

# Trading in Networks: Theory and Experiments

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## Abstract

We propose a model of posted prices in networks. The model maps traditional concepts of market power, competition and double marginalization into networks, allowing for the study of pricing in complex structures of intermediation, such as supply chains, transportation and communication networks and financial brokerage.

We provide a complete characterization of equilibrium prices. Our experiments complement our theoretical work and point to *node criticality* as an organizing principle for understanding pricing, efficiency and the division of surplus in networked markets.

**JEL Classification:** C70, C71, C91, C92, D40.

**Keywords:** Intermediation, competition, market power, double marginalization.

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# 1 Introduction

Supply, service and trading chains are a defining feature of the modern economy. They are prominent in agriculture, in transport and communication networks, in international trade, in markets for bribes and in finance. Goods and services pass through individuals or firms located along these chains. The routing of economic activity, the earnings of individuals and the efficiency of the system depend on the prices set by these different intermediaries. The aim of this paper is to understand how the network structure of chains shapes market power and thereby determines prices and efficiency.

To fix ideas, consider pricing in a transport network. A tourist wants to travel on the Eurostar from London to Paris to see the Louvre. The first leg of the journey is from Home to St. Pancras Station, using one of a number of different services, such as taxi companies, bus services and the Underground. Once at St. Pancras Station, the only service provider to Paris Nord Station is Eurostar. Upon arriving at Paris Nord, there are a number of alternatives (bus, Metro and taxi) to get to the Louvre. The network consists of alternative paths, each comprised of local transport alternatives in London and in Paris and a common node (the Eurostar Company). Each of the service providers sets a price, and the traveler picks the cheapest ‘path.’ Section 2 of this paper develops a number of other applications for which pricing in networks is important.

These examples motivate the following model. There is a source node,  $\mathcal{S}$ , and a destination node,  $\mathcal{D}$ . A path between the two is a sequence of interconnected nodes, each occupied by an intermediary. The source node, the destination node and all the paths between them, together, define a network. The passage of goods from source to destination generates *value*. Intermediaries simultaneously post a price to get a share of this value; the prices determine a total cost for every path between  $\mathcal{S}$  and  $\mathcal{D}$ . We assume that the good moves along a least-cost path and an intermediary earns payoffs only if she is located on it. Posted prices are the norm in transport and communication networks, and they are a good approximation in environments in which trade occurs at a high frequency, such as over-the-counter financial markets. We characterize the Nash equilibria of the pricing game.

A node is said to be critical if it lies on all paths between  $\mathcal{S}$  and  $\mathcal{D}$ . Our main finding is that *criticality* of nodes defines market power and, consequently, pricing, earnings and the efficiency of economic activity in networked markets. We now elaborate on the scope of this finding and locate it in the context of the literature.

In the benchmark model, intermediaries know the value. We prove existence and provide

a complete characterization of Nash equilibrium (Theorem 1). For a given network, there typically exist multiple equilibria: a) they range from efficient to inefficient (where trade breaks down completely) and b) in every efficient equilibrium, all the surplus goes either to  $\mathcal{S}$  and  $\mathcal{D}$  or all of it goes to the intermediaries. The presence of critical traders is *sufficient* but *not necessary* for intermediation rents; non-critical intermediaries may extract rents because intermediaries on competing paths mis-coordinate and price themselves out of contention. In the presence of critical traders, there exist equilibria in which the entire surplus accrues to these traders, but there also exist equilibria in which it is captured by the non-critical intermediaries. Standard equilibrium refinements do not help us in this situation: either they are too demanding and we face non-existence problems, or they are insufficiently restrictive.

To gain a deeper understanding of the relation between networks and market power, we take the model to the laboratory. Our experiments highlight the ability of human subjects to coordinate on efficient outcomes. They show that critical traders set high prices and extract most of the surplus. Thus, our theoretical work and experiments, taken together, establish that the presence of critical intermediaries is *both necessary and sufficient* for large surplus extraction by intermediaries and that most of the surplus does accrue to critical traders.

In markets with multiple vertically related firms, double marginalization is a major concern for policy and regulation; see, e.g., Lerner (1934), Tirole (1993) and Spulber (1999).<sup>1</sup> In our benchmark model, the number of intermediaries per se has no impact on the efficiency of trade because the value is perfectly known to all intermediaries. We extend our benchmark model to a setting in which value is uncertain. We prove existence and provide a complete characterization of equilibrium in this model (Theorem 2). As in the benchmark model, there typically exist multiple equilibria. However, the new model also exhibits important differences. Intermediaries who set positive prices and lie on a least-cost path all set the same price; this price and the efficiency of trade are falling in the number of intermediaries. The multiplicity of equilibrium motivates an experimental investigation. Our experiments highlight the impact of the length of trading chains, especially the number of critical intermediaries, on prices and the efficiency of trade.

Our model offers a generalization of the classical models of price competition (à la Bertrand) and the Nash demand game (Nash, 1950) to a setting with multiple price-setting agents, in which coordination, competition and double marginalization are important. In the theoret-

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<sup>1</sup>Double marginalization figured prominently in the Microsoft antitrust case in the United States: it was used as an argument against splitting Microsoft into two firms, one specializing in operating systems and the other specializing in software development (Economides (2001)).

ical literature, there has been considerable recent interest in the study of intermediation in networks. There are, broadly, three protocols for “price” formation: auctions (Kotowski and Leister (2012)), bargaining (Condorelli and Galeotti (2011), Gofman (2011), Manea (2013), Siedlarek (2012), Bedayo et al. (2015)) and posted prices (Acemoglu and Ozdaglar (2007a, 2007b), Blume et al. (2007) and Gale and Kariv (2009)). As we study a model with posted prices, our paper falls in the third strand of work.<sup>2</sup> There are three main differences between our paper and the papers cited above: 1) the generality of our network framework (which encompasses all networks and allows for incomplete information); 2) our complete characterization of equilibrium; and 3) our methodological combination of theory and experiments. To the best of our knowledge, the result on the role of node criticality in shaping pricing and division of surplus is novel.<sup>3</sup> Building upon the results in the current paper, Condorelli and Galeotti (2015), show that node criticality is also useful for the analysis of market power in networks, under different trading protocols (including auctions and bilateral bargaining).

We contribute to the economic study of networks. The research on networks has been concerned with the formation, structure and functioning of social and economic networks; for book-length surveys, see Goyal (2007), Jackson (2008), Vega-Redondo(2007) and Bramouille, Galeotti and Rogers (2015). The problem of ‘key players’ has traditionally been studied in terms of maximal independent sets, Bonacich centrality, eigenvector and degree centrality; see, for example, Ballester et al. (2006), Bramouille and Kranton (2007), De Marzo et al. (2003), Elliot and Golub (2013), Galeotti et al. (2010) and Golub and Jackson (2010). The contribution of our paper is to show that criticality of nodes, which is very different from “classical” measures of centrality, offers an appropriate measure of market power.<sup>4</sup>

Our paper also contributes to the large body of experimental work on bargaining and trading in markets. Our finding on efficiency in the benchmark model echoes a recurring

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<sup>2</sup>For an early paper on the relation between price and quantity competition, see Sonnenschein (1968). For models of networks in which traders choose quantities, see Babus and Kondor (2013), Malamud and Rostek (2013) and Nava (2010). Our paper also broadly relates to Ostrovsky (2008), which extends the study of pairwise stability developed in the matching literature to more general environments of trade, such as supply chains. However, our focus on how the structure of supply chains affects market power is very different from the questions studied in Ostrovsky (2008).

<sup>3</sup>Acemoglu and Ozdaglar (2007a, 2007b) consider parallel paths between the source and destination pair. This rules out the existence of “critical” traders. Blume et al. (2007) consider a setting with only a single layer of intermediation; this rules out coordination problems and the interaction between coordination and the market power of intermediaries. Finally, Gale and Kariv (2009) study multiple layers of intermediaries and full connectivity across adjacent layers; this rules out “critical” traders.

<sup>4</sup>This is easily seen in a network with a single chain – say, with 4 intermediaries – between the  $\mathcal{S}$  and  $\mathcal{D}$ . Standard measures of centrality assign greater centrality to the two middle nodes, whereas all nodes are critical. Our theory and experiments suggest that all the four intermediaries set the same price.

theme in economics, first pointed out in the pioneering work of Smith (1962), and more recently highlighted in the work of Gale and Kariv (2009). The special case of one critical intermediary can be interpreted as a dictator game; our results on full extraction of surplus stand in contrast to the general message from the research on dictator games; see Engel (2011). The case of two critical intermediaries may be viewed as a symmetric Nash demand game. Our experiments reveal a high frequency of trade and equal division of surplus; these results are consistent with those in the existing literature, such as Roth and Murnighan (1982), Roth (1995), and Fischer et al. (2006). Charness et al. (2007) study efficiency and surplus division with bargaining in two-sided networked markets. To the best of our knowledge, our paper is the first experimental study of chains of intermediation in networks.<sup>5</sup> The treatments involving a combination of critical and non-critical intermediaries are novel relative to the literature. These treatments provide us a first glimpse into the interaction between market power and competition in supply chains and related environments.

The rest of the paper is organized as follows. In section 2 we describe the model and discuss how a number of important questions in applications can be studied within our framework. Section 3 analyzes the benchmark model where value is common knowledge, while Section 4 takes up the model with unknown value. Section 5 discusses potential sources of anomalous pricing behavior in the experiments. Section 6 concludes. All proofs are presented in the Appendix I. Supplementary material is presented in Appendices II. The paper also uses Online Appendices for sample instructions of experiments and further data analysis.<sup>6</sup>

## 2 The Model

There is a source node,  $\mathcal{S}$ , and a destination node,  $\mathcal{D}$ . A path  $q$  between  $\mathcal{S}$  and  $\mathcal{D}$ , is a sequence of distinct nodes  $\{i_1, \dots, i_l\}$  such that  $g_{\mathcal{S}i_1} = g_{i_1i_2} = \dots = g_{i_l\mathcal{D}} = 1$ . The set of paths is denoted by  $\mathcal{Q}$ . Every node  $i$  is called an *intermediary*; let  $\mathcal{N} = \{1, 2, 3, \dots, n\}$ ,  $n \geq 1$ , denote the set of intermediaries. The nodes  $\mathcal{N} \cup \{\mathcal{S}, \mathcal{D}\}$  and the paths  $\mathcal{Q}$  define a network,  $g$ .

Every intermediary  $i$  simultaneously posts a price  $p_i \geq 0$ . Let  $p = \{p_1, p_2, \dots, p_n\}$  denote the price profile. The network  $g$  and the price profile  $p$  define a cost for every path  $q$  between  $\mathcal{S}$  and  $\mathcal{D}$ :

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<sup>5</sup>There is a large sociological literature on exchange. We share with this literature the motivation of how power may emerge in networks, but we are also interested in questions of efficiency, and our formulation in terms of posted prices and our results are quite different. We refer the reader to Easley and Kleinberg (2010) for a survey of this work.

<sup>6</sup><http://www.homepages.ucl.ac.uk/~uctpsc0/Research/CGG.I.OfflineAppendices.pdf>

$$c(q, p) = \sum_{i \in q} p_i. \quad (1)$$

Payoffs arise out of active intermediation: an intermediary  $i$  obtains  $p_i$  only if he lies on a feasible least cost path. A *least-cost* path  $q'$  is one such that  $c(q', p) = \min_{q \in \mathcal{Q}} c(q, p)$ . Define  $c(p) = \min_{q \in \mathcal{Q}} c(q, p)$ . A path  $q$  is feasible if  $c(q, p) \leq v$ , where  $v$  is the value of economic ‘good’ generated by the path. All paths generate the same value  $v$ . If there are multiple least-cost paths, one of them is chosen randomly to be the active path. Given  $g, p$  and  $v$ , we denote by  $\mathcal{Q}^v = \{q \in \mathcal{Q} : c(q, p) = c(p), c(p) \leq v\}$  the set of feasible least-cost paths, and intermediary  $i$ ’s payoff is:

$$\pi_i(p, v) = \begin{cases} 0 & \text{if } i \notin q, \forall q \in \mathcal{Q}^v \\ \frac{\eta_i^v}{|\mathcal{Q}^v|} p_i & \text{if } i \in q, q \in \mathcal{Q}^v, \end{cases} \quad (2)$$

where  $\eta_i^v$  is the number of paths in  $\mathcal{Q}^v$  that contain intermediary  $i$ .

We consider the case in which intermediaries know the value of  $v$  when they choose their price. In this scenario, we normalize  $v$  to be equal to 1, and, therefore, intermediary  $i$ ’s profit is  $\Pi_i(p) = \pi_i(p, 1)$ . We also examine the situation in which intermediaries face demand uncertainty when they set their intermediation price. In this case, we assume that it is common knowledge that  $v$  has a distribution  $F(\cdot)$  on the interval  $[0, 1]$ , with a continuously differentiable density  $f(\cdot)$ . Given network  $g$  and price profile  $p$ , the expected payoff to intermediary  $i$  is:

$$\Pi_i(p) = E_v[\pi_i(p, v)].$$

We study (pure strategy) Nash equilibrium of the posted price game. A price profile  $p^*$  is a Nash equilibrium if for all  $i \in \mathcal{N}$ ,  $\Pi_i(p^*) \geq \Pi_i(p_i, p_{-i}^*)$  for all  $p_i \geq 0$ . An equilibrium is efficient (resp. inefficient) if trade occurs (resp. does not occur) regardless of the realization of  $v$ . When  $v = 1$  is known, an equilibrium  $p^*$  is efficient if  $c(p^*) \leq 1$  (resp.  $c(p^*) > 1$ ); otherwise, the equilibrium  $p^*$  is inefficient. Under demand uncertainty, an equilibrium  $p^*$  is efficient (resp. inefficient) if, and only if,  $c(p^*) = 0$  (resp.  $c(p^*) > 1$ ); when  $c(p^*) \in (0, 1)$ , we say that the equilibrium  $p^*$  is partially efficient.

In principle, nodes that lie on many paths have more opportunities to act as an intermediary. The betweenness centrality of a node  $i \in \mathcal{N}$  is the fraction of paths on which

intermediary  $i$  lies.<sup>7</sup> Let  $\eta_i = |\{q \in \mathcal{Q} | i \in q\}|$  and define betweenness centrality of intermediary  $i$  as  $c_i = \eta_i / |\mathcal{Q}|$ , where  $c_i \in [0, 1]$ . Intermediary  $i$  is said to be *critical* if  $c_i = 1$ . Let  $\mathcal{C} = \{i \in \mathcal{N} : c_i = 1\}$  be the set of critical intermediaries. Observe that criticality is a property of the network *per se*, and is independent of the price profile. For simplicity, we suppress the dependence of  $\mathcal{C}$  on  $g$ .

The model offers a general framework to study the relation between networks and the pricing behavior of traders. We now discuss a number of applications to illustrate the scope of the model.

## 2.1 Applications

**1. Transportation and communication Networks:** The example we sketched in the introduction falls under the large umbrella of transportation and communication networks (which include airlines, shipping, Internet and cable TV). Traditionally, these sectors have been heavily regulated or under public-sector control. The large-scale privatization in the UK (during the 1980s) was a precursor to a global trend. Now, it is common for a consumer to make a choice among alternative bundles of services provided by a number of distinct service providers. A key policy concern is the nature of market power in these networks.<sup>8</sup>

**2. Supply chains:** Consider a Sony Vaio Laptop. It usually has an Intel processor, a hard drive from Seagate Technology, Hitachi, Fujitsu or Toshiba, RAM from Infineon or Elpida, a wireless chipset from Atheros or Intel, an optical drive from Hitachi or Matsushita, and a graphic card from Intel, NVIDIA or AMD. The speakers may be from HP or Sony. The different intermediate input suppliers set prices, and Sony picks the best combination of inputs and prices.

Anderson and Wincoop (2004) show that trade intermediation costs amount to a significant tax on international transactions. Hummels et al. (2001) show that production supply chains increasingly traverse the world and decisively shape the pattern and volume of trade. Antras and Costinot (2011) is a recent attempt to understand international trade with intermediaries, whereas Antras and Chor (2013) study the optimal organization of a supply chain. The empirical significance of supply chains motivates a systematic study of strategic pricing in general networks.

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<sup>7</sup>We consider all paths and not just the shortest paths; in this, we follow Borgatti and Everett (2005).

<sup>8</sup>Firms in communication and transportation networks use a rich set of price strategies; discrimination with regard to source and destination is common.

**3. Corruption:** The bribing of public officials for access to goods and services and for the granting of licenses and permits is a prominent feature of economic life in many countries. Shleifer and Vishney (1993) and Ades and Di Tella (1999) argue that the level of bribes should be viewed as a function of officials' 'market power.' In some contexts, there is a single line of officials (or committees) that must approve a decision, while in others, there may exist multiple competing chains of decision makers (as on highway tolls; Olken and Barron (2009)). These examples motivate an inquiry into the ways that the network of decision making shapes the power of officials in the market for bribes.

**4. Intermediation in agriculture:** Consider coffee. At the start, there is a farmer in a developing country who typically works on a small farm. The farmer chooses from among a few intermediaries who process his coffee cherries to obtain beans. These intermediaries then sell the beans to one of the small number of exporting trading firms. The exporters sell to dealers/brokers, who, in turn, sell to roasters (such as Nestle). The roasters then sell to large supermarkets and local stores. Finally, consumers buy the coffee from a retailer.

Such long chains of intermediation are common across the agricultural sector (see, for example, Fafchamps and Minten (1999)). Historically, the market power of intermediaries has been a major concern and has led to large-scale state intervention in this sector. However, by the 1990s, it was felt that state agencies discouraged innovation and the entry of new intermediaries, leading to a very inefficient system (see Bayley (2002) and Meerman (1997)). Recent decades have witnessed a large-scale liberalization of the intermediation sector. The effects of liberalization have, however, been mixed; for a discussion, see Trauba and Jayne (2008). This research motivates a theoretical study of the determinants of pricing and division of surplus in intermediation networks.

**5. Financial Intermediation:** Consider the market for municipal bonds in the United States, which is the largest capital market for state and municipal issuers. It has market capitalization of over \$4 trillion, with daily trading volumes of around \$ 10-20 billion. Li and Schürhoff (2012) show that trading of these bonds is organized as a decentralized over-the-counter (OTC) broker-dealer market. The network of traders has a core-periphery structure, with roughly 20-30 dealer firms at the core and several hundred peripheral dealer firms (around 700 firms trade in municipal bonds in any given month). Bonds move from the municipality through an average of six inter-dealer trades. There is systematic price dispersion across dealers, with dealers in the core maintaining systematically larger margins. These empirical patterns motivate a theoretical study of how traders choose partners and how the ensuing network shapes pricing margins and profitability.



