral network, the content providers are forced to "multi-home" or pay multiple transit providers for delivering their content (see for example Armstrong, 2006 section on the "competitive bottlenecks"). In contrast, the content providers in a neutral network, "single-home" or pay just one transit provider for connectivity. However a content provider that pays one transit provider in a neutral network enjoys the benefits of having connectivity to all the transit providers, because all the transit providers are interconnected. This is in contrast to most two-sided market models where the participants of one platform do not benefit from the presence of participants of another platform, i.e. Microsoft Xbox users do not benefit from more game makers writing Nintendo Playstation games. This is an important structural difference.

Other researchers have also used the ideas of two-sided markets to study network neutrality. Hermalin and Katz (2006) model network neutrality as a restriction on product space, and consider whether ISPs should be allowed to offer more than one grade of service. Hogendown (2007) studies two-sided market where intermediaries sit between "conduits" and content providers. In his context, net-neutrality means content has open access to conduits where an "open access" regime affords open access to the intermediaries. Weiser (2007) discusses policy issues related to two-sided markets.

The novelty of our model over other work in the two-sided market literature is our explicit modeling of platform investment choices. In the existing literature, the platform incurs the cost of serving the users, which usually is assumed linear in the number of users, but does not make an investment choice.

2 Model

Figure 2 illustrates our setting. In the model, there are M content providers and N transport providers. Each transport provider T_n is attached to "end" users U_n $(n = 1, 2, \ldots, N)$ and charges them p_n per click. Transit provider T_n has its end user base U_n, over which it has a monopoly. Thus, the end users are divided between transit providers, with each transit provider having $1/N$ of the entire market. This assumption reflects the market power of regional transit providers. Each transport provider T_n also charges each content provider C_m an amount equal to q_n per click. Content provider C_m invests c_m and transport provider T_n invests t_n.

The rate B_n of clicks of end users U_n depends on the price p_n but also on the quality of the network, which we proxi by provider investments. The rate of clicks B_n, which characterizes end user demand, depends on price and investments as

$$B_n = \left\{ \frac{1}{N^{1-w}} (c_1^v + \cdots + c_M^v) \left[(1-\rho) t_n^w + \frac{\rho}{N} (t_1^w + \cdots + t_N^w) \right] \right\} e^{-p_n/\theta} \tag{1}$$

where $\rho \in (0, 1)$, $\theta > 0$, and $v, w \geq 0$ with $v + w < 1$. For a given network quality (the expression in the curly brackets) the rate of clicks exponentially decreases with price p_n.

The term $c_1^v + \cdots + c_M^v$ is the value of the content providers as seen by a typical end user. This expression is concave in the investments of the individual providers. The interpretation is that each content provider adds value to the network, i.e., end users value a network in which content is produced by numerous content providers higher than the network in which the content is provided by a single provider whose investment equal cumulative investment of all content providers, i.e., as in classical monopolistic competition model by Dixit and Stiglits (1977), our end users exhibit a preference for variety of content. The term in square brackets reflects the value of the transport provider investments for end users. When $\rho = 0$, End user U_n values investments of all transit providers equally, when $\rho = 1$, only investment of his local provider matters for the user, and when $\rho \in (0, 1)$ end user U_n values investment of his local transport provider n more than investments of other provider $k \neq n$, still, investments of other providers add to the value of the network for end user U_n. This effect captures a typical network externality (see Thijssen, 2004 for a discussion of investment spill-over effects). The factor $1/N^{1-w}$ is a convenient normalization. It reflects the division of the end user pool among N providers and it is justified as follows. Suppose there were no spill-over and each transit provider were to invest t/N. The total rate of clicks should be independent of N. In our model, the total rate of click is proportional to $(1/N^{1-w})(N(t/N)^w)$, which is indeed independent of N.

The rate R_{mn} of clicks from end users U_n to C_m is given by

$$R_{mn} = \frac{c_m^v}{c_1^v + \cdots + c_M^v} B_n. \tag{2}$$

Thus, the total rate of clicks for content provider C_m is given by

$$D_m = \sum_n R_{mn}. \tag{3}$$

We assume that content providers charge a fixed amount a per click to the advertisers. Each content provider's objective is to maximize its profit which is equal to net revenues from end user clicks net outside option. Thus

$$R_{Cm} = \sum_{n=1}^{N} (a - q_n) R_{mn} - \beta c_m \tag{4}$$

where the term $\beta > 1$ is the outside option (alternative use of funds c_m).

Transport provider T_n profit is

$$R_{Tn} = \ (p_n + q_n) B_n - \alpha t_n. \tag{5}$$

where $\alpha > 1$ is the outside option of the transit provider. We assume providers of each type are identical and we will focus on finding symmetric equilibria in both the neutral and non-neutral cases.

To compare the neutral and non-neutral cases, we make the following assumptions.

(a) Neutral Case: In stage 1 each T_n simultaneously chooses (t_n, p_n, q_n). In stage 2 each C_m chooses which transit provider to connect to and also chooses c_m.

(b) Non-Neutral Case: In stage 1 each T_n simultaneously chooses (t_n, p_n, q_n). In stage 2 each C_m chooses c_m.

