Fifty-Fifth Annual Allerton Conference
Allerton House, UIUC, Illinois, USA
October 3-6, 2017

Optimal Pricing Policy of Network Goods

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***Abstract*—We study the optimal pricing policy of a strategic monopolist selling durable goods in a dynamic pricing game with multiple rounds. Customers are forward-looking and experience a (positive) network externality, i.e., each customer's utility depends not only on her valuation of the item and the offered price, but also the weighted sum of the number of other customers who have purchased the item. The monopolist announces and commits to a price sequence and strategic buyers decide on when (if ever) to buy the good in a perfect Bayesian equilibrium. We fully characterize the optimal pricing policy and show that it is linearly increasing in time, where the slope of the price path is described by a single network measure: sum of the entries of the inverse of network externality matrix, termed network effect. Our result shows that increasing the number of rounds and network effect increases both revenue and social welfare. We also establish that increasing network asymmetry, increases the network effect which in turn increases the revenue.**

I. Extended Abstract

The benefits that users derive from various products such as digital products (e.g., computer softwares and smartphone apps) and electronics (e.g., smart phones, hardware devices, and computers) depends, among other things, on the externalities of users who have contributed to improvement of various aspects of the product. These improvements are provided via customers' feedback such as product satisfaction survey resulting in adjusting features and increasing the compatibility of the product. Many online forums provide a platform for exchanging information/opinions regarding the product and customers observe the extent of these externalities over time. Therefore, customer strategies in such settings with externalities, called network effects, will focus, among other things, on not just whether but when to make a purchase. This in turn implies that seller strategies must build up the number of early users to increase these network effects. Sellers will try to achieve this, among other things, by choosing the right dynamic price path for their products. Despite the ubiquity of these concerns, there is little work on dynamic pricing with network effects.

In this paper, we study the problem of dynamic pricing in the presence of network effects. We consider a dynamic game between a seller and a set of buyers. All buyers and seller are forward-looking. The seller announces and *commits* to a price sequence and buyers decide whether and when to buy a single item. The utility of each buyer depends on her valuation of the item, the price, and the (weighted) number of other customers who have already bought the item. Different weights capture differentiation in buyers' preferences regarding various aspects of a product. For example, customers of Microsoft Office products receive positive network effects from previous users. This is because of the improvement of various features of their products by fixing errors and incorporating suggestions provided by their customers. Therefore, by purchasing a certain release of Microsoft office, a buyer enjoys all the features and improvements in the product provided by previous users' feedback.

We consider a Perfect Bayesian Equilibrium (PBE) and show that the optimal price path is non-decreasing. We then show that the equilibrium behavior of buyers (in PBE) can be characterized by a threshold rule in which buyers purchase at different rounds if and only if their valuations exceeds a certain threshold. As the optimal price sequence is non-decreasing, by postponing purchase to future rounds each buyer faces the following tradeoff: on one hand, she has to pay a higher price and on the other hand, her utility from the network effects becomes larger.

Building on this characterization, we consider a block-model with m blocks such that each block (group) h has a fraction of the total number of buyers equal to $\alpha_h n$, where $\alpha_h \in [0, 1]$. The network effects between any pair of buyers depends only on the block they belong to. In particular, we denote the networks effects between any two buyers from blocks h and h' by $E_{hh'}$. This model captures the setting in which different buyers of a product with network effects, have different preferences for various aspects/features of the product. This can be a result of horizontal product differentiation in which buyers evaluate a product based on a variety of characteristics (see Chapter 7, [1] and Chapter 8 [2]). For instance, in evaluating a software quality a group of buyers might care more about user interface of the software while others might care about software functional quality or structural quality. Buyers with similar preferences belong to the same group and have the same network effects on buyers from other group. Using techniques from probability theory (namely, Berstein polynomial convergence [3] and [4]), for this general setting, we explicitly find the optimal pricing policy as well as the optimal normalized revenue in the limit as the number of buyers goes to infinity. Interestingly, we establish that for any distribution for buyers' valuations, the optimal pricing policy is linearly increasing.