In Examples 1, 2 and 3, a consumer or a firm will choose the path: it is reasonable to suppose that the cheapest path will be picked. In Examples 4 and 5, on the other hand, the agent who owns an object will sell it to the highest bidder downstream and has no interest in the cost of the entire path.

The latter two examples motivate the following Bid-Ask price variant of our model. Following Gale and Kariv (2009), suppose that every intermediary  $i \in \mathcal{N}$  simultaneously sets a bid and ask  $(b_i, a_i)$ . The source  $\mathcal{S}$  accepts the highest bid, and the destination  $\mathcal{D}$  buys as long as the lowest ask price is not greater than  $v$ . The object passes from intermediary  $i$  to a connected intermediary  $j$  with the highest bid  $b_j$ , subject to the condition that  $b_j \geq a_i$ . We study this alternative model of pricing in Appendix II. The analysis there establishes that every equilibrium outcome in our model is also an equilibrium outcome of the Bid-Ask model; the converse is not true in general. However, for some important classes of networks – that include trees and multi-partite networks – the equilibrium outcomes in the two models are equivalent. So, for these networks, our equilibrium characterization result in the benchmark model, Theorem 1, also holds for the Bid-Ask model.

### 3 Complete information: Networks, market power and efficiency

We prove existence and provide a complete characterization of Nash equilibrium for the case in which  $v$  is known. For any given network, there typically exist multiple equilibria with widely varying pricing, efficiency and division of surplus. We take the model to the laboratory. The experiments highlight two points: 1) the ability of human subjects to coordinate on efficient outcomes; and 2) the role of node criticality as an important network property for understanding market power.

We say that trader  $i$  is *essential* under  $p$  if he belongs to every feasible least-cost path. Given price profile  $p$ , for path  $q$ , let  $c_{-j}(q, p) = \sum_{i \in q, i \neq j} p_i$ , be the total cost of all intermediaries other than  $j$ .<sup>9</sup>

#### Theorem 1

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<sup>9</sup>It is worth noting the distinction between essential and critical nodes. Criticality is a property of the network per se, while essentiality is defined by the network and the price profile together. So, a node may be essential even if there are no critical nodes in the network: this point is taken up in the discussion on multiple equilibria below.

A. **Existence:** In every network, there exists an efficient equilibrium.

B. **Characterization:** An equilibrium  $p^*$  is inefficient ( $c(p^*) > 1$ ); or intermediaries extract all the surplus ( $c(p^*) = 1$ ); or they earn nothing ( $c(p^*) = 0$ ). Moreover,

1.  $p^*$  is an equilibrium in which intermediaries earn nothing if, and only if, no trader is essential.
2.  $p^*$  is an equilibrium in which intermediaries earn all the surplus if, and only if, (i) if trader  $i$  belongs to the least-cost path, and he sets a positive price then trader  $i$  is an essential trader; and (ii) if trader  $i$  belongs only to non-least-cost paths, and he belongs to path  $q$  then  $c_{-i}(q, p^*) \geq 1$ .
3.  $p^*$  is an inefficient equilibrium if, and only if, if trader  $i$  belongs to path  $q$  then  $c_{-i}(q, p^*) \geq 1$ .

The argument for the existence of an efficient equilibrium is constructive. First, consider a network with no critical traders. The 0 price profile is a Nash equilibrium, as no intermediary can earn positive profits by deviating and setting a positive price. If an intermediary sets a positive price,  $\mathcal{S}$  and  $\mathcal{D}$  will circumvent him, as there exists a zero cost path without him. Next, consider a network with critical traders. It may be checked that a price profile in which critical traders set positive prices that add up to 1 and all non-critical traders set 0 price is an equilibrium.

The characterization yields a number of insights. The *first* observation is that in every efficient equilibrium, intermediation costs take on extreme values. The intuition is as follows: if the feasible least-cost path is unique, then intermediaries in that path exercise market power; thus, if intermediation costs are below the value of exchange, an intermediary in that path could slightly increase his intermediation price while guaranteeing that exchange takes place through him. In contrast, when there are multiple feasible least-cost paths, there is price competition among intermediaries on different paths. In that case, whenever intermediation costs are larger than zero, an intermediary demanding a positive price gains by undercutting his price. Price competition drives intermediation costs down to zero.

The *second* observation is on how critical traders have market power. Observe that a critical trader is essential. Hence, the presence of critical traders is sufficient to ensure that intermediaries extract all surplus in every efficient equilibrium.

Criticality dictates that all surplus must accrue to intermediaries, but the theory is permissive about how it is distributed among them. To see this point, consider the Ring with Hubs

and Spokes network presented in Figure 1, and suppose that  $\mathcal{S}$  and  $\mathcal{D}$  are located on  $(a_1, d_1)$ . Then, there exists an equilibrium in which all surplus accrues to the critical intermediaries, e.g.,  $A$  and  $D$  charge  $1/2$  and all other intermediaries charge  $0$ . However, there is also an equilibrium in which the entire surplus is earned by non-critical intermediaries, e.g.,  $A$  and  $D$  charge  $0$ ,  $B$  and  $C$  charge  $1/2$ , and  $F$  and  $E$  charge  $1$ .

The *final* observation is about the multiplicity of equilibria. Consider the ring network with six traders presented in Figure 1, and suppose that  $\mathcal{S}$  is located at  $A$  and  $\mathcal{D}$  is located at  $D$ . The three equilibria described by Theorem 1 are possible in this network: all intermediaries set price  $0$ ; all of them set price  $1$ ; and intermediaries  $B$  and  $C$  set price  $1$ , while intermediaries  $E$  and  $F$  set price  $1/2$  each. In the last case, note that  $E$  and  $F$  are essential but not critical. Thus, criticality is not necessary for surplus extraction by intermediaries.

This multiplicity motivates an exploration of equilibrium refinements. We consider a number of possible refinements, including strictness, strong Nash equilibrium, elimination of weakly dominated strategies, and coalition proof equilibrium. We find that, in some cases, these refinements are too strong; for example, there does not exist a strict or strong Nash equilibrium in some networks. In other cases, the refinement is not effective; for example, a wide range of outcomes (including those with coordination failure) may be sustained under elimination of weakly dominated strategies and coalition proof. We discuss these refinements in greater detail in Appendix II. Given the limited usefulness of standard equilibrium refinements, we turn to an experimental investigation of posted prices in networks.<sup>10</sup>

## 3.1 Posted prices in the Laboratory

### 3.1.1 Experimental Design

We have chosen networks that allow us to examine the roles of coordination, competition and market power. These networks are depicted in Figure 1.

The ring networks with four, six and ten traders allow us to focus on coordination and competition.<sup>11</sup> For every choice of  $\mathcal{S}$  and  $\mathcal{D}$ , there are always two competing paths of intermediaries. In Ring 4, for any non-adjacent pair, there are two paths with a single intermediary

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<sup>10</sup>Goyal and Vega-Redondo (2007) consider a cooperative solution concept the kernel in their work. They show that non-critical traders would earn  $0$ , and critical traders would split the surplus equally in allocations in the kernel. Our analysis above reveals that this solution is a Nash equilibrium of the pricing game but that there exist a variety of other equilibria.

<sup>11</sup>We have also run experiments on a ring network with eight traders. The results are in line with those presented in this section, but to simplify exposition, we do not present them.

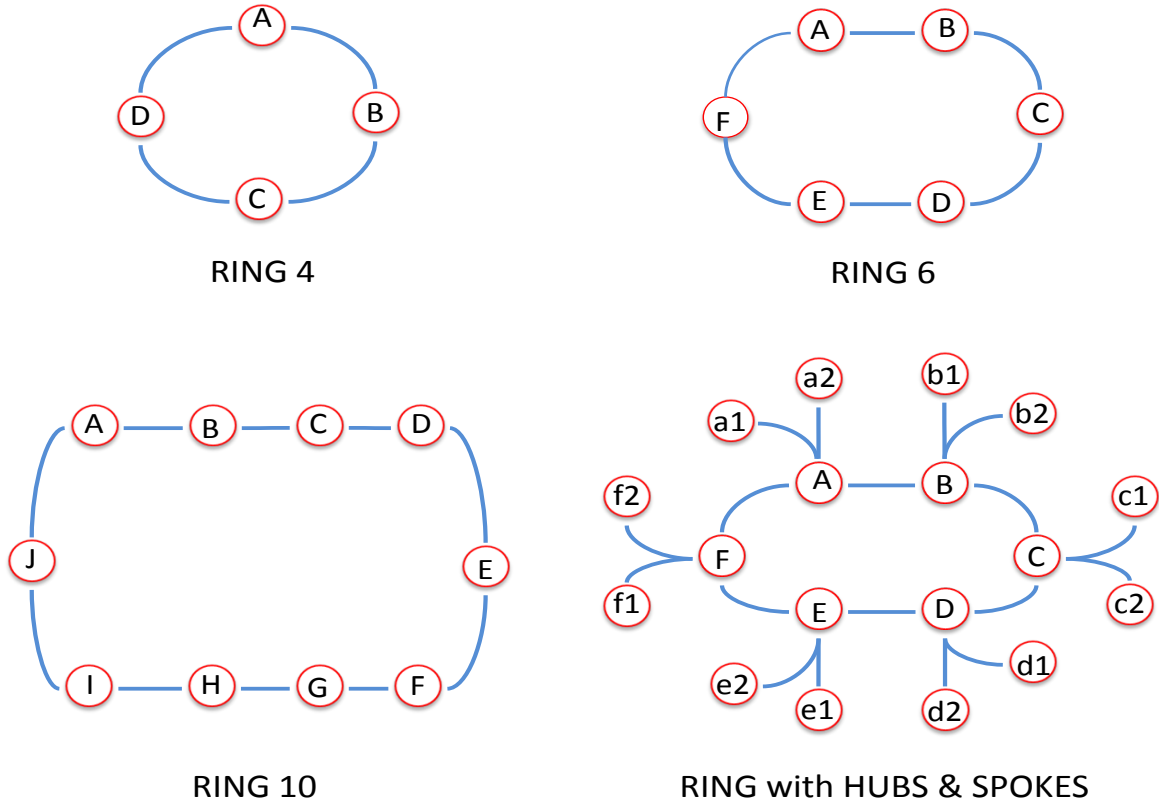


Figure 1: Networks in the benchmark design

each. Ring 6 and Ring 10 allow for situations with a higher (and possibly unequal) number of intermediaries on either path.

The Ring with Hubs and Spokes network allows for a study of the impact of market power: for instance, if  $\mathcal{S}$  is located at  $a_1$  and  $\mathcal{D}$  is located at  $a_2$ , intermediary  $A$  is a pure monopoly, while if  $\mathcal{D}$  is  $b_1$ , then the intermediaries  $A$  and  $B$  play a symmetric Nash demand game. This network also creates the space for both market power and competition to come into play. For instance, if  $\mathcal{S}$  is located at  $a_1$  and  $\mathcal{D}$  is located at  $e_1$ , then there are two competing paths: a shorter path (through  $A$ ,  $F$ , and  $E$ ) and a longer path (through  $A$ ,  $B$ ,  $C$ ,  $D$ , and  $E$ ). Traders  $A$  and  $E$  are the only critical intermediaries.

To put these experimental variations into perspective, we summarize the equilibrium analysis for the selected networks. In Ring 4, there is a unique equilibrium that corresponds to the Bertrand outcome. In every other network, whenever there are at least two intermediaries on every path, there exist both efficient and inefficient equilibria. This observation motivates our first question:

**Question 1:** *How does the efficiency of trade vary with ring size and the presence of critical traders?*

Treatment	Session		Total
	1	2	
Ring 4	16 / 240	16 / 240	32 / 480
Ring 6	18 / 180	24 / 240	42 / 420
Ring 10	20 / 120	20 / 120	40 / 240
Ring w. hubs/spokes	18 / 180	24 / 240	42 / 420

Table 1: Treatments in Benchmark Model

If trading does take place, Theorem 1 predicts an extremal division of trade surplus: either intermediaries earn 0 surplus or they extract all trade surplus. In Ring 4, the intermediation cost is 0 in the unique equilibrium; but in all other Rings, both extremal outcomes are possible in equilibrium. In the Ring with Hubs and Spokes, whenever exchange involves critical traders, equilibrium dictates full surplus extraction by intermediaries. These considerations motivate the second question:

**Question 2:** *Is the division of surplus extremal? How does it vary with the presence of critical traders?*

Finally, we turn to the situation in the Ring with Hubs and Spokes where all three forces of interest – coordination, competing paths and critical traders – are present. Theorem 1 tells us that all surplus must accrue to intermediaries, but it is silent on how the surplus is distributed among them. This observation motivates our third question:

**Question 3:** *What is the division of surplus between critical and non-critical intermediaries?*

### 3.1.2 Experimental procedures

We ran the experiments at the Experimental Laboratory of the Centre for Economic Learning and Social Evolution (ELSE) at University College London (UCL) between June and December 2012. The subjects in the experiment were recruited from the ELSE pool of human subjects consisting of UCL students, across all disciplines. Each subject participated in only one of the experimental sessions. After subjects read the instructions, an experimental administrator read the instructions aloud. Each experimental session lasted around two hours. The experiment was computerized and conducted using the experimental software z-Tree, developed by Fischbacher (2007). Sample instructions are reported in the Online Appendix. Each session used one network treatment, and we ran two sessions for each treatment. Each session consisted of 60 independent rounds. Table 1 provides an overview of the experimental design. In each cell, we report number of subjects/number of group observations.

We employed random matching with random assignment of network positions across rounds. In each round of a treatment, subjects were assigned with equal probability to one of the possible positions of a network. In Ring  $n$ , all nodes were possible positions. In Ring with Hubs and Spokes, each spoke node was a computer-generated agent, and the remaining nodes were all feasible positions for the human subjects. Groups with one subject per intermediary position were then randomly formed. The position of a subject and the groups formed in each round depended solely on chance and was independent of the subject’s position and the groups formed in previous rounds, respectively.

We deliberately chose the protocol of random matching with random assignment. This procedure anonymized the identity of the subjects throughout a session and, thus, helped avoid “repeated games” effects that arise if the same fixed group of subjects play a game repeatedly. The advantage of using subjects repeatedly under this protocol was that it allowed us to collect a large amount of data from a given number of subjects, while they had an opportunity to learn how to play a game. Other protocols, in which subjects never again meet someone who they have played before require large subject pools or provide fewer observations with less opportunity for subjects’ learning. It is worth emphasizing that, as we only varied the network structure, any experimental difference in subjects’ behavior across treatments will be evidence of network effects because we kept the random matching and assignment protocol constant across all treatments.<sup>12</sup>

For each group, a pair of two non-adjacent nodes was randomly selected as  $\mathcal{S}$  and  $\mathcal{D}$ . Each pair of two non-adjacent nodes was equally likely to be selected. All of the subjects in each group were informed of the position of  $\mathcal{S}$  and  $\mathcal{D}$  in the network. All traders were informed that the surplus/value of exchange was 100 tokens. Then, all human subjects in an intermediary role were asked to submit an intermediation price: a real number (up to two decimal places) between 0 and 100. The computer calculated the intermediation costs across different paths. Exchange took place if the least-cost among all paths was less than or equal to 100. If there were multiple feasible least-cost paths then one of them was chosen at random.

At the end of the round, subjects observed all posted prices in their group, the trading outcome, and the earnings of all the subjects. We assumed that each of  $\mathcal{S}$  and  $\mathcal{D}$  was allocated one half of the net surplus— i.e., one half of 100 minus the intermediation costs. Then, the subjects moved to the next round.

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<sup>12</sup>As we shall see, our findings are in line with existing experimental literature that shows that the random matching protocol is an effective way to minimize the repeated games effects (Duffy and Ochs (2009)). We discuss possible repeated games effects after we report the first finding in the next section.

Network	minimum distance of buyer-sell pair				
	All ( $\geq 2$ )	2	3	4	5
Ring 4	1.00 (480)	1.00 (480)	--	--	--
Ring 6	1.00 (420)	1.00 (289)	1.00 (131)	--	--
Ring 10	1.00 (240)	1.00 (49)	1.00 (87)	1.00 (69)	1.00 (35)
Ring with Hubs and Spokes	0.95 (420)	1.00 (126)	0.94 (155)	0.90 (109)	0.90 (30)

Note. The number of group observations is reported in parentheses.

Table 2: Frequency of Trading

In each round, earnings were calculated in terms of tokens. For each subject, the earnings in the experiment were the sum of his or her earnings over 60 rounds. At the end of the experiment, subjects were informed of their earnings in tokens. The tokens were exchanged for British pounds, with 60 tokens equaling £1. Subjects received their earnings plus £5 show-up fee privately, at the end of the experiment.

### 3.1.3 Findings

We start by examining the efficiency of trade in networks. Table 2 reports the relative frequency of trade across different treatments.

Trade occurs with probability 1 in ring networks, regardless of their size and of the distance between  $\mathcal{S}$  and  $\mathcal{D}$ . In Ring with Hubs and Spokes, the frequency of trade is around 0.95. So, market power does not have any significant effect on efficiency of trading. Overall, despite the need for coordination among intermediaries along the same path, the presence of competition between paths and the presence of market power of some intermediaries, traders across all treatments are very successful in coordinating on prices that ensure exchange.

**Finding 1:** *The level of efficiency is remarkably high in all networks. Trading in Rings with four, six, and ten intermediaries occurs with probability 1. In the Ring with Hubs and Spokes, trading occurs with probability around 0.95.*

In Rings, we distinguish trading situations with respect to distances of the two competing paths between  $\mathcal{S}$  and  $\mathcal{D}$ , denoted by  $(d(q), d(q'))$ . In Ring with Hubs and Spokes, we distinguish trading situations with respect to (i) the number of critical intermediaries ( $\#Cr$ ), (ii) the

number of intermediation paths ( $\#Paths$ ), and (iii) the distance of each path ( $d(q), d(q')$ ). Figure 2 presents the average intermediation costs, conditional on trading, based on the last 20 rounds, with a 95% confidence interval across different trading situations.

In the Online Appendix, we report the movement across rounds in average intermediation costs across distinct trading situations in Rings and Ring with Hubs and Spokes (see Table 12). When there are no critical traders (resp. there are only critical traders), there is a clear downward trend (resp. upward trend) in intermediation costs across rounds. In treatments with both critical and non-critical traders, intermediation costs are stable over time.

There is potentially a more subtle issue that can arise in our setting.<sup>13</sup> In our experiments, subjects know that there is random assignment to locations across rounds. So, for instance, they know that each of them will have a chance to occupy critical nodes. This may lead them to be not overly concerned about the surplus accruing to critical nodes in any specific round. Thus, the relationship between network location and surplus could potentially be due to this repeated game effect. A simple way to investigate this point is to examine the players' behavior and the division of surplus in the last round of the game. If this argument were valid, then the allocation of surplus would be very different in the last round, as non-critical players, for instance, might insist on a fair share of the surplus. But Table 12 in the Online Appendix shows us that there is essentially no difference in behavior of prices in the later rounds versus the last round. Thus, we conclude that this type of 'repeated game' effect is not an issue in our experiment.