In a neutral network, content providers need only pay the transit provider with which they are directly connected; transit providers elsewhere in the network cannot charge. Thus

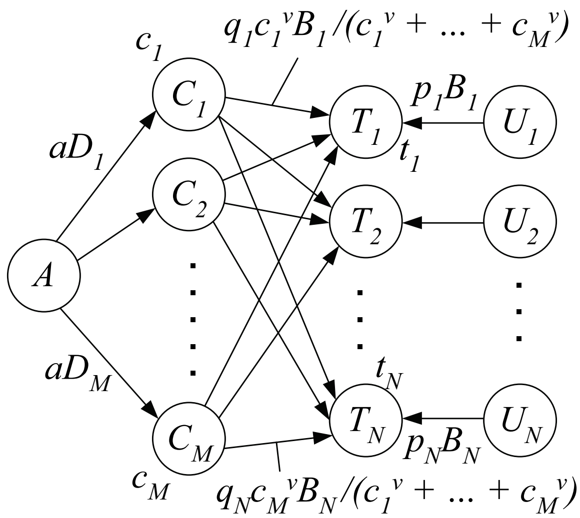

Figure 2: The flows of dollars and bits.

in a neutral network content providers can select which of the transit providers they will connect to and pay. This power to select a transit provider forces transit providers to compete on the price they charge content providers. The Bertrand competition between the transit providers in the neutral case forces the prices $\{q_n\}$ to be zero. In contrast, in an non-neutral network all transit providers have the ability to charge each content provider. This shifts the balance of prices in the direction of transit providers, and allows them to extract a non-zero price. In both regimes, we assume that the investments of content providers observe transport provider investments, and can adjust their investments based on the transport provider choices.

3 Non-Neutral Case

In a non-neutral regime, each transport providers chooses (t, p, q) and the each content provider chooses c. To analyze this situation, we study how C chooses the optimal c for a given (t, p, q). We then substitute that value of c in the expression for R_T and we optimize for (t, p, q).

The best choice for c_m given (t, p, q) maximizes

$$R_{Cm} = aD_m - \sum_n q_n R_{mn} - \beta c_m = N^{w-1} c_m^v [\sum_n (a - q_n)((1-\rho)t_n^w + \frac{\rho}{N}(t_1^w + \cdots + t_N^w))e^{-p_n/\theta}] - \beta c_m. \tag{6}$$

Note that this expression for R_{Cm} does not depend on investments of other content providers C_j, $j \neq m$. Therefore, each content provider need not consider the simultaneous investment decisions of the other content providers. Assuming that the term in square brackets is positive, we find that

$$\beta c_m^{1-v} = vN^{w-1}[\sum_k (a - q_k)((1-\rho)t_k^w + \frac{\rho}{N}(t_1^w + \cdots + t_N^w))e^{-p_k/\theta}] =: \beta c^{1-v}. \tag{7}$$

For that value of c_m, we find that

$$R_{Tn} = MN^{w-1}(q_n + p_n)F_n e^{-p_n/\theta}(\frac{\nu}{N\beta})^{v/(1-v)}[\sum_k (a - q_k)e^{-p_k/\theta}F_k]^{v/(1-v)} - \alpha t_n \quad (8)$$

where

$$F_n = (1-\rho)t_k^w + \frac{\rho}{N}(t_1^w + \cdots + t_N^w) = \phi t_n^w + \frac{\rho}{N}\sum_{k\neq n} t_k^w \quad (9)$$

with

$$\phi := 1 - \rho + \frac{\rho}{N} < 1, \text{ if } N > 1. \quad (10)$$

The transport provider T_n chooses investment and prices (t_n, p_n, q_n) that maximize his profit given by equation (8). The simultaneous decisions of each of the transit providers affect each other, therefore in order to find a Nash equilibrium we need to identify a point where the best response functions intersect. Writing that the three corresponding partial derivatives of (8) are equal to zero, and then finding the symmetric intersection point of the best response functions, we find the following solutions (see appendix):

$$p_n = p = \theta - a; \quad (11)$$

$$q_n = q = a - \theta\frac{v}{N(1-v)+v}; \quad (12)$$

$$t_n = t \text{ with } (Nt)^{1-v-w} = x^{1-v}y^v e^{-(\theta-a)/\theta}; \quad (13)$$

$$c_m = c \text{ with } c^{1-v-w} = x^w y^{1-w} e^{-(\theta-a)/\theta}; \quad (14)$$

$$R_{Cm}^{1-v-w} = R_C^{1-v-w} := \left(\frac{\theta v(1-v)}{N(1-v)+v}\right)^{1-v-w} x^w y^v e^{-(\theta-a)/\theta}; \quad (15)$$

$$R_{Tn}^{1-v-w} = R_T^{1-v-w} := \left(\frac{M\theta(N(1-v) - wN\phi(1-v) - vw)}{N(N(1-v)+v)}\right)^{1-v-w} x^w y^v e^{-(\theta-a)/\theta} \quad (16)$$

$$R_C/c = \frac{\beta(1-v)}{v} \quad (17)$$

$$R_T/t = \frac{\alpha}{w}[\frac{N(1-v)}{N\phi(1-v)+v} - w] \quad (18)$$

$$B^{1-v-w} = M^{1-v-w}x^w y^v e^{-(\theta-a)/\theta} \quad (19)$$

where $B := \sum_n B_n = \sum_m D_m$ is the total click rate and

$$x := \frac{M\theta w}{\alpha}\frac{N\phi(1-v)+v}{N(1-v)+v} \text{ and } y := \frac{\theta}{\beta}\frac{v^2}{N(1-v)+v}. \quad (20)$$