Our characterization shows that the properties of both optimal pricing policy and the optimal revenue depends on the quantity $1/\left(\mathbf{1}^T E^{-1} \mathbf{1}\right)$ which we term *network effect*. In particular, the extent of the price difference at two consecutive rounds (slope of the price path) is higher for higher network effect and the optimal revenue is increasing and concave in the total number of rounds and increasing and convex in network effect. The network effect (and hence the optimal revenue) is higher for "asymmetric" networks. More precisely, for a "weakly tied" block-model, for a given sum of network externalities, the revenue is larger for networks in which sum of the products of out-degree and in-degree is lower. For instance, a star network has a higher revenue than a chain network which has a higher revenue than a ring network.

We then consider the effects of price discrimination among different groups of buyers. We show that the optimal pricing policy is linearly increasing with a slope which is in form of a "Bonacich centrality". We establish that in earlier rounds monopolist offers lower prices to groups with higher centralities in order to encourage them to purchase, which in turn further incentivize other customers to purchase in the subsequent rounds.

Moreover, we study two extensions of our model. In particular, we study the effects of non-committed seller in a setting with two rounds and uniform network effects. For this setting, we explicitly find the optimal price equilibrium as well as the optimal revenue. Finally, we consider a variation of our model in which buyers obtain utility from the purchase of other buyers in any round of the game. We provide an example which shows that the optimal pricing policy can either be increasing or decreasing. We then provide a full characterization of the optimal non-decreasing pricing policy and highlight its dependence on the network effects. Full paper is available online.[1]

A. Related Literature

Our paper relates to two series of works: (i) the study of markets with network effects and (ii) the study of markets with strategic forward-looking buyer behaviors.

1) Network Externalities: Markets for products with network externalities has been first studied in [5], [6], and [7]. Network effects can either be direct or indirect. If the utility that a customer derives from the product increases as the number of adopters increases, then a direct network effect exist as studied in [6], [8]. Examples include communication services such as mobile phone and instant messaging systems as the value of such services is a function of the number of others who also use the service. Indirect or complementary network effects arise when there is a positive link between the utility to a customer and the number of other users of the product because of complementary products. This form of network effects might exist because of interchangeability of complementary products such as computer software, video games, and electric cars because of availability of alternative fueling stations.

Given the importance of network effects in markets, empirical investigations have examined the implications of direct and indirect network effects in a variety of industries including [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22]. In particular, [13] examine the adoption of electronic bill presentment and payment technology and show the existence of network effects and its implications, [14] examine the impact of network effects in the context of nationally shared electronic banking networks, [15] demonstrate the presence of network effects in ATM adoption decisions, [20] empirically study firms' choice of organizational form and examine network effects on formations of limited liability partnerships (LLPs) and limited liability companies (LLCs), [21] empirically study the market for Web server software and establish the existence of network effects, [22] study the effect of network effects on the pioneer survival in technology market, and [11] empirically study the network effects in software product market and establish that the network effects significantly has increased the price of products.

Moreover, on the theory side an extensive study has examined the strategic and welfare implications of network effects. A consistent finding in the literature is that network externalities alter customer behavior [6], [23], [24], [25], [26], [27], [28]. In particular, [23] deal with indirect positive network effects and show that its effect may inhibit innovation. [26] studies the incentive of an exclusive holder of a technology to share it with competitors in a market with network effects and shows that the innovator is better off as one of many oligopolists firms rather than as a monopolist (a related question is recently studied in [29]). The Marketing literature has examined pricing with "experience" or "network" effects [30], [31], [32], [33], [34], [35], and [36]. In particular, [35] and [37] study the optimal static pricing policy of a seller selling a divisible good (service) to consumers with network effects. They consider a two-stage game in which a seller decides on the prices and then buyers decide their consumption in an equilibrium. Given a set of prices, their model takes the form of a network game among agents that interact locally, which relates to a series of papers such as [38], [39], [40], [41], and [42] (a related model is more recently investigated in [43] and [44]). More recently, [45] have considered the promotion planning for network goods and studied the effects of network structure on the revenue. Also, closely related are [46], [47] which focus on algorithmic question of finding revenue maximizing strategy.