In Ring 4, intermediation costs are around five percent of the surplus. In the other rings, intermediation costs vary between ten and twenty percent of the surplus. The overall conclusion is that intermediation costs in all ring networks are modest and, between the two efficient equilibria, are much closer to the one with zero intermediation cost, especially in the smaller rings.

In the Ring with Hubs and Spokes, when  $\mathcal{S}$  and  $\mathcal{D}$  are served by a sole critical intermediary, the situation is analogous to the dictator game, widely studied in the experimental literature (for a survey, see Engel (2011)). We find a surplus extraction of 99 percent, which is much higher than that reported in the experimental literature. This suggests that traders located at critical nodes in a network interpret their location as a form of 'earned endowment,' in the sense of Cherry et al. (2002). This may give rise to a sense of entitlement that is distinct from the standard dictator game.<sup>14</sup>

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<sup>13</sup>We are grateful to a referee for drawing our attention to this issue.

<sup>14</sup>We also note that in our design, in some situations, both  $\mathcal{S}$  and  $\mathcal{D}$  are computer-generated agents, while



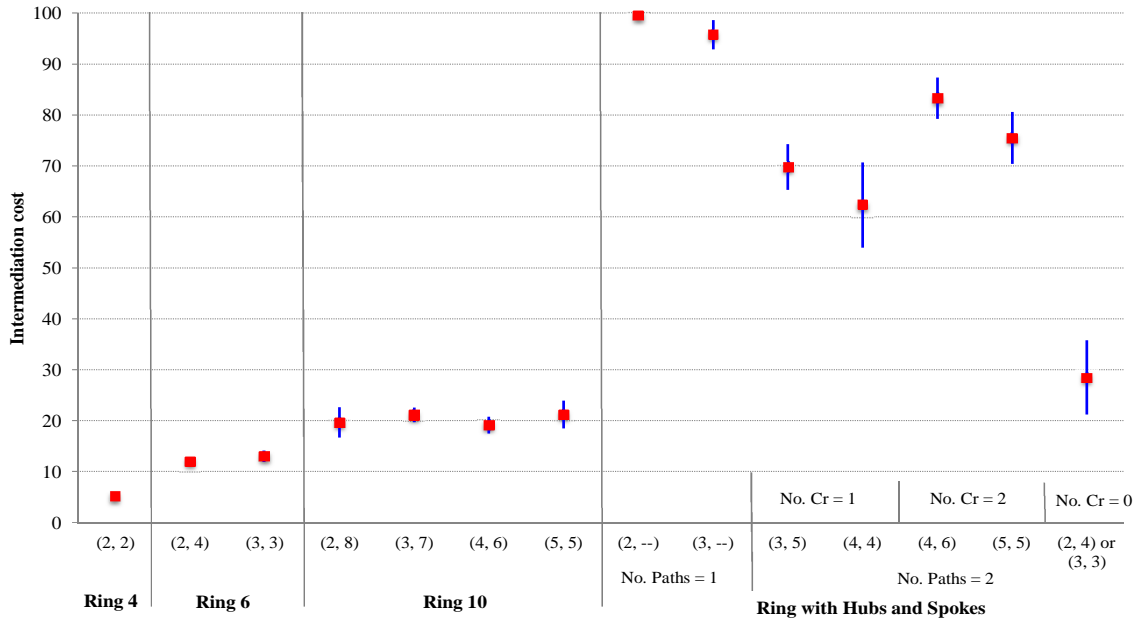


Figure 2: Costs of intermediation

When  $\mathcal{S}$  and  $\mathcal{D}$  are connecting via one single path with two intermediaries, the game played by the two intermediaries is analogous to a symmetric Nash demand game. We find that intermediaries extract, in total, around 96 percent of the surplus and that they share it roughly equally.<sup>15</sup> These findings are consistent with those in the experimental literature of Nash bargaining (e.g., Roth and Murnighan (1982) and Fischer et al. (2006)).

Finally, when there are two competing paths and critical traders, the intermediation cost ranges between 62 percent and 83 percent. In the case without critical intermediaries, this cost falls sharply to around 28 percent, which is comparable to the low-cost outcome found in Rings. We summarize this discussion in our second finding.

**Finding 2:** *The presence of critical traders is both necessary and sufficient for large surplus extraction by intermediaries. In Rings with four, six, and ten traders, intermediation costs are small (ranging from 5 percent to 20 percent). In the Ring with Hubs and Spokes, with critical traders, intermediation costs are large (ranging from 60 percent to over 95 percent).*

We now turn to the issue of how surplus is divided between critical and non-critical intermediaries. Table 3 presents the average fraction of intermediation costs charged by critical traders, conditional on exchange (here, data are grouped into the blocks of 20 rounds, due to small samples). The number within parentheses is the number of group observations. Looking

in others, one of them is a human subject. We find no behavioral difference across these cases. This leads us to believe that the human subject vs. computer issue does not play a major role in explaining the behavior of the subjects in our experiment.

<sup>15</sup>See Table 13 in the Online Appendix

Network	(#Cr,#Paths, d(q),d(q'))	Rounds		
		1 ~ 20	21 ~ 41	41 ~ 60
Ring with Hubs and Spokes	(1, 2, 3, 5)	0.56 (20)	0.68 (26)	0.72 (25)
	(1, 2, 4, 4)	0.48 (16)	0.56 (13)	0.67 (10)
	(2, 2, 4, 6)	0.73 (16)	0.77 (19)	0.80 (24)
	(2, 2, 5, 5)	0.65 (8)	0.67 (8)	0.74 (11)

Notes. The number in a cell is the average fraction of costs charged by critical traders. The number of observations is reported in parentheses. #Cr denotes the number of critical intermediaries, #Paths denotes the number of paths connecting buyer and seller, d(q) denotes the length of path q between buyer and seller.

Table 3: Surplus division among intermediaries

at the last 20 rounds, we observe that 67 percent to 80 percent of intermediation costs go to critical trader(s). In all the cases, regardless of whether an exchange takes place along the shorter or longer path, the number of non-critical traders is at least as large as the number of critical traders. To summarize:

**Finding 3:** *In the Ring with Hubs and Spokes, critical intermediaries set higher prices and earn a much higher share of surplus than non-critical intermediaries.*

We have established that network structure – reflected in the criticality of nodes – has powerful effects on intermediation costs and the division of surplus. To gain a deeper understanding of the mechanisms of competition and market power, we now examine the pricing behavior of traders directly.

We focus on the last 20 rounds and Figure 3 depicts average prices.<sup>16</sup> In the Ring with six and ten traders, there is tight competition between paths. Intermediaries on a longer path choose, on average, prices somewhere between five and ten, independently of the distances of the two paths across all ring networks. Responding strategically to this, intermediaries on a shorter path choose higher prices, which were proportionate to the difference in distance between the two paths. As a result, even when the two paths are very asymmetric, they have very similar intermediation costs and trade occurs frequently – roughly one third of the time – along the longer path! Table 4 provides data on these patterns.

In the Ring with Hubs and Spokes, the pricing of critical and non-critical intermediaries is very different. Critical intermediaries post much higher prices than non-critical intermediaries. The non-critical intermediaries post prices that are similar to intermediaries in Rings. For

<sup>16</sup>In the Online Appendix, Table 13 reports average prices charged across rounds by intermediaries in Rings and Ring with Hubs and Spokes, respectively.

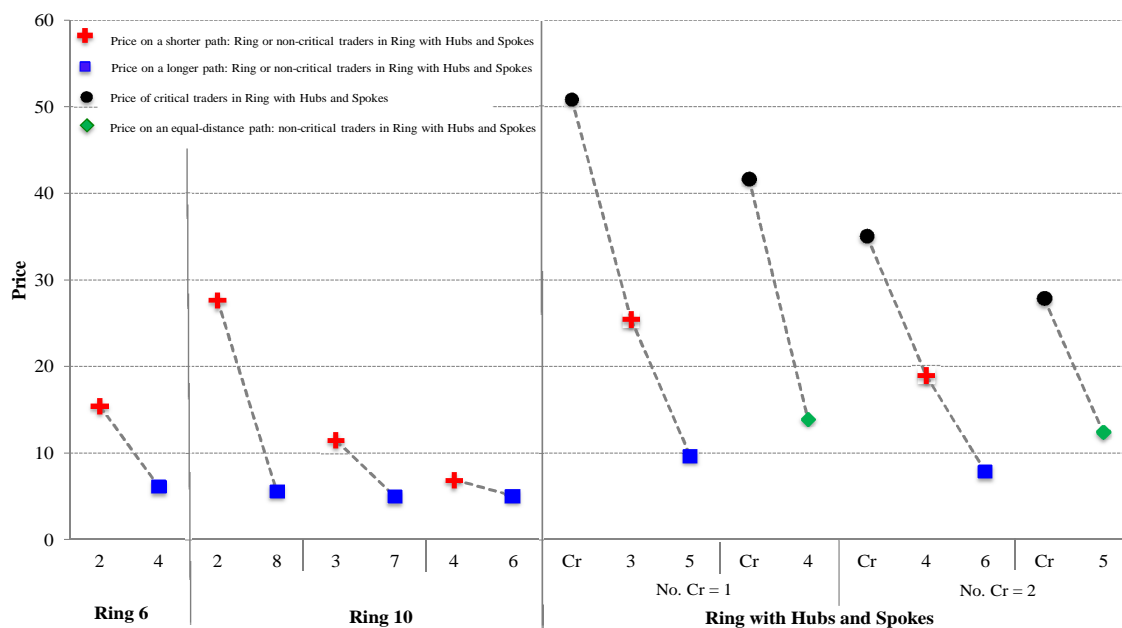


Figure 3: Competition among intermediaries

Network	$(d(q), d(q'))$	$ \text{cost1} - \text{cost2} $	Freq. on a shorter path
Ring 4	(2, 2)	3.99	--
Ring 6	(2, 4)	4.45	0.65
	(3, 3)	4.01	--
Ring 10	(2, 8)	15.20	0.64
	(3, 7)	5.30	0.68
	(4, 6)	6.82	0.68
	(5, 5)	5.01	--

Notes. We report the sample median of differences in costs between two competing paths, using the sample of last 20 rounds. The number in the last column is the frequency of trading on a shorter path.

Table 4: Short versus long paths

Dependent variable: price	Ring 6	Ring 10			Ring with Hubs and Spokes			
	(2, 4)	(2, 8)	(3, 7)	(4, 6)	#Cr = 1	#Cr = 2		
					(3,5)	(4,4)	(4,6)	(5,5)
(1) Non-critical & on a shorter path	9.478 (1.123)***	22.234 (5.421)***	6.316 (0.677)***	2.351 (0.394)***	18.571 (2.807)***		11.464 (1.468)***	
(2) Critical					40.173 (2.920)***	27.554 (4.340)***	27.923 (1.731)***	14.338 (1.626)***
Constant	5.380 (0.415)***	2.250 (0.139)***	3.524 (0.454)***	4.454 (0.237)***	9.085 (3.537)**	13.333 (1.852)***	8.028 (1.298)***	5.662 (1.626)***
$H_0: (1) = (2)$ or $H_0: (2) = 0$ ( <i>p</i> -value)					0.000	0.000	0.000	0.000
R-squared	0.313	0.464	0.336	0.330	0.728	0.771	0.776	0.840
Number of obs.	376	112	224	200	134	50	156	66

Notes: Each regression controls for individual heterogeneity by including dummies for individual subjects. Robust standard errors, are reported in parentheses. \*, \*\*, and \*\*\* represent 10%, 5%, and 1% significance level.

Table 5: Regression of pricing on network position

instance, when there is one critical intermediary and the two competing paths are of distance three and five, the critical intermediary charges, on average, a price close to 50; the only non-critical intermediary lying in the shorter path charges a price close to 24; and the three non-critical intermediaries in the longer path post a price around eight. Similar behavior is observed in the other cases. This demonstrates the strong impact of network criticality on pricing behavior and the division of surplus.

To further check the sharp differences in pricing behavior among different types of intermediaries presented in Figure 3, Table 5 presents the results of regressions of prices on dummies for critical and non-critical traders on a shorter path. Data are from the last 20 rounds, and we control for individual heterogeneity by including individual subject dummies. Robust standard errors are reported in parentheses. In Ring networks, traders on a shorter path choose significantly higher prices than those on a longer path. In the Ring with Hubs and Spokes, critical intermediaries choose significantly higher prices than non-critical intermediaries. The price difference between non-critical intermediaries on short and long path is statistically significant.

Finally, while intermediation costs do take on extreme values, they depart significantly from the theoretical predictions. In Section 5, we show that the observed departures from equilibrium pricing and surplus extraction are consistent with a model of noisy best response with risk aversion.

## 4 Uncertain demand: competition and market power

In our benchmark model, the number of intermediaries *per se* has no impact on the efficiency of trade because the value of surplus is perfectly known to all intermediaries. We now extend the benchmark model to allow for uncertain demand. We prove existence and provide a complete characterization of equilibrium in this model. As in the benchmark model, there typically exist multiple equilibria, with very different pricing, efficiency and division of surplus. However, the analysis also reveals important differences with the benchmark model: active intermediaries are predicted to all set the same price, and the number of active intermediaries has powerful effects on pricing and the efficiency of trade. Our experiments highlight the interplay between these theoretical predictions and the role of node criticality.

The next result proves existence and provides a complete characterization of equilibrium, for all networks. Let  $e(g, p)$  be the number of essential traders— i.e., the number of traders that lies on all paths  $q \in \mathcal{Q}^1$ . Define  $h(x) = f(x)/[1 - F(x)]$  to be the hazard rate.

**Theorem 2** *Assume that the hazard rate is increasing.*

A. **Existence:** *In every network, there exists an efficient or a partially efficient equilibrium.*

B. **Characterization:**

1. *An efficient equilibrium exists if, and only if, there are no critical traders.*
2.  *$p^*$  is a partially efficient equilibrium if, and only if, (a) there exists some essential trader— i.e.,  $e(g, p^*) \geq 1$ ; every essential trader charges a price*

$$\hat{p}^* = \frac{1}{h(e(g, p^*)\hat{p}^*)}; \quad (3)$$

*and every non-essential trader in the least-cost path sets a price equal to 0; and (b) if trader  $i$  belongs only to non-least-cost paths and he belongs to path  $q$ , then  $c_{-i}(q, p^*) \geq 1$ .*

3.  *$p^*$  is an inefficient equilibrium if, and only if, if trader  $i$  belongs to path  $q$  then  $c_{-i}(q, p^*) \geq 1$ .*

Theorem 2 brings out two important implications of pricing in networks under uncertain demand.<sup>17</sup> The first is that a lack of criticality is necessary and sufficient for the existence

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<sup>17</sup>All parts of the result, except for part [2], continue to hold if we relax the increasing hazard rate assumption. In part [2], we exploit the increasing hazard rate assumption for the sufficiency part of the proof only.

of an efficient equilibrium. So, whenever there are critical intermediaries, the equilibrium will involve some inefficiency. This is novel relative to Theorem 1. The second observation relates to equilibrium pricing by essential traders: they set a unique common price that solves condition (3). As  $c(p^*) \in (0, 1)$ , intermediaries always share surplus with  $\mathcal{S}/\mathcal{D}$ .

We now show how pricing, efficiency and division of surplus, vary with the number of essential traders.

**Proposition 1** *Assume that the hazard rate is increasing. Suppose that  $p^*$  and  $p'$  are two partially efficient equilibria, with  $e(g, p^*) > e(g', p')$  essential traders, respectively. Then:*

1. *The price for essential traders under  $p^*$  is strictly lower than the price under  $p'$ .*
2. *The intermediation cost under  $p^*$  is strictly higher than under  $p'$  – i.e.,  $c(p^*) > c(p')$ . Hence,  $p^*$  is less efficient than  $p'$ .*
3. *The sum of intermediaries' payoffs and the sum of  $\mathcal{S}/\mathcal{D}$ 's payoffs are both lower under  $p^*$  than under  $p'$ .*

This proposition brings out another novel implication of pricing under uncertain demand: recall that, in the benchmark model, there is no systematic relation between the number of essential traders and intermediation costs (cf. Theorem 1). In contrast, under demand uncertainty, the more essential traders there are, the lower is the price that each charges, but the higher is the cost of intermediation. Hence, a greater number of essential traders leads to greater inefficiency. This follows from a classical problem of double-marginalization. Each of the essential traders faces a downward-sloping demand curve and has the incentive to mark up the intermediation price above its marginal cost. An increase in the number of essential traders reduces the mark-up charged by each intermediary, but the total intermediation cost must rise, because intermediaries do not fully internalize the benefit of lowering the mark-up.

#### 4.0.4 Experimental design and procedures

We study the effects of uncertain demand on pricing, the division of surplus and efficiency of trade. In particular, we test the new theoretical predictions on equal pricing and on partially efficient equilibrium. With this in mind, in addition to rings of size four, six and ten and the Ring with Hubs and Spokes, we also consider Line networks with six and eight traders.<sup>18</sup> Figure 4 presents these networks.

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<sup>18</sup>In the Line network with six and eight traders, the pair  $\mathcal{S}$  and  $\mathcal{D}$  are always the two end nodes and computer-generated agents.