4 Neutral Case

The neutral case is similar to the non-neutral case, except that $q_n = 0$ as we argued in section 2 for $n = 1, \ldots, N$. The best choice of c given $\{q_n = 0, p_n, t_n\}$ is such that

$$\beta c_m^{1-v} = vN^{-1}[\sum_k a((1-\rho)t_k^w + \frac{\rho}{N}(t_1^w + \cdots + t_N^w))e^{-p_k/\theta}] =: \beta c^{1-v}.$$

For that value of c_m, we find that

$$R_{Tn} = MN^{-1} p_n F_n e^{-p_n/\theta} (\frac{\nu}{\beta})^{v/(1-v)} [\sum_k a e^{-p_k/\theta} F_k]^{v/(1-v)} - \alpha t_n \tag{21}$$

where

$$F_n = \phi t_n^w + \frac{\rho}{N} \sum_{k \neq n} t_k^w.$$

The transport provider T_n chooses investment and price (t_n, p_n) that maximize the above expression. We find a symmetric Nash equilibrium by writing that the two corresponding partial derivatives of (21) with respect to a single transit providers actions are zero, and that the other transit providers make the same actions, and solving all of the resulting equations. This analysis leads to the following solutions (see appendix):

$$\begin{aligned}
p_n &= p_0 := \frac{\theta N(1-v)}{N(1-v)+v}; &(22)\\
q_m &= 0; &(23)\\
t_n &= t_0 \text{ where } (Nt_0)^{1-v-w} = x^{1-v} y_0^v e^{-p_0/\theta} &(24)\\
c_m &= c_0 \text{ where } c_0^{1-v-w} = x^w y_0^{1-w} e^{-p_0/\theta} &(25)\\
R_{Cm}^{1-v-w} &= R_{C0}^{1-v-w} := (a(1-v))^{1-v-w} x^w y_0^v e^{-p_0/\theta} &(26)\\
R_{Tn}^{1-v-w} &= R_{T0}^{1-v-w} := \left(\frac{M\theta(N(1-v) - wN\phi(1-v) - wv)}{N(N(1-v)+v)} \right)^{1-v-w} x^w y_0^v e^{-p_0/\theta} &(27)\\
R_{C0}/c_0 &= \frac{\beta(1-v)}{v} &(28)\\
R_{T0}/t_0 &= \frac{\alpha}{w}[\frac{N(1-v)}{N\phi(1-v)+v} - w] &(29)\\
B_0^{1-v-w} &= M^{1-v-w} x^w y_0^v e^{-p_0/\theta} &(30)
\end{aligned}$$

where B_0 is the total click rate, x is given in (20), and

$$y_0 := \frac{av}{\beta}. \tag{31}$$

5 Comparison

In this section we compare the Nash equilibria of the two regime. In section 5.1 we derive expressions for the welfare of end users, and the ratio of social welfare in the neutral vs. non-neutral regimes. In section 5.2 we demonstrate that the return on investments is the same in both regimes. In section 5.3 we compare the revenue and social welfare of the two regimes for a range of parameters.

5.1 User Welfare and Social Welfare

Before proceeding we define the following notation.

$$\pi := \frac{v}{N(1-v)+v} \text{ and } \delta := \frac{a}{\theta}. \tag{32}$$

In order to compute end user welfare, we use the total click rate as aggregate user demand. This enables us to calculate consumer surplus and use it as a measure of end user welfare. We compute the consumer surplus by taking the integral of the demand function from the equilibrium price to infinity. This integral is taken with the investment levels of content and transit providers fixed. We find

$$W_U(\text{non-neutral}) = M\theta x^{w/(1-v-w)} y^{v/(1-v-w)} e^{-\frac{\theta-a}{\theta(1-v-w)}}.$$

The expression for the neutral case is the same, but with y exchanged for y_0. The ratio of the social welfare in the neutral vs. non neutral cases has the form

$$\frac{W_U(\text{neutral}) + NR_T(\text{neutral}) + MR_C(\text{neutral})}{W_U(\text{non-neutral}) + NR_T(\text{non-neutral}) + MR_C(\text{non-neutral})}$$
$$= \frac{1+\delta(1-v)+(\pi/v)(N(1-v)-wN\phi(1-v)-wv)}{1+\pi(1-v)(\pi/v)(N(1-v)-wN\phi(1-v)-wv)}[(\delta/\pi)^v e^{\pi-\delta}]^{1/(1-w-v)}.$$

5.2 Return on Investment

Proposition 1

$$p = \theta(1-\delta).$$

Also, we note that

$$p + q = p_0 = \theta(1-\pi).$$

Moreover,

$$\frac{R_C}{c} = \frac{R_{C0}}{c_0} \text{ and } \frac{R_T}{t} = \frac{R_{T0}}{t_0}.$$

That is, the total revenue per click of the transit providers is the same in both regimes and so are the rate of return on investments of the content and transit providers.

The rate of return on investments are the same in both the neutral and non-neutral cases. However, the size of those investments and resulting profits might be quite different in the two regimes as we see in the next subsection.