The most related papers to our work are [48], [49], [50], [30], and [51]. [48] and [49] use an optimal control methodology to develop a dynamic pricing schedule for a service with expanding network (e.g., communication network). They show that it is optimal for a monopolist to set a lower price when consumers anticipate rapid network growth. [50] show that an increasing price trajectory is optimal for a duopoly durable goods market with strong network effects. [30] study a setting with two buyers in which a monopolist price a product that is subject to network externalities and show that the optimal price increases over time. Finally, [51] study the effect of network externalities in market growth. They argue that despite the conventional wisdom which suggests that network effects should derive faster market growth due to bandwagon effect ([52], [53], [54], [55]), there is a chilling effect due to the "wait-and-see" behavior of consumers. Therefore, the growth of network goods has a slow initial phase followed by a fast

[1] Available at SSRN: https://ssrn.com/abstract=2980109.

growth stage.

2) Strategic Buyers: Settings with strategic buyers are commonly studied in the literature to describe rational and forward-looking buyers, who make inter-temporal purchasing decisions with the goal of maximizing their utility. Many empirical works suggested that assuming myopic customer behavior is no longer a tenable assumption (see [56], [57]). The importance of forward-looking customer behavior in shaping firms' pricing decision has been broadly identified by practitioners and firms are largely investing in price optimization algorithms ([58]) and a recent literature has pursued to provide managerial insights for firms to adjust their approach to dynamic pricing [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [71], [73], [74], [75] (see [76] for a survey on dynamic pricing literature). In particular, [77] study the optimal pricing policy of a committed seller that faces customers arriving over time which are strategic in timing their purchases and have heterogeneous valuation and willingness to wait before purchasing. They show that cyclic pricing policies is optimal for this setting. [78] study the effect of pricing on expanding the installed base through word-of-mouth, and [79] consider a model with two periods and study the effect of social learning on the optimal pricing. They show that the optimal price path can either be increasing or decreasing depending on whether the seller is committed.

The literature with strategic consumer behavior typically assumes firms employ one of two classes of dynamic- pricing policies: (i) with commitment (ii) without commitment (see [80], [81], [82], [83] for committed pricing and [34], [84], [85], [86] for non-committed pricing). A question of particular interest in our work is which class of policies (i.e., with or without commitment) is preferred by the firm. We show that a policy with committed pricing leads to a higher revenue for the seller.[2]

The most related papers to our work are [103] and [104]. In particular, building on the model presented in [103], [104] study a setting in which a seller who must sell her inventory (single item) before some deadline, facing a group of buyers with independent private values, sets prices in some time periods. In contrast with our problem, they show that the optimal price sequence is decreasing and buyers face the following trade-off: by buying early they pay a higher price with a higher chance of obtaining the item and by waiting they face a lower price with a lower chance of obtaining the item as other buyers also accept the lower price (a related problem is more recently studied in [105]).

[2]Our paper also relates to a vast literature on the "Coase conjecture" [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97]. [98] claimed that the price set by a monopolist who is unable to commit to future prices will quickly converge to marginal cost as the time between sales becomes arbitrarily short. The Coase conjecture was confirmed and disconfirmed under a variety of conditions. In all cases the equilibrium solutions obey "Coasian dynamics" ([99]). Coasian dynamics consist of two properties: (i) higher valuation buyers make their purchase no later than lower valuation buyers (skimming property) and (ii) equilibrium price is nonincreasing over time (price monotonicity property). In this paper, we show that the second property does hold when network externalities are present. This is consistent with the findings of [100], [101], [102] in a different model with network effects.

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