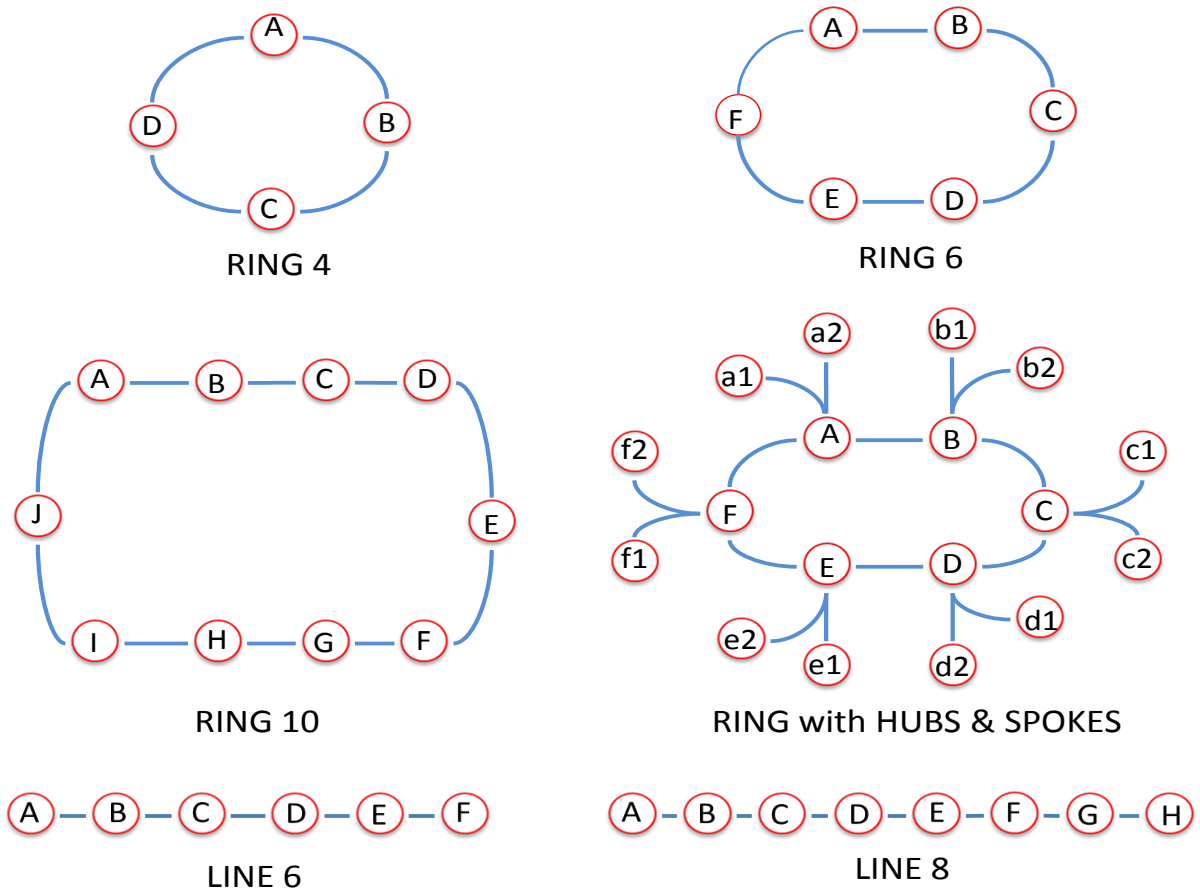


Figure 4: Networks in the uncertain demand case

Recall that in ring networks, there always exists an efficient equilibrium, but in rings with six and ten traders, there are also inefficient and partially efficient equilibria. In Lines and in Ring with Hubs and Spokes (with critical intermediaries), an efficient equilibrium does not exist, but a partially efficient equilibrium does. The frequency of trade declines with the number of critical traders in this equilibrium. These observations motivate the following question.

**Question 1A:** *In the presence of uncertain demand, how does the efficiency of trade vary with ring size and the presence of critical traders?*

Our theoretical analysis reveals that in equilibrium, all essential traders –critical and non-critical – must set the same price and that this price declines in the number of essential traders. This motivates our second question:

**Question 2A:** *In the presence of uncertain demand, how does pricing vary with network location and the number of critical traders?*

Treatment	Session				Total
	1	2	3	4	
Ring 4	16 / 240	24 / 360			40 / 600
Ring 6	18 / 180	18 / 180			36 / 360
Ring 10	30 / 180	30 / 180			60 / 360
Ring w. Hubs/Spokes	18 / 180	18 / 180	24 / 240	30 / 300	90 / 900
Line 6	16 / 240	20 / 300			36 / 540
Line 8	18 / 180	18 / 180			36 / 360

Table 6: Treatments with uncertain demand

#### 4.0.5 Procedures

The experiment was run at the Experimental Laboratory of the University of Essex (ESSEXLab; <http://www.essex.ac.uk/essexlab/>) in May and October 2013. The subjects in the experiment were recruited from the ESSEXLab pool consisting of undergraduate and Master’s students across all disciplines at the University of Essex. The experimental procedures followed the one we described in Section 2.3; sample instructions are reported in Online Appendix I. We note that in the experiment, the value of exchange  $v$  is randomly drawn to be an integer between 1 and 100 at the beginning of each round. Table 6 summarizes the experimental design and treatments. In each cell, we report number of subjects / number of group observations in a session.

#### 4.0.6 Findings

We start with an examination of efficiency of trade. Table 7 presents data on the frequency of trade across the different networks. We split the data of Ring with Hubs and Spokes with respect to the number of paths. The cases in which there is only one path between  $\mathcal{S}$  and  $\mathcal{D}$  correspond to line networks with one or two critical intermediaries. In Table 7 and subsequent tables, we refer to these cases as Line 3 and Line 4, respectively. We refer to all other cases as belonging to Ring with Hubs and Spokes.

Our first observation is that, for fixed a network architecture, the distance between  $\mathcal{S}$  and  $\mathcal{D}$  has an impact on efficiency. In the Ring network with ten traders, the frequency of trade declines from 0.73 to 0.57 as we move from distance 2 to distance 5. In the Ring with Hubs and Spokes, the frequency falls from 0.60 to 0.45 as we move from distance 3 to distance 5. In line networks, the frequency of trade falls from 0.65 to 0.25 as we move from distance 2 to distance 6. Our second observation is on the effects of critical intermediaries. For a fixed distance, the frequency of trade in a ring network and in a line network differ considerably. The frequency of trade in Ring with Hubs and Spokes lies somewhere between that in rings



Network	#Paths	minimum distance between buyer and seller						
		All ( $\geq 2$ )	2	3	4	5	6	7
Ring 4	2	0.89 (600)	0.89 (600)	--	--	--	--	--
Ring 6	2	0.73 (360)	0.74 (234)	0.69 (126)	--	--	--	--
Ring 10	2	0.64 (360)	0.73 (108)	0.62 (114)	0.60 (91)	0.57 (47)	--	--
Ring with Hubs and Spokes	2	0.51 (504)	--	0.60 (158)	0.47 (270)	0.45 (76)	--	--
Line 3	1	0.65 (227)	0.65 (227)	--	--	--	--	--
Line 4	1	0.53 (169)	--	0.53 (169)	--	--	--	--
Line 6	1	0.36 (540)	--	--	--	0.36 (540)	--	--
Line 8	1	0.25 (360)	--	--	--	--	--	0.25 (360)

Notes. The number of group observations is reported in parentheses. #Paths denotes the number of paths connecting buyer and seller. The samples of Line 3 and 4 are from sessions with Ring with Hubs and Spokes.

Table 7: Frequency of trade

and that in lines, for each fixed distance.

To draw out more clearly the effects of distance and the number of critical traders on efficiency, we compare efficiency between ring networks and line networks in Figure 5.<sup>19</sup> We calculate the frequency of trade in ring networks after pooling all the observations in rings with four, six and ten traders, where the length of the shortest path between  $\mathcal{S}$  and  $\mathcal{D}$  is the same (circles on the dotted line in Figure 5). The frequency of trade declines with distance. We also present the frequency of trade in line networks (squares on the solid line in Figure 5). We note that the frequency of trade is lower at every distance level and that the gradient remains significant all the way through. To summarize:

**Finding 1A:** *In the presence of uncertain demand, networks have large effects on efficiency. The frequency of trade falls with distance and falls even more sharply with the number of critical traders.*

We now turn to the pricing behavior of traders by focusing on the last 20 rounds of the experiment. We first present average prices of different types of intermediaries in the Ring networks and the Ring with Hubs and Spokes in Figure 6. In addition, we report in Table 8 the regression results of prices on dummies for critical and non-critical intermediaries, respectively, on a shorter path. We control for individual heterogeneity by including dummies for individual

<sup>19</sup>In the online Appendix, we report average intermediation costs (see Table 14) and average prices for network location (see Table 15) over time and across treatments.

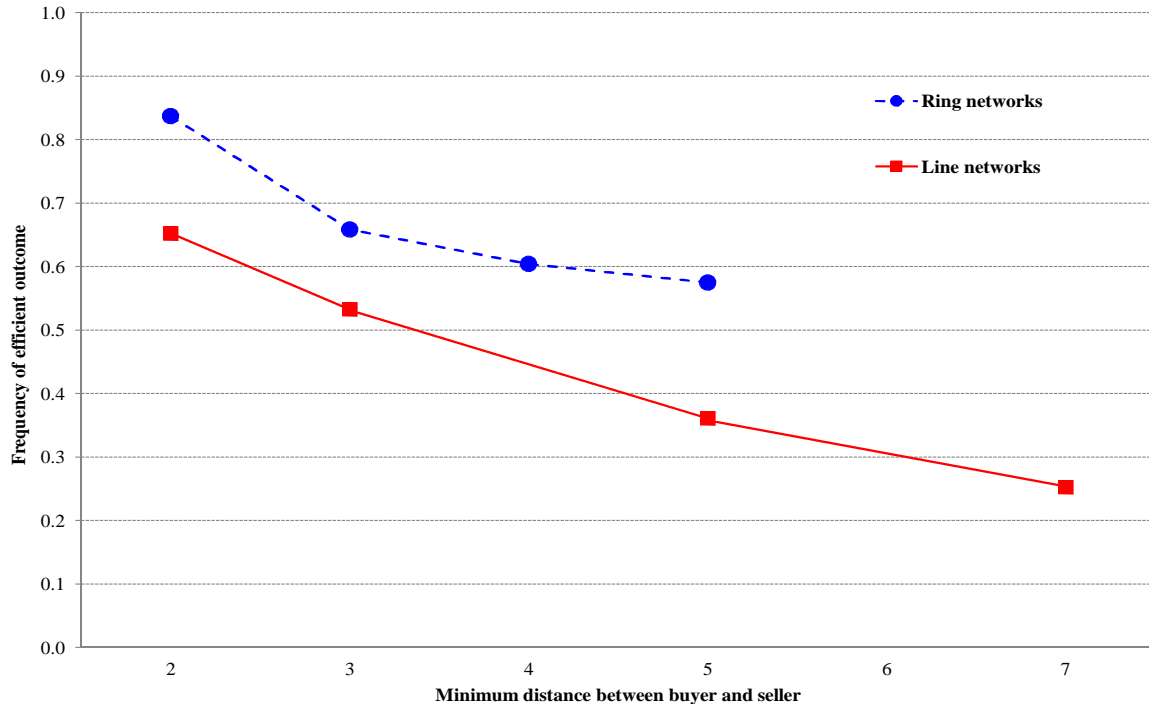


Figure 5: Efficiency and distance

subjects. As in our benchmark experiment, there is clear evidence that subjects responded strategically to the distances of the two paths. Intermediaries on a shorter path chose higher prices that appeared proportionate to the difference in distance between the two paths. In all the networks, this difference in prices chosen by those on a shorter path and on a longer path is statistically significant. As a consequence, trade often occurs along the longer path.

Our next finding pertains to pricing by critical versus non-critical traders in the Ring with Hubs and Spokes. We find that critical intermediaries choose prices that are similar to those of non-critical traders on a shorter path or to all non-critical traders when the two paths are of equal distance. In all trading cases except for the case of  $(\#Cr, d(q), d(q')) = (2, 4, 6)$ , we cannot reject the null hypothesis either that prices chosen by critical and non-critical intermediaries on a shorter path are equal or that critical intermediaries choose the same price as non-critical intermediaries when the two paths are of equal distance. These findings are in line with the predictions of the theory.

Next, we examine the pricing behavior in Line networks. Theorem 2 (in a partially efficient equilibrium) predicts the declining patterns of prices with distance: 50 in Line 3; 33.3 in Line 4; 20 in Line 6; and 14.3 in Line 8. Figure 7 presents the sample average of prices with 95 percent confidence interval across Line networks, along with the theoretically predicted price. As theory predicts, average prices fall with distance between  $\mathcal{S}$  and  $\mathcal{D}$ : 34 in Line 2;

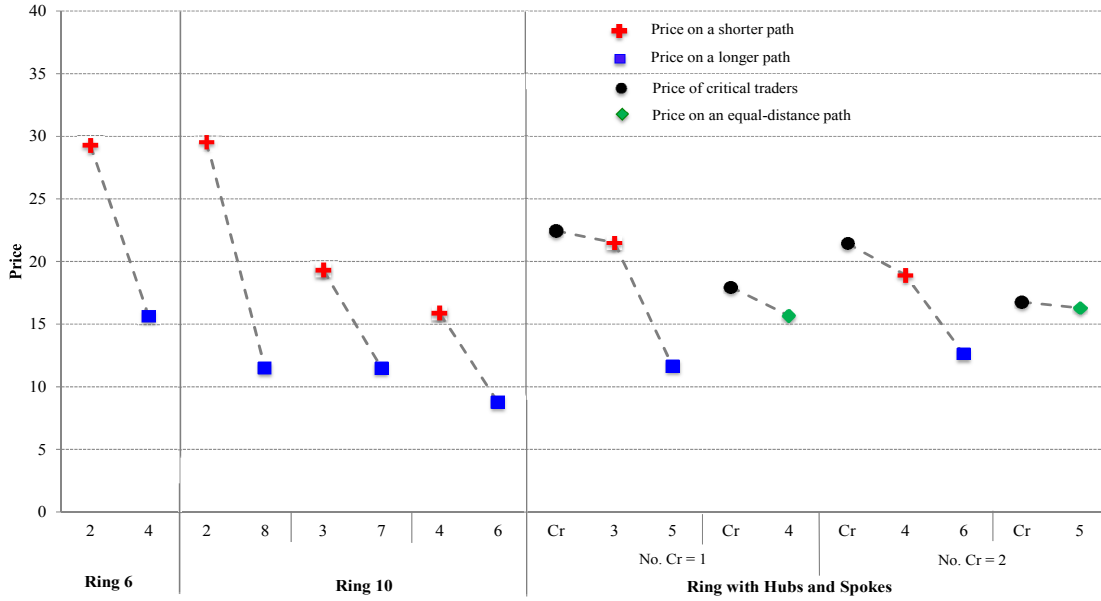


Figure 6: Pricing behavior in Rings and Ring with Hubs and Spokes

Dependent variable: price	Ring 6	Ring 10			Ring with Hubs and Spokes			
	(2, 4)	(2, 8)	(3, 7)	(4, 6)	#Cr = 1		#Cr = 2	
					(3,5)	(4,4)	(4,6)	(5,5)
(1) Non-critical & on a shorter path	13.644 (2.567)***	19.086 (3.281)***	9.017 (1.734)***	6.977 (2.187)***	10.492 (1.689)***		4.511 (2.035)**	
(2) Critical					11.318 (1.689)***	2.840 (2.315)	8.598 (1.677)***	-1.278 (2.233)
Constant	15.645 (1.943)***	7.750 (3.233)**	10.357 (2.928)***	1.907 (2.338)	6.647 (1.136)***	7.449 (0.754)***	7.536 (0.918)***	9.000 (0.397)***
$H_0: (1) = (2)$ or $H_0: (2) = 0$ (p-value)					0.679	0.223	0.029	0.568
R-squared	0.1416	0.387	0.349	0.312	0.326	0.345	0.223	0.376
Number of obs.	312	280	312	200	280	145	378	144

Notes: Each regression controls for individual heterogeneity by including dummies for individual subjects. Robust standard errors, are reported in parentheses. \*, \*\*, and \*\*\* represent 10%, 5%, and 1% significance level.

Table 8: Regressions of pricing on network position

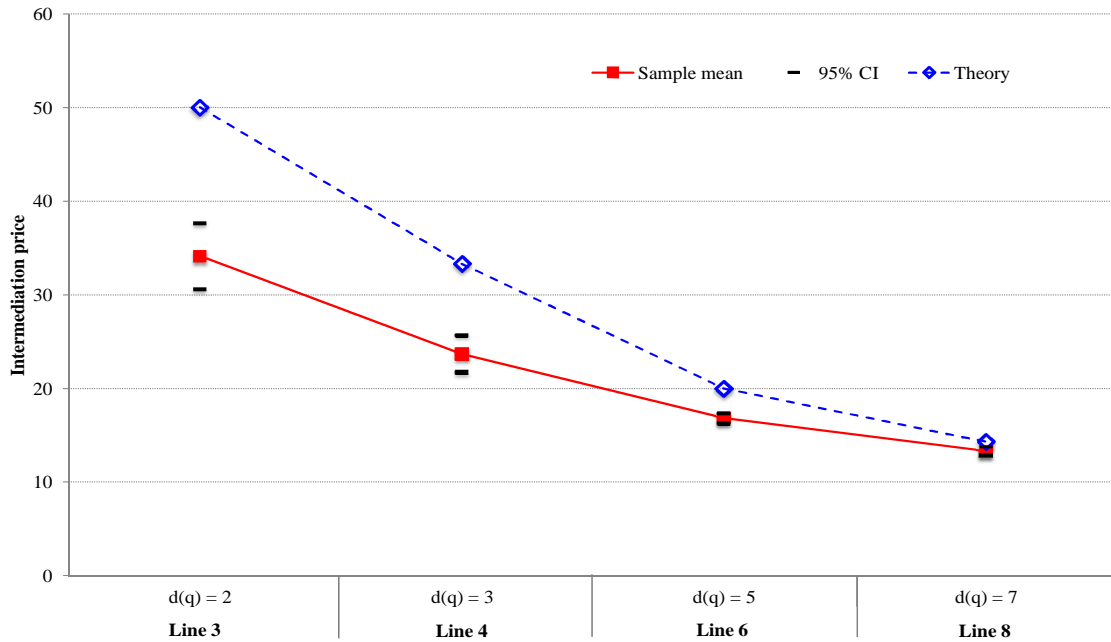


Figure 7: Pricing behavior in Line networks

24 in Line 3; 17 in Line 6; 13 in Line 8. However, average prices quantitatively depart from the predictions in a manner that subjects underprice relative to the equilibrium. The gap between empirical prices and equilibrium prices shrinks with distance. We shall return to these departures in the next section.

We finally turn to the empirical investigation of the theoretical prediction that critical traders across different positions set a common price. We focus on Line 6 and Line 8 networks for this analysis. Table 9 reports the regression results of prices on dummies for network positions, using the last 20 rounds of the data. The average prices in position  $A$  of Line 6 and Line 8 networks are, respectively, about 20 and 13. The coefficients of position dummies are not significantly far from zero, and we cannot reject the null hypothesis of the equivalence of prices between any two positions in each Line network at an usual significance level.

We summarize the pricing behavior in networks with demand uncertainty as follows.

**Finding 2A:** (i) Subjects responded strategically to the distances of two paths. Critical traders and non-critical traders on a shorter path set similar prices, while non-critical traders on a longer path set much lower prices. (ii) Average prices in Line networks decline with distance, as theory predicts. However, average prices are lower than equilibrium prices; the gap between them shrinks with distance.