5.3 Comparative Statics

Dividing the expressions for the neutral case by the corresponding expressions the non-neutral case, we define ratios such as

$$r(R_C) := \left(\frac{R_C(\text{neutral})}{R_C(\text{non-neutral})}\right)^{1-v-w}$$

where $R_C(\text{non-neutral})$ is the revenue per content provider in the non-neutral case as expressed in (15) and $R_C(\text{neutral})$ is the revenue per content provider in the neutral case (26). We define $r(c), r(t)$, and $r(R_T)$ similarly. We find

$$r(R_T) = r(t) = r(B) = \left(\frac{\delta}{\pi}\right)^v e^{\pi-\delta} \quad (33)$$

$$r(R_C) = r(c) = \left(\frac{\delta}{\pi}\right)^{1-w} e^{\pi-\delta} \quad (34)$$

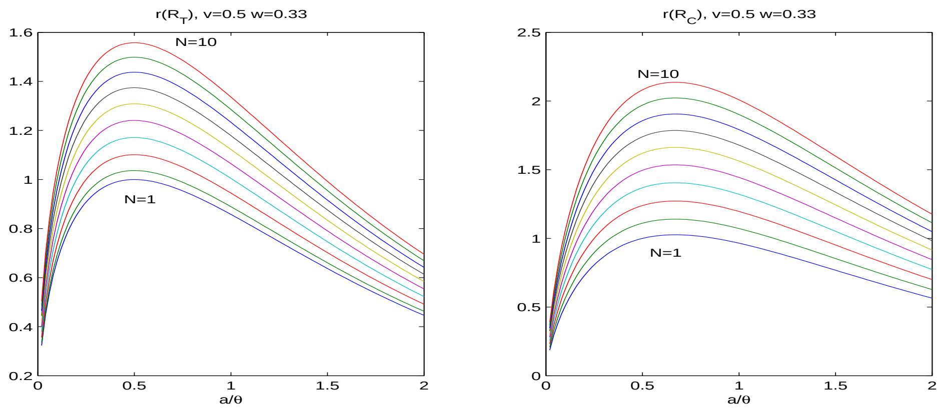

Figure 3: The ratios of revenues $v = 0.5, w = 0.33$ for different values of N.

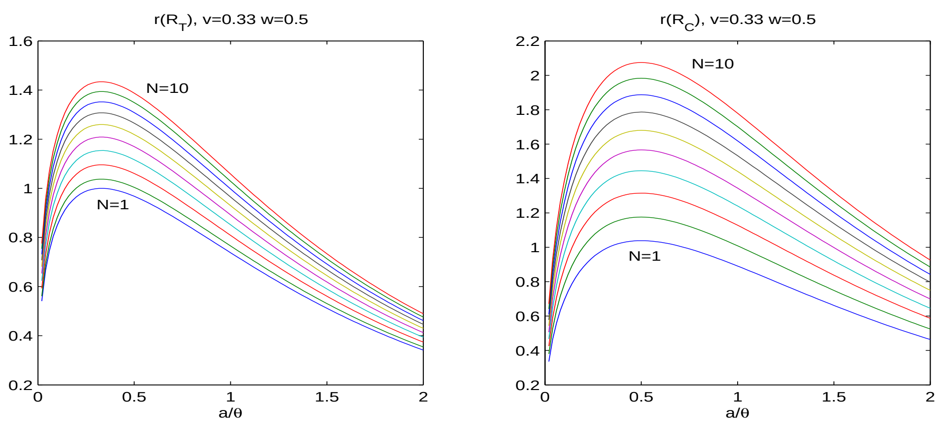

Figure 4: The ratios of revenues $v = 0.33, w = 0.5$ for different values of N.

Figure 3 shows the ratios of revenues in the neutral vs. the non-neutral cases for both content and transit providers. Figure 4 shows the same ratios, but for different values of v and w. The figures show that for small or large values of a/θ, the ratio of advertising revenue per click to the constant characterizing price sensitivity, the non-neutral regime is preferable to both content and transit providers. (Here we say "preferable" in that the revenues are larger, though we have seen that the rate of return on investments are the same.) For mid range values of a/θ, the neutral regime is preferable to both, though the values of a/θ where the transition between neutral being preferable to non-neutral are not exactly the same for content providers and transit providers. Furthermore, as N, the number of transit providers increases, the range of a/θ values for which neutral is superior increases, while also the degree by which it is superior (in terms of revenues to content and transit providers) increases.

These results can be explained by the following reasoning. When a/θ is large, the content providers' revenues from advertising are relatively high, and the transit providers' revenue from end users are relatively low. Because of this, the transit providers do not have a strong incentive to invest, unless they can extract some of the content providers' advertising revenue by charging the content providers. Thus in the neutral regime, the transit providers under invest, making the rewards for them as well as content providers less than it could have been in a non-neutral regime.

When a/θ is very small, the revenues from content providers' advertising revenue is relatively low, and the transit provider's end user revenue is relatively high. In order to get the content providers to invest adequately, the transit providers need to pay the content providers. That is why for small enough a/θ the price q is negative (see Figure 5), representing a per click payment from the transit providers to the content providers.

It is also interesting to note that our content providers obviously get some share of the surplus generated jointly by them and the transit providers in the-neutral case. This is in contrast to the multi-homing case of Armstrong (2006) (which is roughly analogous to our non-neutral case), the surplus is fully extracted from group-2 agents (content providers in our case) – the entire surplus is shared between between the platform and the end users. We do not have this extreme result, because in our model content providers invest after transit providers announce prices. Thus, transit provider commitment to prices permits content providers to retain a positive fraction of the surplus.

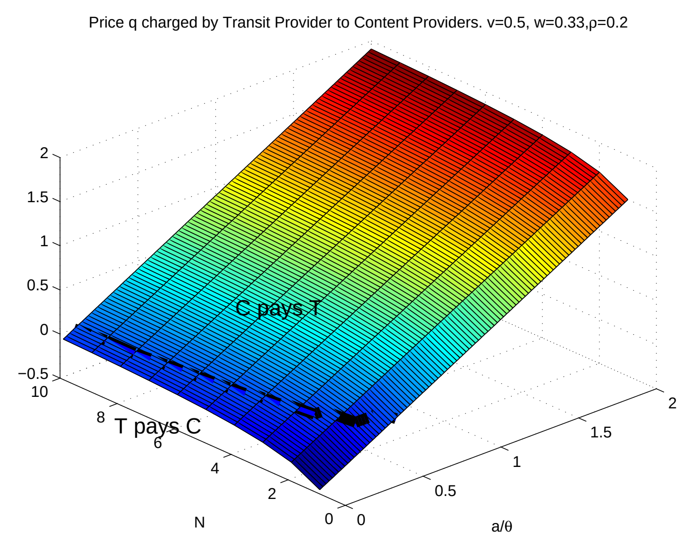

Figure 5: The price q charged by transit providers to content providers. The price is negative for small enough a/θ.

Finally, when a/θ is in between the two extremes both content providers and transit providers have adequate incentive to invest. However another effect comes into play. As N increases in the non-neutral regime there are more transit providers that levy a charge against each content provider. As the price transit providers charge content providers increases, it becomes less attractive for content providers to invest. Thus a transit provider choosing the price to charge content providers is balancing the positive effect of earning more revenue per click from content providers versus the negative effect of having fewer clicks because the content providers have reduced their investment. But each transit provider sees all the positive of raising its price, but the negative effect is borne by all the N transit providers. Consequently, the transit providers have overcharge the content providers in Nash equilibrium, and the degree of this overcharging increases with N. This is analogous to the tragedy of the commons where people overexploit a public resource. Another perhaps more direct analogy is the "castles on the Rhine effect" where each castle owner is incentivized to increase transit tolls on passing traffic without realizing that if all castles do the same, the traffic on the Rhine will decrease (Kay, 1990).

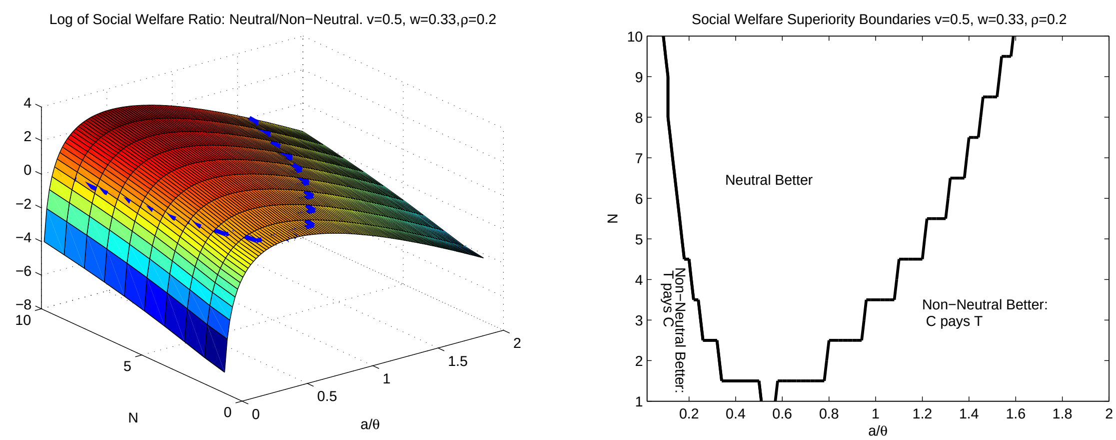

Figure 6: Left: The Log of the Ratio of Social Welfare. Neutral Welfare divided by Non-Neutral Welfare. Right: Regions of Social Welfare Superiority for Neutral vs. Non-Neutral.

Figure 6 shows a three dimensional plot of the ratio of social welfare in the neutral vs. non-neutral cases. The plot shows how the ratio changes for different N and a/θ. The second panel of Figure 6 is essentially a simplified version of the first panel showing just the boundaries in the parameter space where neutral is preferable to neutral and vice versa.

6 Conclusions

We study how the network regime affects investment incentives of transit and content providers. We show that parameters such as advertising rate, end user price sensitivity, and the number of transit providers influence whether a neutral or non-neutral regime achieves a higher social welfare. From our results, when the ratio of advertising rates to the constant characterizing price sensitivity is an extreme value, either large or small, the non-neutral regime is preferable. If the ratio of advertising rates to the constant characterizing price sensitivity is not extreme, then an effect like the "castles on the Rhine effect" becomes more important. Transit providers in a non-neutral regime have the potential to over charge content providers, and this effect becomes stronger as the number of transit providers increases.