Dependent variable: price	Line 6 (d(q) = 5)	Line 8 (d(q) = 7)
Constant	19.579 (0.939)***	12.753 (1.212)***
Position B	0.029 (0.686)	-1.030 (0.772)
Position C	-0.383 (0.684)	-0.588 (0.775)
Position D	0.362 (0.781)	-0.006 (0.849)
Position E		-0.205 (0.758)
Position F		-0.764 (0.777)
R-squared	0.200	0.190
Number of obs.	720	720

Notes: Each regression controls for individual heterogeneity by including dummies for individual subjects. Robust standard errors, are reported in parentheses. \*, \*\*, and \*\*\* represent 10%, 5%, and 1% significance level.

Table 9: Regressions of pricing in line network

## 5 Explaining the Pricing Behavior

We have found that subjects' behavior conforms to equilibrium predictions broadly and that the number of critical traders has powerful effects on economic outcomes. However, pricing behavior does depart significantly from equilibrium predictions: 1) intermediation costs depart from both 0 and 100, and 2) in the uncertain demand case, prices set by critical traders are systematically lower than the equilibrium prediction. In this section, we argue that risk aversion and noisy best response help provide an explanation for these departures.

### 5.1 Risk aversion

The experimental literature shows that people exhibit moderate levels of risk aversion in decisions involving even small stakes in a strategic environment (e.g., Goeree et al. (2002, 2003)) and in a non-strategic environment (e.g., Holt and Laury (2002)). First, we theoretically explore the effects of risk aversion in our setting and then estimate a model of risk aversion from our data.

Suppose that individual subjects share a common degree of risk aversion, characterized by the following power utility function:  $u(x; \rho) = \frac{x^{1-\rho}}{1-\rho}$ , where  $\rho \geq 0$  represents the CRRA

Networks	Average prices	Equilibrium	
		$\rho = 0$	$\rho = 0.5$
Line 3	32.21	50	33.33
Line 4	22.14	33.33	25
Line 6	16.84	20	16.67
Line 8	13.32	14.29	12.50

Table 10: Risk Aversion and Prices in Line Networks

coefficient. In a Line network with  $\eta$  intermediaries, the equilibrium price of each intermediary  $i$  and the associated intermediation cost are

$$p_i^* = \frac{1 - \rho}{(\eta + 1) - \eta\rho} \text{ and } c(p^*) = \frac{\eta(1 - \rho)}{(\eta + 1) - \eta\rho}.$$

It is possible to verify that both equilibrium price and intermediation cost decrease in  $\rho$ .<sup>20</sup>

In order to get a sense of how risk aversion comes into play, Table 10 compares average prices in the data with equilibrium prices for two different levels of risk aversion – when  $\rho = 0$  (risk-neutral) and when  $\rho = 0.5$ . We observe that a moderate level of risk aversion can provide a much better fit with the observed prices. Applying the argument of risk aversion to other networks is less transparent due to the multiplicity of equilibrium. In the next section, we combine risk aversion with a model of noisy best response.

## 5.2 Strategic uncertainty

We study a standard model of noisy best response. The model contains two key assumptions. First, we assume that each intermediary forms consistent beliefs about the behavior of traders occupying distinct locations in a network. Beliefs are consistent in the sense that they correspond to the empirical distribution of choices from the data.<sup>21</sup> Second, we assume that a trader makes errors in choosing a price and that the probability of choosing a particular price depends positively on its associated payoff. We further assume the conventional logistic choice function with payoff-sensitivity parameter  $\lambda \geq 0$ ; as  $\lambda$  approaches 0, choice behavior becomes purely random, while as  $\lambda$  goes to infinity, the individual chooses a best response with certainty.<sup>22</sup> Further details of the model are given in Appendix II.

<sup>20</sup>The derivation of the equilibrium with risk aversion follows along the lines of the proof of Theorem 2; the details are omitted.

<sup>21</sup>For instance, in Ring 10 network, where  $S$  and  $D$  are  $B$  and  $H$ , intermediary  $A$  forms beliefs about the behaviors of two distinct traders—the trader on the shorter path and the trader on the longer path. These beliefs are consistent with empirical distributions of the behaviors of traders on a shorter path and on the longer path.

<sup>22</sup>We have tried to develop a stochastic equilibrium model, such as the Quantal Response equilibrium (QRE), proposed by McKelvey and Palfrey (1995). Solving such an equilibrium is complicated because it

We combine the model of strategic uncertainty with risk aversion by assuming the above power utility function, and we estimate the payoff-sensitivity parameter ( $\lambda$ ) and the CRRA coefficient ( $\rho$ ). We pool the data of all ring networks to estimate a single common CRRA coefficients in each experiment. We do the same with the data on all line networks under demand uncertainty. For the Ring with Hubs and Spokes, we focus on the samples of those trading situations in which critical and non-critical intermediaries co-exist. With regard to decision-error parameters, we allow them to vary across distinct trading situations because they entail different strategic incentives.

Table 11 presents the maximum likelihood estimation results of the benchmark experiment and the experiment with demand uncertainty. In the estimation, we use the last 30 rounds of the samples, and we discretize the choice data to be the set of integer numbers, ranging from 0 to 100, by rounding observed choices to their nearest integer. We report the estimated  $\rho$  and  $\lambda$ s and their standard errors, along with the maximized log likelihood value, in each estimation case. We use the bootstrap method in computing standard errors with 500 replications. To see how the model fits the data, we present the difference of average price and predicted price and its 95% confidence interval in each trading situation.

First, subjects in our experiments exhibited a moderate level of risk aversion. The estimated CRRA coefficients range from 0.46 (for ring networks of the benchmark experiment) to 0.67 (for ring networks with uncertain demand). The CRRA estimate of line networks is around 0.61. These estimates are similar to those reported in the literature.<sup>23</sup>

Second, Table 11 shows that the estimated  $\lambda$ s are large and significant for all trading situations, suggesting that the subjects in the experiments responded ‘optimally’ against others’ pricing.

Third, the estimated model closely replicates the average prices of the data. In most of the trading situations, the difference between empirical and predicted average prices is small: the difference is less than 5 in 37 cases out of a total of 46 distinct situations. In the majority of cases, we cannot reject the null hypothesis for the equivalence of empirical and predicted average prices at the 5 percent significance level.

Finally, we plot the predicted distribution of prices and the observed prices to get a further

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requires us to find a distribution from a system of equations involving the convolutions of multiple probability distributions. A numerical approach is also computationally demanding. This practical challenge leads us to adopt a non-equilibrium model of noisy best response under strategic uncertainty.

<sup>23</sup>Goeree et al. (2002, 2003) report  $\rho = 0.52$  and  $0.44$  for first-price private value auctions and asymmetric matching pennies games, respectively. Holt and Laury (2002) report that most of their subjects in their lottery-choice experiment exhibit risk aversion corresponding to the  $0.15 - 0.68$  range of CRRA coefficient.

Network	(#Cr,#Paths, d(q),d(q'))	Distance of own path / criticality	Experiment with demand uncertainty			Benchmark experiment		
			$\rho$ (St. Err.) & Log likelihood	$\lambda$ (St. Err.)	(sample mean - predicted mean) [95% CI]	$\rho$ (St. Err.) & Log likelihood	$\lambda$ (St. Err.)	(sample mean - predicted mean) [95% CI]
Ring 4	(2, 2)	2		10.30 (0.72)	-9.26 [-10.12, -8.30]		34.17 (6.68)	-6.23 [-7.32, -5.30]
Ring 6	(2, 4)	2		5.88 (0.69)	2.63 [1.18, 4.12]		16.12 (2.91)	-1.03 [-3.43, 0.78]
		4		33.94 (2.87)	-2.47 [-4.80, -0.84]		84.11 (22.28)	-1.43 [-4.44, -0.26]
Ring 10	(3, 3)	3		14.76 (1.00)	0.56 [-0.54, 1.50]		35.01 (6.99)	-2.59 [-4.57, -1.81]
		2		9.06 (2.03)	2.07 [-0.92, 4.33]		14.78 (5.72)	-1.36 [-18.91, 4.53]
	(2, 8)	8	0.667 (0.018)	269.12 (76.88)	-1.03 [-2.48, 0.07]	0.461 (0.062)	149.00 (51.75)	-4.80 [-13.40, -0.60]
		3	-9860.7	16.56 (1.91)	-1.82 [-4.42, 0.15]	-6482.5	12.62 (1.06)	-8.35 [-11.96, -4.68]
	(3, 7)	7		115.79 (23.69)	0.13 [-0.80, 0.89]		103.96 (27.32)	-1.06 [-2.39, -0.15]
		4		15.63 (1.11)	-4.10 [-6.49, -1.97]		7.49 (0.48)	-19.42 [-23.08, -13.89]
	(4, 6)	6		54.61 (7.30)	-0.06 [-1.83, 1.19]		103.55 (29.98)	-0.39 [-3.58, 0.28]
		5		38.86 (2.45)	-0.27 [-1.34, 0.69]		64.00 (11.66)	-0.67 [-1.54, -0.04]
Ring with Hubs & Spokes	(1, 2, 3, 5)	Critical		38.84 (6.18)	-3.86 [-5.99, -1.88]		7.97 (1.73)	-5.69 [-7.10, -4.51]
		3 / non-critical		13.84 (1.86)	1.16 [-0.58, 2.50]		5.62 (1.84)	-3.71 [-7.77, -0.57]
	5 / non-critical			72.59 (8.79)	-1.92 [-3.80, -0.39]		56.35 (23.67)	-1.50 [-3.84, 0.18]
		Critical	0.578 (0.023)	17.09 (4.51)	-8.97 [-12.56, -5.63]	0.480 (0.078)	3.29 (0.80)	-11.23 [-15.27, -7.65]
	Non-critical	&		27.69 (2.55)	-0.96 [-2.21, -0.03]	&	23.80 (5.62)	-0.47 [-1.57, 0.15]
		Critical	-5054.3	27.44 (3.68)	-2.07 [-3.68, -0.59]	-2036.3	16.60 (3.65)	0.20 [-2.88, 3.54]
	(2, 2, 4, 6)	4 / non-critical		21.66 (3.01)	0.75 [-0.93, 1.81]		9.22 (2.37)	-2.88 [-7.55, -0.12]
		6 / non-critical		125.45 (19.44)	-2.63 [-5.13, -0.61]		58.96 (21.04)	-1.45 [-6.31, 0.15]
	(2, 2, 5, 5)	Critical		26.23 (3.29)	-5.83 [-9.01, -2.83]		11.44 (3.16)	-5.28 [-9.24, -1.86]
		Non-critical		38.78 (3.99)	0.26 [-1.19, 1.47]		24.38 (5.98)	-1.34 [-2.74, -0.53]
Line	(1,1,2,--)	Critical		16.71 (2.95)	1.10 [-1.12, 3.17]			
	(2,1,3,--)	Critical	0.608 (0.010)	32.17 (5.45)	-0.98 [-2.68, 0.73]			
	(4,1,5,--)	Critical	&	49.38 (2.11)	-0.14 [-0.57, 0.36]			
	(6,1,7,--)	Critical	-8034.1	69.72 (2.75)	0.20 [-0.16, 0.57]			

Table 11: Estimation of strategic uncertainty model with risk aversion



sense of the quality of the match between our model and subjects’s behavior. The overall quality of the match between the model and the experimental data appears to be good across the different treatments. This fit is particularly good in the case of pure market power, as represented in the line networks. Figures 8 and 9 in the online appendix present a selective set of these plots from both experiments.

## 6 Concluding remarks

We propose a general model of posted prices in networks. Our theoretical analysis provides a complete characterization of posted price equilibrium for arbitrary structures of intermediation. This is a first step towards understanding the functioning of intermediated networks. Our experiments complement our theoretical work and point to *node criticality* as an organizing principle for understanding pricing, efficiency and the division of surplus in networked markets.

Our model extends naturally to the case of an arbitrary number of source-destination pairs. The key assumption is that traders know the location of the source-destination in the network, and can discriminate based on this location. In some applications, traders set prices that apply uniformly to all intermediated trades, independently of the location of the origin and destination. An example of uniform prices are road tolls: two drivers who use a bridge across a river will pay the same amount, regardless of where they started or where they end up. This motivates the study of pricing in a model in which the network origin and destination of trades are unknown.

In a companion paper, Choi et al. (2014), we study this setting. We suppose that all traders simultaneously post prices: the price that a trader sets applies to all potential trades that go through him. Once prices are set, an  $\mathcal{S}/\mathcal{D}$  pair is picked at random from the set of all traders. As before, a feasible least-cost path is selected. Given a profile of prices, a trader faces the following trade-off. A higher price raises the payoff if trade does take place, but it rules out long-distance trade between farther-away  $\mathcal{S}/\mathcal{D}$  pairs. The theory and experiments suggest that location uncertainty leads to breakdown of long distance trade and creates large losses in efficiency.

We have assumed that all intermediaries have zero costs and that this is common knowledge. It would be natural to examine the case in which intermediaries have private information about their marginal costs. At a general level, residual uncertainty about marginal costs of

upstream and downstream intermediaries leads to a trade-off similar to the one introduced by demand uncertainty or by uncertainty of the location of source and destination. That is, when an intermediary sets the price, he faces the trade-off between charging a high price and obtaining a high profit, but with low probability, or charging a low price, which leads to a low profit, but with high probability. In an early paper, Spulber (1995) studies a setting with one intermediary per path; in a recent paper, Minarsch and Leister (2015) provide partial characterization of pricing equilibrium for special classes of networks. The analysis of pricing with asymmetric information in general networks remains an open problem.

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## Appendix I: Proofs

### Proof of Theorem 1:

**Existence:** If  $\mathcal{C} = \emptyset$ , set  $p_i^* = 0$  for all  $i \in \mathcal{N}$ . Note that no intermediary can earn positive profits by deviating and setting a positive price, because, since there are no critical traders,

there is always an alternative zero cost path. If  $\mathcal{C} \neq \emptyset$ , then consider a price profile  $\mathbf{p}^*$  such that  $p_i^* = 0$  if  $i \notin \mathcal{C}$ , and for  $j \in \mathcal{C}$  set  $p_j^*$  so that  $\sum_{j \in \mathcal{C}} p_j^* = 1$ . It is easily checked that no critical or non-critical intermediary has a profitable deviation from this profile.

**Characterization:** We first show that  $c^*(p^*) \in (0, 1)$  cannot be sustained in equilibrium. We consider two cases.

**Case 1:** Suppose  $|\mathcal{Q}^*| = 1$ ; in this case a trader  $i$  on  $q \in \mathcal{Q}^*$  can raise his price slightly and strictly increase payoffs.

**Case 2:** Suppose  $|\mathcal{Q}^*| > 1$ ; consider a path  $q \in \mathcal{Q}^*$  and fix a trader  $i \in q$  with  $p_i > 0$ . Note that such a trader always exists, given that  $c(p^*) > 0$ . We have two possibilities:

**2a:** If intermediary  $i$  is essential, he can raise his price slightly and he will remain essential as all other prices remain as before and the sum of prices being less than 1. So there is a strictly profitable deviation.

**2b:** If  $i$  is not essential, given that  $|\mathcal{Q}^*| > 1$ , the probability that  $i$  is used in exchange is at most  $1/2$ . If trader  $i$  lowers his price slightly, he ensures that he is on the unique feasible least cost path. Thus the deviation strictly increases payoff.

Now we take up each of the remaining three possibilities with regard to intermediation costs and characterize the conditions for which they can be sustained in equilibrium.

**1.** Assume  $c(p^*) = 0$ . We first establish sufficiency. In equilibrium every trader makes payoff 0. Consider an increase in price by some intermediary  $i$ . As no intermediary is essential under  $p$ , there exists an alternative path between  $b$  and  $s$  at cost 0, and this path excludes trader  $i$ . So there is no profitable deviation, and  $p^*$  is an equilibrium.

We now establish necessity. Suppose there is a trader  $i$  who is essential under  $p^*$ . As  $c(p^*) = 0$ , essential trader  $i$  can raise his price slightly, still ensure that exchange takes place through him, and thereby he strictly raises his payoffs. So  $p^*$  is not an equilibrium.

**2.** Assume  $c(p^*) = 1$ . We first establish sufficiency. Consider intermediary  $j \in q$ , with  $q \in \mathcal{Q}^*$ . If  $p_j^* > 0$  then intermediary  $j$  is essential and so trade occurs with probability 1 via  $j$  and he earns  $p_j^*$ . If  $j$  raises his price then total costs of intermediation exceed 1 and no trade takes place, yielding a zero payoff to  $j$ . If  $j$  lowers his price, trade does occur with probability 1 via him, so he only succeeds in lowering his payoff below  $p_j^*$ . Next consider trader  $k \in q$  with  $q \in \mathcal{Q}^*$  such that  $p_k = 0$ . It is easily verified that  $k$  cannot increase his payoff by raising his price. Finally, consider  $l \notin q$ ,  $\forall q \in \mathcal{Q}^*$ . This trader earns 0 in  $p^*$ . A deviation to a lower positive price leaves the trade probability via  $l$  at 0, as  $c_{-l}(q'^*) \geq 1$  for all  $q'$  such that  $l \in q'$ .

We have shown that  $p^*$  is an equilibrium.

We now establish necessity. Suppose  $j \in q$ , with  $q \in \mathcal{Q}^*$ ,  $p_j^* > 0$  and  $j$  is not essential. So the probability that exchange occurs via trader  $j$  is at most  $1/2$ . Trader  $j$  can lower his price slightly and this will push the probability of trade via himself to 1, and thereby he strictly raises his payoff. Next consider  $k \notin q$  for all  $q \in \mathcal{Q}^*$  and suppose  $c_{-k}(q'^*) < 1$  for some  $q'$  such that  $k \in q'$ . Under  $p^*$ , the payoff to  $k$  is 0. But since  $c(p^*) = 1$ , there is a price  $p_k = 1 - c_{-k}(q'^*) - \epsilon$  such that, for small  $\epsilon > 0$ , the probability of trade via  $k$  is 1 and  $p_k > 0$ . This is therefore a profitable deviation.

**3.** Assume  $c(p^*) > 1$ . We first establish sufficiency. All traders earn 0 under profile  $p^*$ . It can be checked that no deviation to another price can generate positive payoffs given that  $c_{-j}(q, p^*) \geq 1$ , for all  $j$  and for all  $q \in \mathcal{Q}$ . A deviation to price 0 yields payoff 0. This proves sufficiency.

We now establish necessity. Suppose that  $c(p^*) > 1$  and that there is some  $j \in q$  such that  $c_{-j}(q, p^*) < 1$ . Then there is a price  $p_j = 1 - c_{-j}(p^*) - \epsilon$ , for some  $\epsilon > 0$  such that trade takes place via trader  $j$  with probability 1 and  $p_j > 0$ . This constitutes a profitable deviation. ■

### Proof of Theorem 2:

**Existence:** If there are no critical traders in  $g$ , then existence of efficient equilibrium follows the arguments developed in Theorem 1. If there are critical traders then set  $p_i = 0$  for every non-critical intermediary  $i$ , and for every critical intermediary set  $p^* = 1/h(\eta p^*)$ , where  $\eta$  is the number of critical players. The constructed profile satisfies part 2. Therefore there always exists a partially efficient equilibrium in the presence of critical traders.