In our comparison of the neutral and non-neutral networks we assume that the transport providers choose their strategy first and that the content providers follow. We justify this assumption by the difference in time scales of investments. There are several limitations of our model. First we have a fixed number of network providers that is independent of the network regime. Second, we do not consider heterogeneity in the providers nor in the end users. Third, we assume full commitment to the declared prices, i.e. the transit providers cannot later change the prices declare in the first stage. We also have not modeled the price content providers charge advertisers as a decision variable, but we have modeled the price transit providers charge end users. Though we feel that the present model has the right features to capture the effects of interest in this paper, in future models we might also consider the pricing between content providers and advertisers endogenously.

7 Appendix 1: Calculations for Non-Neutral Case

Recall that R_{Cm} is given by (4) where R_{mn} is defined in (2) and B_n is given in (1). Putting these expressions together, we find

$$R_{Cm} = N^{w-1} c_m^v \sum_n (a - q_n) F_n e^{-p_n/\theta} - \beta c_m \tag{35}$$

where F_n is defined in (9). Given the values of (p_n, q_n, t_n), the value of c_m that maximizes R_{Cm} is such that the derivative of (35) with respect to c_m is equal to zero. That is,

$$v N^{w-1} c_m^{v-1} \sum_n (a - q_n) F_n e^{-p_n/\theta} - \beta = 0.$$

Equivalently, one finds (7). That is,

$$c_m = c = \left(\frac{v N^{w-1}}{\beta} \sum_n (a - q_n) F_n e^{-p_n/\theta} \right)^{1/(1-v)}. \tag{36}$$

Now, R_{Tn} is given by (5) where B_n is given in (1). Combining these expressions, we find

$$R_{Tn} = (q_n + p_n) B_n - \alpha t_n = N^{w-1}(q_n + p_n)(c_1^v + \cdots + c_M^v) F_n e^{-p_n/\theta} - \alpha t_n. \tag{37}$$

Substituting the values of c_n given by (36) into (37), we find (8) that we recall below:

$$R_{Tn} = M N^{w-1}(q_n + p_n) F_n e^{-p_n/\theta} \left(\frac{v N^{w-1}}{\beta}\right)^{v/(1-v)} \left[\sum_k (a - q_k) e^{-p_k/\theta} F_k\right]^{v/(1-v)} - \alpha t_n. \tag{38}$$

We now write that the partial derivatives of (37) with respect to q_n, p_n, and t_n are all equal to zero.

Derivative with respect to q_n

If the derivative of (38) with respect to q_n is equal to zero, then so is that of

$$(q_n + p_n)[\sum_k (a - q_k)e^{-p_k/\theta} F_k]^{v/(1-v)}.$$

That is, with $A := \sum_k (a - q_k)e^{-p_k/\theta} F_k$,

$$A^{v/(1-v)} - (q_n + p_n)\frac{v}{1-v} A^{v/(1-v)-1} F_n e^{-p_n/\theta} = 0,$$

so that

$$A = (q_n + p_n)\frac{v}{1-v} F_n e^{-p_n/\theta}. \tag{39}$$

Derivative with respect to p_n

If the derivative of (38) with respect to p_n is equal to zero, then so is that of

$$(q_n + p_n)e^{-p_n/\theta} A^{v/(1-v)}.$$

Hence,

$$e^{-p_n/\theta} A^{v/(1-v)} - (q_n+p_n)e^{-p_n/\theta}\frac{1}{\theta}A^{v/(1-v)} - \frac{v}{1-v}(q_n+p_n)e^{-p_n/\theta}\frac{1}{\theta}A^{v/(1-v)-1}(a-q_n)F_n e^{-p_n/\theta} = 0.$$

Using (39) in the last term before the equal sign, we find that

$$e^{-p_n/\theta} A^{v/(1-v)} - (q_n + p_n)e^{-p_n/\theta}\frac{1}{\theta}A^{v/(1-v)} - \frac{1}{\theta}A^{v/(1-v)}(a - q_n)e^{-p_n/\theta} = 0.$$

Multiplying this identity by θ and dividing it by $e^{-p_n/\theta} A^{v/(1-v)}$, we find that

$$\theta = (q_n + p_n) + (a - q_n),$$

which implies (11).

Derivative with respect to t_n

We know that $p_n = p$. Assume that $q_n = q$ for $n = 1, \ldots, N$. Then we find from (38) that

$$R_{Tn} = MN^{w-1}(p + q)F_n e^{-p/(\theta(1-v))} \left(\frac{(a - q)v}{N^{1-w}\beta}\right)^{v/(1-v)} [t_1^w + \cdots + t_N^w]^{v/(1-v)} - \alpha t_n. \tag{40}$$

Observe that the partial derivative of F_n with respect to t_n is equal to $\phi w t_n^{w-1}$. Consequently, writing that the partial derivative of (40) with respect to t_n is equal to zero, we find that

$$\phi w t_n^{w-1} MN^{w-1}(p + q)e^{-p/(\theta(1-v))} \left(\tfrac{(a-q)v}{N^{1-w}\beta}\right)^{v/(1-v)} [t_1^w + \cdots + t_N^W]^{v/(1-v)}$$
$$+ MN^{w-1}(p + q)F_n e^{-p/(\theta(1-v))} \left(\tfrac{(a-q)v}{N^{1-w}\beta}\right)^{v/(1-v)} \tfrac{v}{1-v} w t_n^{w-1}[t_1^w + \cdots + t_N^W]^{v/(1-v)-1} - \alpha = 0.$$