**Characterization:** The proof of Part 1 and Part 3 uses the arguments developed in the proof of Part 1 and Part 3 of Theorem 1, and are therefore omitted. We now prove Part 2.

First consider necessity. Suppose  $p^*$  is equilibrium and  $c(p^*) \in (0, 1)$ . Take an arbitrary least cost path  $q \in \mathcal{Q}^1$ . Observe that every player  $i$  who is not essential and who belongs to path  $q$  must set price 0. For otherwise, a positive price by player  $i$ ,  $p_i > 0$ , is dominated by a slightly lower price  $p'_i < p_i$ , that ensures the path  $q$  becomes the unique lowest cost path. This observation and the hypothesis that  $c(p^*) > 0$ , implies that there must exist essential players, i.e.,  $e(g, p^*) \geq 1$ , and that  $c(p^*) = \sum_{i \in \mathcal{E}(g, p^*)} p_i^*$ .

Second, the optimal price of an essential player  $i \in \mathcal{E}(g, p^*)$  solves

$$p_i^* = \arg \max p_i [1 - F(p_i + c_{-i}^*(p^*))]. \quad (4)$$



It is easy to see that  $p_i^* \in (0, 1 - c_{-i}^*(p^*))$ ; the first order condition then says that for all  $i \in \mathcal{E}(g, p)$ ,

$$p_i^* = \frac{1 - F(c(p^*))}{f(c(p^*))}.$$

But this implies that  $\forall i, j \in \mathcal{E}(g, p^*)$ ,  $p_i^* = p_j^*$  and  $p_i^* \in (0, \frac{1}{e(g, p^*)})$ . So equilibrium price is given by

$$p_i^* = \frac{1 - F(e(g, p^*)p^*)}{f(e(g, p^*)p^*)}.$$

The existence of such a  $p^* \in (0, \frac{1}{e(g, p^*)})$  follows from the assumption that  $f(\cdot)$  and  $F(\cdot)$  are both continuous functions and that  $f(0) > 0$ . Finally consider an intermediary  $i$  who does not belong to any path in  $\mathcal{Q}^1$  and suppose that  $c_{-i}(q^*) < e(g, p^*)p^*$  for some path  $q'$  such that  $i \in q'$ . Then player  $i$  can charge a price  $p = e(g, p^*)p^* - c_{-i}(q^*) - \epsilon > 0$  and now whenever trade occurs it will occur via path  $q'$ ; hence, this is a strictly profitable deviation for intermediary  $i$ . The proof that these conditions are sufficient is straightforward, given that the hazard rate is increasing. ■

**Proof of Proposition 1:** From Theorem 2 we know that in a partially efficient equilibrium every essential player sets price,  $p_i^*$ , such that:

$$p_i^* = \frac{1}{h(e(g, p^*)p_i^*)} \quad (5)$$

where  $e(g, p^*) \geq 1$ . The assumption of increasing hazard rate implies that there exists a unique  $p^*$  which solves  $p^* = 1/h(e(g, p^*)p_i^*)$ . We now prove the three parts in the proposition.

Part 1. Implicitly differentiating (5) and simplifying yields:

$$\frac{dp^*}{de(g, p^*)} = -\frac{h'(e(g, p^*)p_i^*)}{h^2(e(g, p^*)p_i^*) + h'(e(g, p^*)p_i^*)} < 0, \quad (6)$$

where the inequality follows from the assumption of increasing hazard rate.

Part 2. Next, note that in a partially efficient equilibrium intermediation costs are  $e(g, p^*)p_i^*$  and therefore the probability that trade does not occur is  $F(e(g, p^*)p_i^*)$ . Again, implicit

differentiation yields

$$\begin{aligned} \frac{dF(e(g, p^*)p_i^*)}{de(g, p^*)} &= f(e(g, p^*)p_i^*) \left[ p_i^* + e(g, p^*) \frac{dp_i^*}{de(g, p^*)} \right] \\ &= f(e(g, p^*)p_i^*) p_i^* \left[ 1 - \frac{h'(e(g, p^*)p_i^*)}{h^2(e(g, p^*)p_i^*) + h'(e(g, p^*)p_i^*)} \right] > 0 \end{aligned}$$

where the second equality follows by substituting the expression for  $\frac{dp_i^*}{de(g, p^*)}$  from above, and the inequality follows from the assumption of increasing hazard rate.

Part 3. The expected payoff of an essential intermediary is  $p^*[1 - F(e(g, p^*)p^*)]$ ; since inessential intermediaries obtain a payoff of zero, the joint profits of intermediaries are

$$\sum_{i \in \mathcal{N}} \Pi_i(p^*) = e(g, p^*)p^*[1 - F(e(g, p^*)p^*)], \quad (7)$$

and

$$\frac{d \sum \Pi_i(p^*)}{de(g, p^*)p^*} = [1 - F(e(g, p^*)p^*)] - e(g, p^*)p^* f(e(g, p^*)p^*) = [1 - F(e(g, p^*)p^*)](1 - e(g, p^*)) \leq 1, \quad (8)$$

where the second equality follows using equilibrium condition  $p^* = 1/h(e(g, p^*)p^*)$ , and the inequality follows because in a partially efficient equilibrium  $e(g, p^*) \geq 1$ . Finally, the joint profit of  $\mathcal{S}$  and  $\mathcal{D}$  is

$$\Pi_{\mathcal{S}}(p^*) + \Pi_{\mathcal{D}}(p^*) = [1 - F(e(g, p^*)p_i^*)] [E[v|v \geq e(g, p^*)p_i^*] - e(g, p^*)p_i^*] \quad (9)$$

$$= \int_{e(g, p^*)p_i^*}^1 x f(x) dx - e(g, p^*)p_i^* [1 - F(e(g, p^*)p_i^*)] \quad (10)$$

and therefore

$$\frac{d[\Pi_{\mathcal{S}}(p^*) + \Pi_{\mathcal{D}}(p^*)]}{de(g, p^*)p^*} = -[1 - F(e(g, p^*)p_i^*)] < 0. \quad (11)$$

■

## Appendix II: Online Appendix

### Different Trading Protocols

**Bid and Ask Model:** In the bid-ask model each intermediary  $i \in \mathcal{N}$  sets  $(b_i, a_i)$  where  $b_i$  is trader  $i$ 's bid price and  $a_i$  is trader  $i$ 's ask price. Then  $\mathcal{S}$  accepts the highest bid, as long as it is non-negative. If there are multiple highest bids,  $\mathcal{S}$  picks one randomly with equal probability.  $\mathcal{D}$  buys as long as the ask is not higher than 1. The object passes from intermediary  $i$  to a connected intermediary  $j$  with the highest bid,  $b_j$ , subject to the condition that the bid  $b_j \geq a_i$ . Ties are broken randomly.

For a posted-price equilibrium  $p^*$  let  $\{U_i(p^*)\}$  be the profile of equilibrium utilities. For a bid-and-ask equilibrium  $(\mathbf{b}^*, \mathbf{a}^*)$  let  $\{U_i(\mathbf{b}^*, \mathbf{a}^*)\}$  be the profile of equilibrium utilities.

**Definition 1.**  $p^*$  is payoff equivalent to  $(\mathbf{b}^*, \mathbf{a}^*)$  whenever: 1.  $U_i(p^*) = U_i(\mathbf{b}^*, \mathbf{a}^*)$  for each  $i \in \mathcal{N}$  and 2.  $U_{\mathcal{S}}(p^*) + U_{\mathcal{D}}(p^*) = U_{\mathcal{S}}(\mathbf{b}^*, \mathbf{a}^*) + U_{\mathcal{D}}(\mathbf{b}^*, \mathbf{a}^*)$ .

**Theorem A:** Fix a network  $g$ . For every posted-price equilibrium  $p^*$  there exists a payoff equivalent bid-and-ask equilibrium  $(\mathbf{b}^*, \mathbf{a}^*)$ .

**Proof of Theorem A:** Suppose  $p^*$  is an inefficient equilibrium. Then it has to be the case that every path connecting  $\mathcal{S}$  and  $\mathcal{D}$  has a distance strictly higher than two. The corresponding equilibrium in the bid-ask model is as follows: every agent bids 0 and asks 1.

We now focus on efficient equilibria. Recall from Theorem 1 that efficient equilibria in posted-price model are extremal.

*Case 1 (S and D extract all surplus):* For such an outcome under posted-prices, there must be no critical intermediaries in  $g$ . For every path  $q \in \mathcal{Q}$  and for every  $i \in q$ , set  $a_i = b_i = 1$ . Under this profile, each intermediary earns 0,  $\mathcal{S}$  earns 1 and  $\mathcal{D}$  earns 0, and so this profile is payoff equivalent to  $p^*$ . To show that this profile  $(\mathbf{b}, \mathbf{a})$  is an equilibrium note that intermediary  $i$  cannot gain by lowering his ask, as each trader connecting to him bids 1. Furthermore, if trader  $i$  lowers his bid, then he will not get the good, because every trader connecting to him asks 1, and, since there are no critical intermediaries,  $\mathcal{S}$  is always connected to at least two intermediaries.

*Case 2 (Intermediaries extract all surplus):* From our characterization of posted-price equilibria we know that there exists  $q^* \in \mathcal{Q}^*$  with  $\sum_{i \in q^*} p_i^* = 1$  and that  $U_i = p_i$  for each  $i \in q^*$ . For convenience, label agents in  $q^*$  as  $\{i_1, \dots, i_n\}$ , where  $g_{\mathcal{S}i_1} = g_{i_1i_2} = \dots = g_{i_n\mathcal{D}} = 1$ . Consider the following bid-ask profile:

- A. Strategy of traders in  $q^*$ :  $a_{i_x} = b_{i_{x+1}}$  for all  $x = 1, \dots, n-1$ , and  $a_{i_n} = 1$ , and  $b_{i_x} = 1 - \sum_{j=i_x, \dots, i_n} p_j^*$  for all  $x = 1, \dots, n$ .
- B. Strategy of traders not in  $q^*$ :  $a_j > 1$  and  $b_j < 0$  for all  $j \notin q^*$

Our first observation is that under this profile, the good flows from  $\mathcal{S}$  to  $\mathcal{D}$  via path  $q^*$  and the payoff of intermediary  $i_x$  is

$$a_{i_x} - b_{i_x} = b_{i_{x+1}} - b_{i_x} = 1 - \sum_{j=i_{x+1}, \dots, i_n} p_j^* - (1 - \sum_{j=i_x, \dots, i_n} p_j^*) = p_{i_x},$$

where the equalities follows by using the construction of the bid-ask profile (see part A); note also that all intermediaries who do not belong to  $q^*$  earn 0. So this profile is payoff equivalent to the posted-price price equilibrium.

We now show that the strategy for every  $j \in q^*$  is optimal. Take  $i_x$ , for some  $x = 1, \dots, n$ . Intermediary  $i_x$  cannot ask more than  $a_{i_x} = b_{i_{x+1}}$  because, all intermediaries not in  $q^*$  are bidding strictly below  $b_{i_{x+1}}$  (note that if  $x = n$  then  $a_{i_n} = 1$  and clearly increasing the asking price is not profitable). Intermediary  $i_x$  cannot change his bid  $b_{i_x}$  either. Indeed, if he decreases his bid, then trade does not occur because agent  $i_{x-1}$  is asking  $b_{i_x}$ . If he increases the bid, then he will unambiguously decrease his profits as he will earn a lower margin.

We next show that the strategy is optimal for every  $j \notin q^*$ . The first case is when  $g_{ji_x} = 0$  for all  $x = 1 \dots n$ . This implies that every intermediary connected to  $j$  bids strictly less than 0 (see part B of the strategy), and so the maximum profit that  $j$  can obtain by deviating and intermediating trade is 0, which is what he gets under the current strategy. Hence, intermediary  $j$  is playing a best response.

The second case is when  $g_{ji_x} = 1$  for a unique  $x = 1 \dots n$ . Suppose that the link is to a upstream intermediary along the trading path. If  $j$  is not linked to the initial  $\mathcal{S}$ , then every downstream intermediary connected to  $j$  bids strictly less than 0 (see part B of the strategy), and so the maximum profit that  $j$  can obtain by deviating and intermediating trade is 0, which is what he earns under the current strategy. Hence,  $j$  is playing an optimal strategy.

If  $j$  is also linked to  $\mathcal{S}$ , then it has to be the case that in the posted price equilibrium  $p_{i_1} = \dots = p_{i_x} = 0$ . This holds because  $i_1, \dots, i_x$  are in the feasible least cost path and they are competing with  $j$ . Part A of the strategy then implies that  $b_{i_x} = 0$  and therefore every intermediary to which  $j$  can sell the object bids, at most, zero which implies that his maximum payoff from buying and reselling is zero, e.g., so  $a_j > 1$  and  $b_j < 0$  is a best reply.

The last and third case is when  $g_{j i_x} = 1$  for at least two  $x = 1 \dots n$ . In this case we can adopt the last argument developed to show that there is no profitable deviation. This concludes the proof. ■

We now develop two examples to show that the converse of Theorem A is not true: there exist equilibrium outcomes in the bid-and-ask model that cannot be sustained in the posted-price model.

**Example 1:** Consider a network where  $\mathcal{S}$  has at least two links and there is at least one critical intermediary. We know that in the posted-price price model, intermediaries extract all surplus in every efficient equilibrium. Consider now the bid-and-ask model and set the following bid-ask profile: all intermediaries set a bid of 1 and an ask of 1. Under this profile the outcome is efficient, the intermediaries obtain zero payoff and  $\mathcal{S}$  obtains the entire surplus. It is easy to verify that this is an equilibrium. ■

**Example 2:** Consider a network where there are  $\eta > 1$  paths between  $s$  and  $b$ , each intermediary belongs only to one path and each of these paths contains at least two intermediaries. Rings where the shortest distance between  $b$  and  $s$  is strictly greater than 2 are an example of such networks with  $\eta = 2$ . In the bid-and-ask model consider the following profile: 1. every intermediary bids  $b \in (0, 1)$ , 2. every intermediary connected to  $\mathcal{D}$  sets an ask  $a = 1$ , and 3. every intermediary not connected to  $\mathcal{D}$  sets an ask of  $b$ .

To see that this is equilibrium first consider an intermediary that is not linked to  $\mathcal{D}$  and is not linked to  $\mathcal{S}$ . Such intermediary can resell the object at  $b$  and therefore it is not profitable to bid more than  $b$ . If they bid  $b$  they get zero. If they bid less than  $b$  they also get zero because each intermediary posts an ask of  $b$ . Consider an intermediary linked to  $\mathcal{S}$ . If he bids  $b$  he gets 0. If he raises his bid, he makes a negative profit because he can resell the object at most at  $b$ . If he lowers his bid, he earns zero because  $\mathcal{S}$  sells to another intermediary. Finally consider an intermediary linked to  $\mathcal{D}$ . Posting an ask of 1 to  $\mathcal{D}$  is clearly optimal. So, if the intermediary bids  $b$  he gets  $1 - b$ . Increasing the bid lowers the intermediary margin, while decreasing the bid leads zero payoff because intermediaries ask  $b$ .

This bid-and-ask equilibrium is efficient and in this equilibrium  $\mathcal{S}$  gets  $1 - b$ , each intermediary not connected to the final  $\mathcal{D}$  earns 0, and each intermediary connected to the final  $\mathcal{D}$  earns  $b/\eta$  (because  $\mathcal{S}$  picks an intermediary with equal probability across all the  $\eta$  paths). ■

**Definition 2.** The bid-ask model is payoff equivalent to the posted-price price model in network  $g$  if the set of equilibrium payoffs in the two models are the same.

We now show that in a wide class of networks, the bid-ask model is payoff equivalent to the posted-price model.

**Example 3: Networks with only critical intermediaries.** Suppose there is only one path between  $\mathcal{S}$  and  $\mathcal{D}$ . The equilibrium with trade in the bid-and-ask model must entail full extraction of surplus by intermediaries. This is because the intermediary linked to  $s$  must set bid at 0 and the intermediary connected to  $\mathcal{D}$  must set an ask of 1. The corresponding payoff outcome can be sustained in the posted-price price model. ■

**Example 4: Network with multiple Bertrand paths.** Suppose that there are at least two paths each with a sole intermediary, no other restrictions are imposed about the architecture of the network. We claim that in all such networks the bid-ask model is payoff equivalent to the posted-price model.

$\mathcal{S}$  must earn the entire surplus in every equilibrium of the bid-and-ask model. Suppose there is an equilibrium where  $\mathcal{S}$  earns surplus  $b < 1$ . This implies that the highest bid that  $s$  receives is  $b$ . Next note that there must exist one of the intermediary in the sole intermediary path, say intermediary  $i$ , who must intermediate trade with probability strictly less than 1, and whenever  $i$  intermediates trade he must get at most  $1 - b$  (because  $1 - b$  is the surplus left after  $\mathcal{S}$  sold the object). If intermediary  $i$  sets a bid slightly above  $b$  he will intermediate trade with probability 1 and so he will strictly gain.

So, in every bid-and-ask equilibrium  $\mathcal{S}$  earns the entire surplus and all other intermediaries earn zero. This outcome can be supported in the posted-price model because the network has no critical intermediaries (as there are two paths, each with a sole intermediary). ■

**Example 5. Competitive Multipartite networks.** We define a  $k$ -multipartite network as follows: there are  $L \geq 1$  layers of intermediation between  $\mathcal{S}$  and  $\mathcal{D}$ . Let  $n_x$  denote the number of nodes in layer  $\ell \in \{1, 2, \dots, L\}$ . By construction  $n_\ell \geq 1$ , for all  $\ell$ . Every intermediary in layer 1 is connected to  $\mathcal{S}$  and a subset of intermediaries in layer 2. Every intermediary in layer  $L$  is linked to  $\mathcal{D}$  and a subset of intermediaries in layer  $L - 1$ . Every intermediary in each layer  $1 < \ell < L - 1$ , is connected to a subset of intermediaries in layer  $\ell - 1$  and a subset of intermediaries in layer  $\ell + 1$ , respectively.

When  $n_\ell = 1$  for all  $\ell = 1 \dots L$  we obtain the Line network as discussed in Example 3. Here our interest is in competitive multipartite networks:  $n_\ell \geq 2$  for each  $\ell \in \{1, \dots, L\}$  and each node in layer  $\ell$  is connected to all nodes in layer  $\ell - 1$ , for all  $\ell \in \{2, \dots, L\}$ .

We now show that in these class of graphs the bid-and-ask model is payoff equivalent to the posted-price price model. First, a competitive multipartite network with only one layer of

intermediation is a special case of the class of networks described in Example 4 and therefore the claim follows. Second, suppose there is more than one layer. Since each path between  $\mathcal{D}$  and  $\mathcal{S}$  contains at least two intermediaries, there is always a bid-and-ask equilibrium which is inefficient, e.g., each intermediary bids  $b < 0$  and ask  $a > 1$ . An inefficient equilibrium exists also in the posted-price model.

We conclude by showing that in every efficient equilibrium of the bid-and-ask model  $\mathcal{S}$  extracts all the surplus. First, note that each intermediary in layer  $L$  can resell the object at an ask of 1 (as they are directly connected to  $\mathcal{D}$ ). Second, since each intermediary in layer  $L$  is connected to all intermediaries in layer  $L - 1$ , it must be the case that the highest bid across  $L$ -layer intermediaries is 1. In fact, since the equilibrium is efficient, the object will arrive at layer  $L - 1$  with probability 1 and, if the highest bid across  $L$ -layer intermediaries is strictly below 1, then one of them strictly gains by posting a slightly higher bid. Since the highest bid across  $L$ -layer intermediaries is 1 and since all intermediaries in layer  $L - 1$  access all intermediaries in layer  $L$ , every  $L - 1$ -layer intermediary can resell the object at a price of 1. So every intermediary in layer  $L - 1$  must set ask 1 and correspondingly set a bid of 1. We can then iterate the argument above to show that, for every layer  $\ell \in 2, \dots, L$  the bid and ask is set equal to 1. Hence,  $\mathcal{S}$  must earn the entire surplus. This outcome is sustainable in the posted-price model if all intermediaries set a price  $p_i = 0$ . It is easily verified that this price profile is an equilibrium in the competitive multi-partite network. ■

**Sequential second price auction:** Consider the following model which is the complete information version of the model of Kotowski and Leister (2012). Two nodes  $\mathcal{S}$  and  $\mathcal{D}$  are connected in a complete multipartite network, i.e. a multipartite network as defined in Example 5 above. Node  $\mathcal{S}$  has an indivisible object.  $\mathcal{S}$  and all intermediaries have no consumption value for the object whereas buyer  $\mathcal{D}$  has a consumption value  $v$ .<sup>24</sup>

Trading occurs via a sequence of second price, sealed-bid auctions: first  $\mathcal{S}$  runs an auction where intermediaries in layer  $\ell = 1$  bid, the winner of this auction runs an auction where intermediaries in layer  $\ell = 2$  bid, and so on. It is assumed that the intermediary in the last layer  $L$  who eventually owns the object sells it to  $\mathcal{D}$  at a price of  $v$ . It follows that if there is only one intermediary in a layer, then the intermediary obtains the object at a price of 0.

For a given strategy profile, define the resale value of an intermediary in layer  $\ell$  as the profit

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<sup>24</sup>Kotowski and Leister (2012) suppose that each intermediary has either a low or high transaction cost. Low transaction cost is normalized to zero; high transaction cost is a number above  $v$ . The level of such cost is private information of the intermediary, but it is common knowledge that an intermediary has a low cost with probability  $p$ . In this section we have assumed that  $p = 1$

that he anticipates to make if he wins the auction. The following proposition characterizes (sub-game perfect) equilibrium where each intermediary bids his resale value. A complete multipartite network, has critical intermediaries if, and only if,  $n_\ell = 1$  for some  $\ell \in \{1, \dots, L\}$ . When there are critical intermediaries, let  $\ell^*$  be the largest index such that  $n_{\ell^*} = 1$ , i.e., the intermediary in layer  $\ell^*$  is critical and there are no critical intermediaries in layer  $\ell > \ell^*$ .

**Theorem B.** Consider a complete multi-partite network with  $L \geq 1$  layers and suppose  $(n_1, \dots, n_L)$  is the distribution of intermediaries across the layers.

1. If there are no critical intermediaries then it is an equilibrium for every intermediary to bid  $v$ . In this equilibrium  $\mathcal{S}$  earns the entire surplus.
2. If there are critical intermediaries, then it is an equilibrium for an intermediary in layer  $\ell \in \{\ell^*, \dots, L\}$  to bid  $v$  and each intermediary in layer  $\ell \in \{1, \dots, \ell^* - 1\}$  bids 0 is an equilibrium. In this equilibrium critical intermediary in layer  $\ell^*$  earns the entire surplus.

**Proof of Theorem B:** Suppose  $\mathcal{C} = \emptyset$ . The resale value of an intermediary in layer  $L$  is  $v$  because, by assumption, an intermediary in the last layer re-sells to  $\mathcal{D}$  at a price  $v$ . Consider then the auction run by an intermediary in layer  $L - 1$ . Since  $\mathcal{C} = \emptyset$ , there are at least two bidders in the auction and their valuation is  $v$ . As standard, bidding  $v$  is a best reply and the profit of the seller is  $v$ . Hence, the resale value of each intermediary in layer  $L - 1$  is  $v$ . The proof follows by iterating this argument.

Next, suppose  $\mathcal{C} \neq \emptyset$ . The argument developed in the previous paragraph holds for every auction run starting from an intermediary in layer  $\ell \in \{\ell^*, \dots, L - 1\}$ . Now consider the auction run by intermediary in layer  $\ell^* - 1$ . Note that, since intermediary in  $\ell^*$  is critical, he buys the object at 0, regardless of his bid. Hence, bidding  $v$  is a best reply. This also implies that the resale value of each intermediary in layer  $\ell^* - 1$  is 0. It is not easy to see that in the auction run by an intermediary in layer  $\ell^* - 2$ , intermediaries in layer  $\ell^* - 1$  play a best reply by bidding 0, which, in turns, implies a resale value of each intermediary in layer  $\ell^* - 2$  equal to 0. Iterating the argument we conclude the proof. ■

We now relate this result to our posted price model. Theorem 1 tells us that in the complete multipartite networks the presence of critical traders implies that in an efficient equilibrium intermediaries extract the entire surplus. The distribution across nodes is not tied down. So, in the auction model, if intermediaries bid their valuation then the equilibrium corresponds to the efficient equilibrium of our posted price model with a very specific division of surplus: the last critical intermediary earns the entire surplus.



## Refinements

In our pricing game there exist multiple equilibria, as the discussion in the main text illustrates. One way forward is to consider standard refinement concepts to see if they will help eliminating some of the equilibrium and thereby clarifying the relation between network structure and behavior. Over the years, game theorists have put forward a very wide range of concepts. In the main text of the paper, we mention that standard refinements do not take us very far. To elaborate on this, we discuss some natural refinements a bit more in detail. The discussion focuses on the case of known demand.

1. Consider the refinement of strictness. It is clear that there does not exist a strict Nash equilibrium in a ring network. The zero price equilibrium yields zero profits all around and so players are indifferent with respect to a positive price. The only other type of Nash equilibrium involves too high prices and breakdown on one path. But clearly there is no strict best response in this case. Hence, in a ring network there is not a strict Nash equilibrium. Consider now a line with  $n > 1$  intermediaries. Strict Nash rules out inefficient equilibrium. Note, however, that every efficient Nash equilibrium where each intermediary charges a positive price is a strict Nash equilibrium. Hence, strict Nash does not pin down the distribution of payoffs across critical intermediaries.
2. Next consider strong equilibrium. Clearly any strong equilibrium must be a Nash equilibrium. However, strong Nash equilibrium must be efficient for intermediaries. But in the ring network full extraction by a single path is not sustainable, as the other path can deviate and undercut. Similarly, full extraction by both paths cannot be sustained as players along one path can undercut and strictly do better. Hence, in a ring network there is not a strong Nash equilibrium. Consider now a line with  $n > 1$  intermediaries. Strong Nash rules out inefficient Nash equilibrium. Note, however, that every efficient Nash equilibrium is a strong Nash equilibrium. Hence, strong Nash does not pin down the distribution of payoffs across critical intermediaries.
3. In the ring it is clear that the elimination of weakly dominated strategies does not rule out inefficient Nash equilibria. Indeed, for an intermediary  $i$ , charging  $p_i = v$  is not weakly dominated and the profile where all agents charge a price  $v$  is a Nash equilibrium (as long as there are at least two intermediaries in each path) and it is inefficient. Moreover, the competitive equilibrium in the ring is in weakly dominated strategies. Finally, the elimination of weakly dominated strategies does not pin down

how surplus is divided across critical traders. For example, in a line, it is clear that every efficient Nash equilibrium where each intermediary charges a positive price survives the elimination of weakly dominated strategies.

4. Coalition proof equilibrium. Coalition proof eliminates inefficient Nash equilibria but (1) it does not resolve how surplus is distributed across essential traders, and (2) it does not imply that intermediaries make profit only if they are critical. We elaborate on these points next.

Take a ring network with at least two intermediaries in each path. Consider a Nash equilibrium that is inefficient. Now take a set of intermediaries that form a path  $q$  between the source and the destination and consider a deviation so that the cost of the path  $q$  is  $v$  and each of these intermediaries charge a positive price. It is always possible to find such a deviation. These intermediaries now earn a positive profit. Furthermore, this deviation is internally consistent as no subsets of intermediaries in path  $q$  have incentive to deviate. In fact, any deviation of any subset of intermediaries in  $q$  will either increase the cost of  $q$  and therefore destroy trade or it will decrease the price charged by some of the deviating intermediaries. So, Nash equilibria that are inefficient are not coalition proof.

Take a ring network with at least two intermediaries in each path. Consider now an equilibrium where intermediaries get all the surplus. This means that the cost of one path, say  $q$ , is  $c(q) > v$  and the cost of the other path, say  $q'$ , is  $c(q') = v$ . We argue that this Nash equilibrium is also a coalition proof equilibrium. Clearly, no subset of intermediaries that include some intermediaries in  $q'$  wishes to deviate. Intermediaries in path  $q$  could deviate so that the cost of  $q$  is  $v - \epsilon$ , where  $\epsilon \geq 0$ . But such a deviation is not internally consistent. In fact, if  $\epsilon > 0$  then some intermediary in  $q$ , who deviated, would like to raise slightly his price. If  $\epsilon = 0$ , then some intermediary in  $q$ , who deviated, would like to undercut his price. So coalition proof does not eliminate Nash equilibria in which intermediaries get all the rent, even if there are not critical traders.

It is also clear that the competitive outcome in the ring is a coalition proof equilibrium.

We finally show that coalition proof does not eliminate the indeterminacy of payoff distribution across critical traders. To see this, take a line with  $n > 1$  intermediaries. Take a Nash equilibrium where intermediaries extract all the surplus. Then the cost of the path must be  $v$ . But then no subset of intermediary can deviate profitable, and so

the equilibrium is also coalition proof.

## Strategic Uncertainty

In the model of strategic uncertainty we make the following two assumptions. First, each trader is assumed to form beliefs about the behaviors of other traders, consistent with their actual behavior. Second, each trader make errors in choosing his own choice and the probability of choosing a particular price is positively associated with its corresponding payoff. We focus on the trading setting with demand uncertainty where the surplus is unknown and drawn from a distribution  $F_v(\cdot)$  on the interval  $[0, 100]$ . Given a utility function  $u$ , the expected utility of intermediary  $i$  with his price  $p_i$  is

$$\tilde{\Pi}_i(p_i) = u(p_i) \times B_i(p_i),$$

where  $B_i(p_i)$  denotes intermediary  $i$ 's beliefs about himself being used for trade. The precise form of this depends on a network  $g$ . We denote  $F_{-j}$  as intermediary  $i$ 's beliefs (joint distribution) about the pricing behaviors of all other intermediaries in a network. We start by considering Line networks.

**Line networks.** Consider a line network with  $\eta \geq 1$  intermediaries. The probability of intermediary  $i$  being used for trade is then given by

$$B_i(p_i) = \int_{v \in [0, 100]} \int_{p_{-i}} \mathbf{1} \left\{ p_i + \sum_{j \neq i} p_j \leq v \right\} dF_{-i} dF_v,$$

where  $\mathbf{1}\{\cdot\}$  is an indicator function.

**Ring networks.** Consider a trading situation  $(d(q_1), d(q_2))$  in a ring network where there are  $n_1 \geq 1$  and  $n_2 \geq 1$  numbers of intermediaries in paths  $q_1$  and  $q_2$ , respectively. Fix intermediary  $i \in q_1$ . The probability of intermediary  $i$  being used for trade is then given by

$$B_i(p_i) = \int_{v \in [0, 100]} \int_{p_{-i}} \mathbf{1} \left\{ \begin{array}{l} p_i + \sum_{j \neq i, j \in q_1} p_j \leq v \\ \& \sum_{j \in q_1} p_j \leq \sum_{k \in q_2} p_k \end{array} \right\} dF_{-i} dF_v.$$

**Ring with Hubs and Spokes.** Consider first a critical intermediary  $i$  in a trading situation  $(d(q_1), d(q_2))$  in a ring network where there are  $n_1 \geq 2$  and  $n_2 \geq 2$  numbers of intermediaries in paths  $q_1$  and  $q_2$ , respectively. The probability of critical intermediary  $i$

being used for trade is

$$B_i(p_i) = \int_{v \in [0,100]} \int_{p_{-i}} \mathbf{1} \left\{ p_i + \min \left\{ \sum_{j \neq i, j \in q_1} p_j, \sum_{k \neq i, k \in q_2} p_k \right\} \leq v \right\} dF_{-i} dF_v.$$

If intermediary  $i$  is non-critical and  $i \in q_1$ , the probability of non-critical intermediary  $i$  being used for trade is

$$B_i(p_i) = \int_{v \in [0,100]} \int_{p_{-i}} \mathbf{1} \left\{ \begin{array}{l} p_i + \sum_{j \neq i, j \in q_1} p_j \leq v \\ \& \sum_{j \in q_1} p_j \leq \sum_{k \in q_2} p_k \end{array} \right\} dF_{-i} dF_v.$$

In estimating the model of strategic uncertainty with the experimental data,<sup>25</sup> we assume that intermediary  $i$  makes a stochastic choice, modelled by a conventional logistic function:

$$\Pr \{p_i = s\} = \frac{\exp(\lambda \tilde{\Pi}_i(s))}{\sum_{t=0}^{100} \exp(\lambda \tilde{\Pi}_i(t))},$$

where  $\lambda$  is a payoff-sensitivity parameter in choice function. If  $\lambda$  goes to zero, the pricing choice becomes purely random. If  $\lambda$  goes to the infinity, the individual chooses an optimal price with probability 1. In the estimation, we assume that each individual intermediary forms consistent beliefs about the behaviors of other traders across distinct trading positions in a network. Beliefs are consistent in the sense that they correspond to empirical distributions of choices from the experiment. We also assume that individual traders share the power utility function

$$u(x; \rho) = \frac{x^{1-\rho}}{1-\rho},$$

where  $\rho$  represents the constant relative risk aversion (CRRA) coefficient.

We use the maximum likelihood estimation (MLE) method to estimate the payoff-sensitivity parameters and the CRRA coefficient of the model of strategic uncertainty with stochastic choice. Let the data consist of  $m$  number of distinct trading positions,  $k_1, \dots, k_m$ , in each of which there are  $n_{k_i}$  number of price choices,  $\{p_{k_i}\}_{k_i=1}^{n_{k_i}}$ . Given the above formulas of expected

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<sup>25</sup>In the estimation we discretize the experimental data to be the set of integer numbers, ranging from 0 to 100, by rounding observed choices to their nearest integer.

payoffs and logistic choice function, we can then construct the log-likelihood function:

$$\mathcal{L}\left(\rho, \lambda_{k_1}, \dots, \lambda_{k_m}; \left\{\{p_{k_i}\}_{k_i=1}^{n_{k_i}}\right\}_{i=1}^m\right) = \sum_{i=1}^m \sum_{k_i=1}^{n_{k_i}} \left\{ \sum_{t=0}^{100} \mathbf{1}\{p_{k_i} = t\} \times \log(\Pr\{p_{k_i} = t\}) \right\}.$$

The set of parameters,  $(\rho, \lambda_{k_1}, \dots, \lambda_{k_m})$ , are chosen to maximize the log-likelihood function. Table 10 in the on-line appendix reports the MLE estimates with last 30 rounds of the data from the experiment with demand uncertainty and the benchmark experiment, respectively. We use the nonparametric bootstrap method of computing standard errors of the model parameters with 500 replications.

## **Additional empirical material**

In this Appendix we report information about intermediation costs and average prices over time and across different treatments, both for the benchmark experiment (Table 12 and Table 13) and for the experiment with demand uncertainty (Table 14 and Table 15). We also present a selective set of plots on distributions of estimated prices and observed prices in the different treatments (Figures 8 and 9).

Network	(#Cr,#Paths, d(q),d(q'))	Rounds						
		1 ~ 10	11 ~ 20	21 ~ 30	31 ~ 40	41 ~ 50	51 ~ 60	60
Ring 4	(0, 2, 2, 2)	19.76	12.77	7.80	6.04	4.81	5.36	8.42
		(80)	(80)	(80)	(80)	(80)	(80)	(8)
Ring 6	(0, 2, 2, 4)	41.77	24.62	18.44	14.08	11.96	12.01	8.06
		(52)	(49)	(50)	(44)	(44)	(50)	(3)
	(0, 2, 3, 3)	39.05	22.92	17.54	14.99	12.92	13.00	12.25
		(18)	(21)	(20)	(26)	(26)	(20)	(4)
Ring 10	(0, 2, 2, 8)	40.40	30.51	22.36	20.35	17.60	20.71	20.00
		(5)	(11)	(11)	(8)	(5)	(9)	(1)
	(0, 2, 3, 7)	41.85	29.66	26.44	22.20	20.11	22.09	27.80
		(17)	(14)	(15)	(13)	(14)	(14)	(1)
	(0, 2, 4, 6)	41.41	29.31	23.53	22.01	20.07	17.54	14.15
(11)		(11)	(10)	(12)	(15)	(10)	(2)	
(0, 2, 5, 5)	43.32	30.73	24.44	20.76	24.54	18.20	--	
		(7)	(4)	(4)	(7)	(6)	(7)	(0)
Ring with hubs	(1, 1, 2, -)	89.19	98.09	98.06	99.20	99.67	99.31	--
		(15)	(22)	(17)	(15)	(15)	(16)	(0)
	(2, 1, 3, -)	87.35	85.00	92.85	97.59	95.00	96.88	--
		(14)	(5)	(18)	(13)	(12)	(8)	(0)
	(1, 2, 3, 5)	66.09	73.44	74.59	74.28	73.50	66.31	60.00
		(11)	(9)	(11)	(15)	(12)	(13)	(1)
	(1, 2, 4, 4)	76.35	71.41	66.43	59.33	58.00	65.17	56.00
		(7)	(9)	(7)	(6)	(4)	(6)	(2)
	(2, 2, 4, 6)	86.06	87.51	86.90	85.53	84.94	81.82	76.00
		(7)	(9)	(7)	(12)	(11)	(13)	(2)
(2, 2, 5, 5)	90.19	84.12	76.83	81.00	71.57	82.25	--	
	(5)	(3)	(3)	(5)	(7)	(4)	(0)	
(0, 2, 2, 4) or (0, 2, 3, 3)	40.60	47.00	46.50	31.33	32.33	25.56	21.75	
	(5)	(5)	(4)	(3)	(6)	(8)	(2)	

Note: The number in a cell is the sample average. The number in parentheses is the number of observations. #Cr denotes the number of critical intermediaries, #Paths denotes the number of paths connecting buyer and seller, d(q) denotes the length of path q between buyer and seller.