The solution is such that $t_n = t$ where

$$\phi w t^{w-1} M N^{w-1}(p+q)e^{-p/(\theta(1-v))}\left(\tfrac{(a-q)v}{N^{1-w}\beta}\right)^{v/(1-v)}[Nt^w]^{v/(1-v)}$$
$$+ MN^{w-1}(p+q)t^w e^{-p/(\theta(1-v))}\left(\tfrac{(a-q)v}{N^{1-w}\beta}\right)^{v/(1-v)}\tfrac{v}{1-v}wt^{w-1}[Nt^w]^{v/(1-v)-1} - \alpha = 0.$$

That is, after some algebra,

$$M(p+q)(\phi + \frac{v}{N(1-v)})w\left(\frac{(a-q)v}{\beta}\right)^{v/(1-v)}(Nt)^{-(1-v-w)/(1-v)}e^{-p/(\theta(1-v))} = \alpha. \quad (41)$$

Now, from (39), with $q_n = q, p_n = p, t_n = t$, we find

$$(a-q)e^{-p/\theta}Nt^w = (q+p)\frac{v}{1-v}t^w e^{-p/\theta},$$

which after some simplifications yields (12). Combining (12) and (11), we find

$$q+p = \frac{\theta N(1-v)}{N(1-v)+v} \text{ and } a-q = \frac{\theta v}{N(1-v)+v}. \quad (42)$$

Substituting these expressions in (41), we find (13).

Calculating $c_n = c$

To calculate c, we substitute (13) into (36) and we find (14).

Calculating R_{Cm}

Note that, from (35) and $p_n = p, q_n = q, t_n = t, c_m = c$,

$$R_C := R_{Cm} = c^v(a-q)(Nt)^w e^{-p/\theta} - \beta c.$$

Substituting the value of $a-q$ from (42), we find

$$R_C = c^v\frac{\theta v}{N(1-v)+v}(Nt)^w e^{-p/\theta} - \beta c.$$

Substituting the value of t from (13), we find that (16) holds.

Calculating R_{Tn}

Recall (40):

$$R_{Tn} = MN^{w-1}(p+q)F_n e^{-p/(\theta(1-v))}\left(\frac{(a-q)v}{N^{1-w}\beta}\right)^{v/(1-v)}[t_1^w + \cdots + t_N^w]^{v/(1-v)} - \alpha t_n.$$

Substituting the values of $p+q$ and $a-q$ from (42), we find

$$R_T := R_{Tn} = \frac{M\theta(1-v)}{N(1-v)+v}(Nt)^{w/1-v}\left(\frac{\theta v^2}{\beta(N(1-v)+v)}\right)^{v/(1-v)}e^{-p/(\theta(1-v))} - \alpha t.$$

Substituting the expression (13) for t, we find (16).

8 Appendix 2: Calculations for Neutral Case

When $q_n = 0$, instead of (35), we find

$$R_{Cm} = N^{w-1} a c_m^v \sum_n F_n e^{-p_n/\theta} - \beta c_m. \tag{43}$$

Expressing that the derivative with respect to c_m is equal to zero, we find

$$N^{w-1} a v c_m^{v-1} \sum_n F_n e^{-p_n/\theta} - \beta = 0,$$

so that

$$c_m = c_0 := \left(\frac{av}{N^{1-w}\beta} \sum_k F_k e^{-p_k/\theta} \right)^{1/(1-v)}. \tag{44}$$

Now, instead of (38), we find

$$R_{Tn} = M N^{w-1} p_n F_n e^{-p_n/\theta} (\frac{avN^{w-1}}{\beta})^{v/(1-v)} [\sum_k e^{-p_k/\theta} F_k]^{v/(1-v)} - \alpha t_n \tag{45}$$

We now write that the partial derivatives of (45) with respect to p_n and t_n are all equal to zero.

Derivative with respect to p_n

If the derivative of (45) with respect to p_n is equal to zero, then so is that of

$$p_n e^{-p_n/\theta} B^{v/(1-v)} \text{ with } B := \sum_k F_k e^{-p_k/\theta}.$$

Hence,

$$e^{-p_n/\theta} B^{v/(1-v)} - \frac{1}{\theta} p_n e^{-p_n/\theta} B^{v/(1-v)} - \frac{v}{1-v} p_n e^{-p_n/\theta} B^{v/(1-v)-1} \frac{1}{\theta} F_n e^{-p_n/\theta} = 0,$$

i.e.,

$$NB = N\frac{1}{\theta} p_n B + \frac{v}{1-v} p_n \frac{1}{\theta} N F_n e^{-p_n/\theta}.$$

Assuming that $t_n = t_0$ and $p_n = p_0$, we see that $B = N t_0^w e^{-p_0/\theta} = N F_n e^{-p_0/\theta}$, so that the identity above implies

$$N\theta = N p_0 + \frac{v}{1-v} p_0,$$

which yields (22).

Derivative with respect to t_n

If the derivative of (45) with respect to t_n is equal to zero, with $p_k = p_0$ for all k, then so is that of

$$F_n[\sum_k F_k]^{v/(1-v)} - \frac{\alpha N^{1-w}}{Mp_0}\left(\frac{N^{1-w}\beta}{av}\right)^{v/(1-v)} e^{p_0/(\theta(1-v))} t_n.$$

Accordingly,

$$\phi w t_n^{w-1}[\sum_k F_k]^{v/(1-v)} + \frac{v}{1-v} F_n w t_n^{w-1}[\sum_k F_k]^{v/(1-v)-1} = \frac{\alpha N^{1-w}}{Mp_0}\left(\frac{N^{1-w}\beta}{av}\right)^{v/(1-v)} e^{p_0/(\theta(1-v))}.$$

With $t_k = t_0$ for all k, one has $F_k = t_0^w$, so that the above identity implies

$$\phi w t_0^{w-1}[N t_0^w]^{v/(1-v)} + \frac{v}{1-v} t_0^w w t_0^{w-1}[N t_0^w]^{v/(1-v)-1} = \frac{\alpha N^{1-w}}{Mp_0}\left(\frac{N^{1-w}\beta}{av}\right)^{v/(1-v)} e^{p_0/(\theta(1-v))},$$

so that, with $\Delta = 1 - v - w$,

$$w[\phi + \frac{v}{N(1-v)}] t^{-\Delta/(1-v)} N^{v/(1-v)} = \frac{\alpha N^{1-w}}{Mp_0}\left(\frac{N^{1-w}\beta}{av}\right)^{v/(1-v)} e^{p_0/(\theta(1-v))}.$$

This identity implies (24).

Calculating $c_n = c_0$

Substituting $t_n = t_0$ and $p_n = p_0$ in (44), we find

$$c_0 = \left(\frac{av}{N\beta}\sum_k F_k e^{-p_k/\theta}\right)^{1/(1-v)} = \left(\frac{av}{\beta} t_0^w e^{-p_0/\theta}\right)^{1/(1-v)} = \left(\frac{av}{\beta}\right)^{1/(1-v)} t_0^{w/(1-v)} e^{-p_0/(\theta(1-v))}.$$

Substituting (24) in that expression, we get

$$\begin{aligned} c_0 &= \left(\tfrac{av}{\beta}\right)^{1/(1-v)} [x^{1-v} y_0^v e^{-p_0/\theta}]^{w/(\Delta(1-v))} e^{-p_0/(\theta(1-v))} = y_0^{1/(1-v)} [x^{1-v} y_0^v e^{-p_0/\theta}]^{w/(\Delta(1-v))} e^{-p_0/(\theta(1-v))} \\ &= x^{w/\Delta} y_0^{(1/(1-v)) + vw/(\Delta(1-v))} e^{-[p_0/(\theta(1-v))](1+(w/\Delta))} = x^{w/\Delta} y_0^{(1-w)/\Delta} e^{-p_0/(\theta\Delta)}, \end{aligned}$$

which is (25).

Calculating R_{Cm}

From (6) with $q_n = 0, p_n = p_0, c_m = c_0$, and $t_n = t_0$, we find

$$R_{Cm} = c_0^v a (N t_0)^w e^{-p_0/\theta} - \beta c_0.$$

Substituting in this expression the values of c_0 and t_0 given by (25) and (24), respectively, we get

$$\begin{aligned} R_{Cm} &= x^{w/\Delta} y_0^{v/\Delta} e^{-p_0/(\theta\Delta)} a - \beta x^{w/\Delta} y^{(1-w)/\Delta} e^{-p_0/\theta} \\ &= x^{w/\Delta} y_0^{v/\Delta} e^{-p_0/(\theta\Delta)} (a - \beta y) = x^{w/\Delta} y_0^{v/\Delta} e^{-p_0/(\theta\Delta)} a(1-v), \end{aligned}$$

which is (26).

Calculating R_{Tn}

Letting $p_n = p_0, q_0 = 0, t_n = t_0$, and $c_m = c_0$ in (45), we get

$$\begin{aligned}
R_{Tn} &= MN^{w-1}p_0t_0^we^{-p_0/\theta}(\frac{avN^{w-1}}{\beta})^{v/(1-v)}(Nt_0^we^{-p_0/\theta})^{v/(1-v)} - \alpha t_0 \\
&= \frac{M\theta(1-v)}{N(1-v)+v}(Nt_0)^{w/(1-v)}e^{-p_0/(\theta(1-v))}y_0^{v/(1-v)} - \alpha t_0 \\
&= \frac{M\theta(1-v)}{N(1-v)+v}x^{w/\Delta}y_0^{vw/(\Delta(1-v))}e^{-p_0w/(\theta\Delta(1-v))}e^{-p_0/(\theta(1-v))}y_0^{v/(1-v)} - \alpha t_0 \\
&= \frac{M\theta(1-v)}{N(1-v)+v}x^{w/\Delta}y_0^{v/\Delta}e^{-p_0/(\theta\Delta)} - \alpha t_0 \\
&= \frac{M\theta(1-v)}{N(1-v)+v}x^{w/\Delta}y_0^{v/\Delta}e^{-p_0/(\theta\Delta)} - \frac{\alpha}{N}x^{(1-v)/\Delta}y_0^{v/\Delta}e^{-p_0/(\Delta\theta)} \\
&= x^{w/\Delta}y_0^{v/\Delta}e^{-p/(\theta\Delta)}[\frac{M\theta(1-v)}{N(1-v)+v} - \frac{\alpha}{N}x] \\
&= \frac{M\theta(N(1-v) - wN\phi(1-v) - vw}{N(N(1-v)+v)}x^{w/\Delta}y_0^{v/\Delta}e^{-p/(\theta\Delta)},
\end{aligned}$$

which is (27).

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