Table 12: Intermediation costs, conditional on trading, in the benchmark case.

Network	(#Cr,#Paths, d(q),d(q'))	Distance of own path / criticality	Rounds						
			1 ~ 10	11 ~ 20	21 ~ 30	31 ~ 40	41 ~ 50	51 ~ 60	60
Ring 4	(2, 2)	2	23.91 (160)	14.98 (160)	10.61 (160)	8.36 (160)	8.84 (160)	10.41 (160)	5.94 (32)
Ring 6	(2, 4)	2	46.41 (52)	28.04 (49)	20.19 (50)	15.79 (44)	16.26 (44)	14.77 (50)	10.00 (3)
		4	16.23 (156)	9.88 (147)	7.49 (150)	6.29 (132)	5.69 (132)	6.53 (150)	6.24 (9)
	(3, 3)	3	22.58 (72)	14.04 (84)	10.01 (80)	8.45 (104)	7.84 (104)	7.79 (80)	7.75 (16)
Ring 10	(2, 8)	2	41.40 (5)	30.81 (11)	24.69 (11)	20.93 (8)	21.80 (5)	30.85 (9)	20.00 (1)
		8	6.69 (35)	6.59 (77)	4.45 (77)	6.13 (56)	3.55 (35)	6.74 (63)	18.00 (7)
	(3, 7)	3	24.15 (34)	15.89 (28)	14.17 (30)	12.29 (26)	10.60 (28)	12.49 (28)	25.00 (2)
		7	7.73 (102)	5.69 (84)	5.56 (90)	4.60 (78)	4.23 (84)	5.73 (84)	4.63 (6)
	(4, 6)	4	17.16 (33)	10.23 (33)	9.00 (30)	8.42 (36)	7.16 (45)	6.56 (30)	6.80 (6)
		6	9.78 (55)	7.61 (55)	5.47 (50)	4.73 (60)	5.19 (75)	4.92 (50)	3.72 (10)
	(5, 5)	5	12.65 (56)	9.25 (32)	7.12 (32)	6.08 (56)	6.66 (48)	5.77 (56)	-- (0)
	(1, 2, 3, 5)	Critical	38.83 (12)	44.97 (11)	50.18 (11)	50.62 (15)	53.85 (13)	47.85 (13)	50.00 (1)
		3 / non-critical	36.67 (12)	40.36 (11)	33.59 (11)	32.09 (15)	26.31 (13)	24.62 (13)	10.00 (1)
		5 / non-critical	16.26 (36)	14.85 (33)	9.39 (33)	8.97 (45)	10.97 (39)	8.41 (39)	8.00 (3)
(1, 2, 4, 4)	Critical	38.29 (8)	36.18 (9)	34.86 (7)	35.83 (6)	35.00 (4)	46.17 (6)	40.50 (2)	
	Non-critical	28.10 (32)	20.28 (36)	17.88 (28)	14.33 (24)	15.31 (16)	13.04 (24)	10.00 (8)	
Ring with hubs	(2, 2, 4, 6)	Critical	33.14 (20)	35.02 (22)	34.86 (20)	32.47 (24)	36.94 (26)	33.18 (26)	29.25 (4)
		4 / non-critical	29.98 (10)	27.78 (11)	23.07 (10)	24.58 (12)	20.46 (13)	17.46 (13)	17.50 (2)
		6 / non-critical	12.69 (30)	9.59 (33)	10.57 (30)	8.11 (36)	7.82 (39)	7.91 (39)	12.33 (6)
(2, 2, 5, 5)	Critical	29.50 (10)	33.50 (10)	23.17 (6)	30.67 (12)	26.36 (14)	30.50 (8)	-- (0)	
	Non-critical	21.17 (20)	16.97 (20)	15.71 (12)	14.08 (24)	12.07 (28)	13.00 (16)	-- (0)	
(2, 1, 3, --)	Critical	45.60 (30)	46.79 (14)	46.43 (36)	48.80 (26)	47.50 (24)	50.00 (20)	-- (0)	

Note: The number in a cell is the sample average. The number in parentheses is the number of observations. #Cr denotes the number of critical intermediaries, #Paths denotes the number of competing paths connecting buyer and seller, d(q) denotes the length of path q between buyer and seller.

Table 13: Pricing Behavior in the benchmark case.

Network	#Paths	#Cr	$(d(q), d(q'))$	Rounds					
				1 ~ 10	11 ~ 20	21 ~ 30	31 ~ 40	41 ~ 50	51 ~ 60
Ring 4	2	0	(2, 2)	18.86 (100)	15.74 (100)	12.15 (100)	10.48 (100)	8.93 (100)	7.35 (100)
Ring 6	2	0	(2, 4)	34.28 (37)	31.01 (34)	27.30 (43)	27.28 (42)	26.88 (42)	24.78 (36)
			(3, 3)	33.64 (23)	33.82 (26)	36.45 (29)	36.02 (18)	27.09 (18)	26.34 (24)
Ring 10	2	0	(2, 8)	41.04 (22)	25.30 (17)	28.19 (22)	27.48 (12)	31.73 (19)	23.31 (16)
			(3, 7)	34.16 (16)	36.26 (17)	37.46 (19)	33.36 (23)	33.08 (14)	31.16 (25)
			(4, 6)	53.50 (14)	38.06 (17)	39.48 (16)	34.62 (19)	35.47 (15)	33.01 (10)
			(5, 5)	60.47 (8)	49.30 (9)	29.69 (3)	27.86 (6)	41.77 (12)	46.12 (9)
Ring with Hubs and Spokes	2	1	(3, 5)	43.75 (20)	41.75 (22)	48.36 (23)	41.30 (37)	39.95 (26)	41.05 (30)
			(4, 4)	55.76 (16)	41.69 (16)	44.94 (21)	43.78 (17)	37.29 (15)	45.82 (14)
	2	2	(4, 6)	71.88 (28)	67.66 (30)	58.02 (30)	54.53 (20)	59.11 (33)	61.00 (30)
			(5, 5)	61.83 (14)	54.30 (13)	49.35 (14)	58.51 (11)	54.18 (13)	56.56 (11)
Line 3	1	1	(2, --)	35.44 (42)	31.67 (41)	31.65 (31)	33.29 (38)	36.50 (36)	31.97 (39)
Line 4	1	2	(3, --)	49.85 (30)	46.49 (28)	51.08 (31)	45.90 (27)	50.37 (27)	44.23 (26)
Line 6	1	4	(5, --)	69.67 (90)	63.67 (90)	59.76 (90)	64.35 (90)	64.92 (90)	69.81 (90)
Line 8	1	6	(7, --)	76.94 (60)	77.32 (60)	69.50 (60)	74.04 (60)	80.58 (60)	79.26 (60)

Note: The number in a cell is the sample average. The number in parentheses is the number of observations. #Cr denotes the number of critical intermediaries, #Paths denotes the number of paths connecting buyer and seller,  $d(q)$  denotes the length of path  $q$  between buyer and seller.

Table 14: Intermediation costs, conditional on trading, in the uncertain demand case

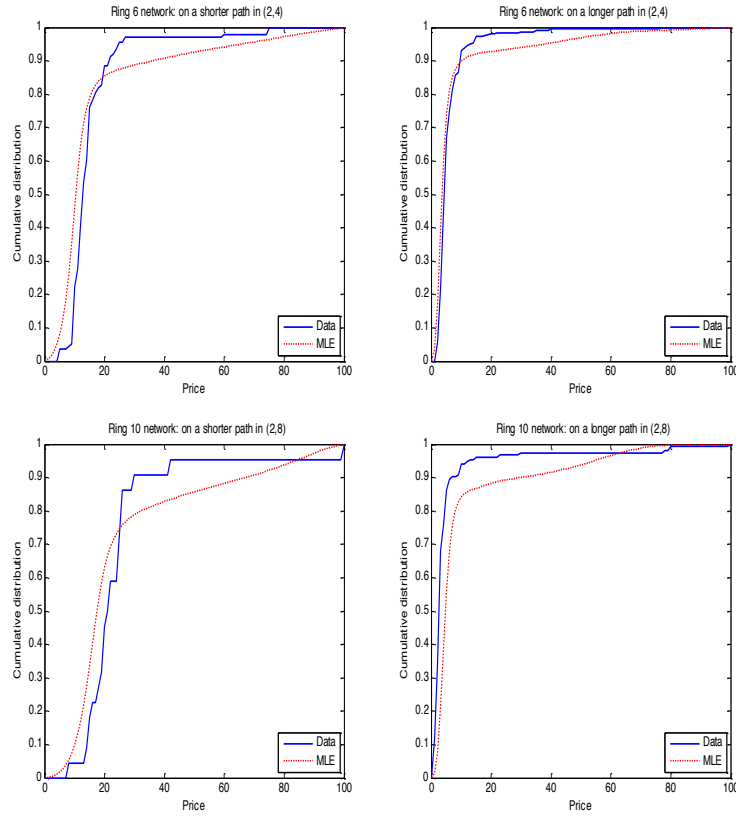


Network	(#Cr,#Paths, d(q),d(q'))	Distance of own path / criticality	Rounds						
			1 ~ 10	11 ~ 20	21 ~ 30	31 ~ 40	41 ~ 50	51 ~ 60	
Ring 4	(2, 2)	2	26.66 (200)	21.47 (200)	16.43 (200)	13.46 (200)	11.76 (200)	10.15 (200)	
Ring 6	(2, 4)	2	37.99 (37)	32.70 (34)	34.38 (43)	32.04 (42)	28.74 (42)	29.93 (36)	
		4	19.78 (111)	17.97 (102)	14.55 (129)	15.59 (126)	17.21 (126)	13.82 (108)	
	(3, 3)	3	21.31 (92)	22.71 (104)	21.68 (68)	24.05 (72)	17.69 (72)	21.11 (96)	
	(2, 8)	2	42.59 (22)	26.00 (17)	31.32 (22)	27.50 (12)	33.68 (19)	24.66 (16)	
8		15.20 (154)	11.05 (119)	8.32 (154)	12.42 (84)	12.67 (133)	10.09 (112)		
Ring 10	(3, 7)	3	19.06 (32)	22.99 (34)	20.15 (38)	17.51 (46)	20.44 (28)	18.69 (50)	
		7	12.29 (96)	7.73 (102)	12.05 (114)	12.44 (138)	11.33 (84)	11.63 (150)	
	(4, 6)	4	21.56 (42)	17.33 (51)	16.06 (48)	13.70 (57)	17.26 (45)	13.88 (30)	
		6	16.51 (70)	11.65 (85)	12.78 (80)	13.68 (95)	8.75 (75)	8.82 (50)	
	(5, 5)	5	17.86 (64)	14.50 (72)	9.07 (24)	8.36 (48)	12.33 (96)	15.05 (72)	
	Ring with Hubs and Spokes	(1, 2, 3, 5)	Critical	23.27 (20)	22.47 (22)	29.39 (23)	22.57 (37)	21.02 (26)	23.68 (30)
3 / non-critical			27.03 (20)	20.30 (22)	22.91 (23)	23.66 (37)	21.35 (26)	21.65 (30)	
5 / non-critical			12.72 (60)	11.87 (66)	13.39 (69)	13.89 (111)	14.25 (78)	9.38 (90)	
(1, 2, 4, 4)		Critical	26.03 (16)	19.03 (16)	22.74 (21)	20.47 (17)	15.73 (15)	20.36 (14)	
		Non-critical	21.72 (64)	16.01 (64)	17.03 (84)	15.57 (68)	15.34 (60)	16.06 (56)	
(2, 2, 4, 6)		Critical	25.47 (56)	25.28 (60)	20.58 (60)	18.43 (40)	20.76 (66)	22.19 (60)	
		4 / non-critical	25.39 (28)	20.33 (30)	18.72 (30)	19.28 (20)	18.99 (33)	18.83 (30)	
		6 / non-critical	13.99 (84)	9.85 (90)	14.84 (90)	16.52 (60)	13.41 (99)	11.80 (90)	
(2, 2, 5, 5)		Critical	19.09 (28)	16.92 (26)	15.43 (28)	16.64 (22)	16.72 (26)	16.81 (22)	
		Non-critical	17.88 (56)	14.68 (52)	14.02 (56)	19.98 (44)	15.94 (52)	16.71 (44)	
Line 3		(2, 1, 2, --)	Critical	35.44 (42)	31.67 (41)	31.65 (31)	33.29 (38)	36.50 (36)	31.97 (39)
Line 4		(2, 1, 3, --)	Critical	24.92 (60)	23.25 (56)	25.54 (62)	22.95 (54)	25.19 (54)	22.11 (52)
Line 6	(4, 1, 5, --)	Critical	17.42 (360)	15.92 (360)	14.94 (360)	16.09 (360)	16.23 (360)	17.45 (360)	
Line 8	(6, 1, 7, --)	Critical	12.82 (360)	12.89 (360)	11.58 (360)	12.34 (360)	13.43 (360)	13.21 (360)	

Note: The number in a cell is the sample average. The number in parentheses is the number of observations. #Cr denotes the number of critical intermediaries, #Paths denotes the number of competing paths connecting buyer and seller, d(q) denotes the length of path q between buyer and seller.

Table 15: Pricing behavior in the uncertain demand case

## Ring networks



## Ring with Hubs and Spokes

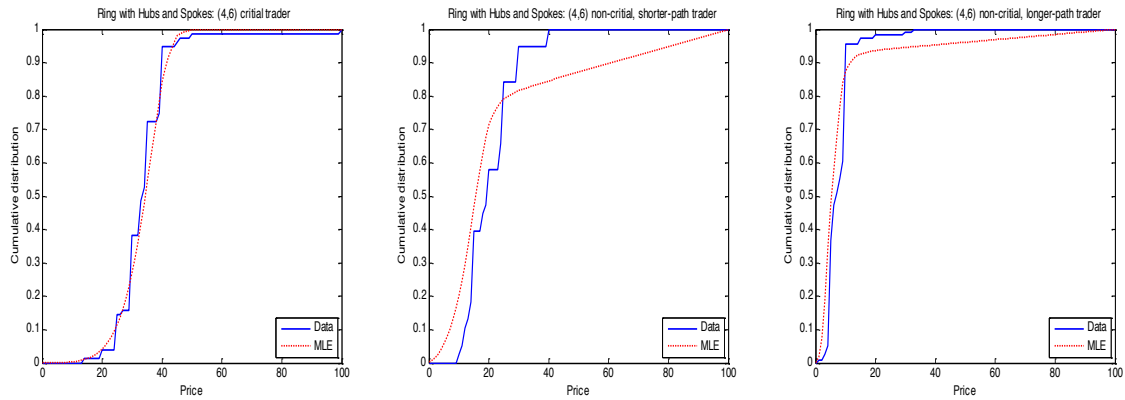
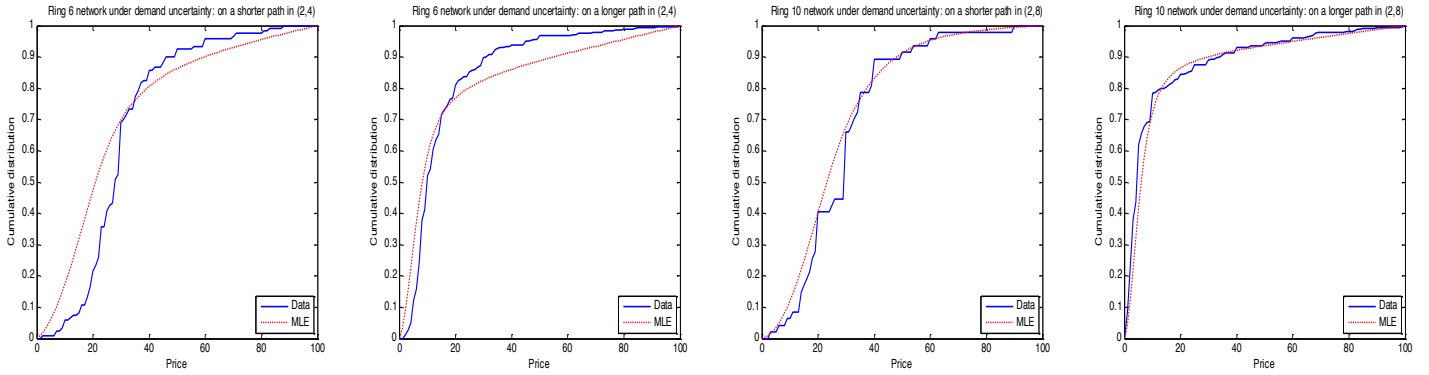
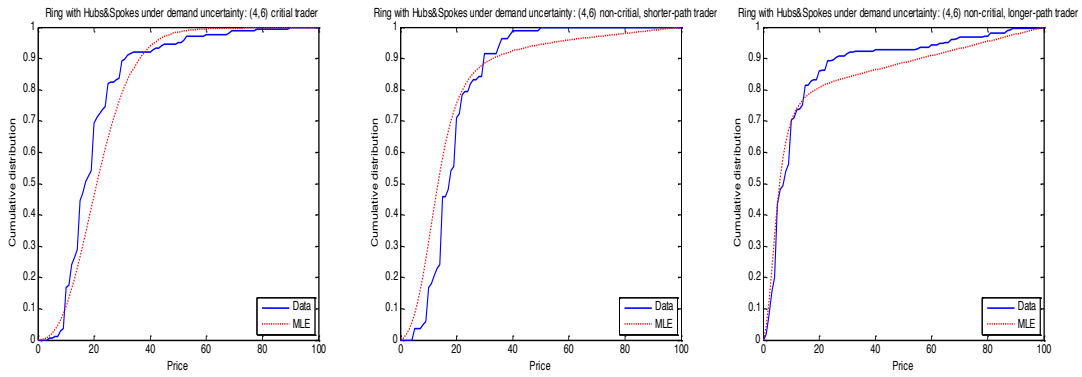


Figure 8: Comparison: predicted vs observed prices in benchmark model

## Ring networks



## Ring with Hubs and Spokes



## Line networks

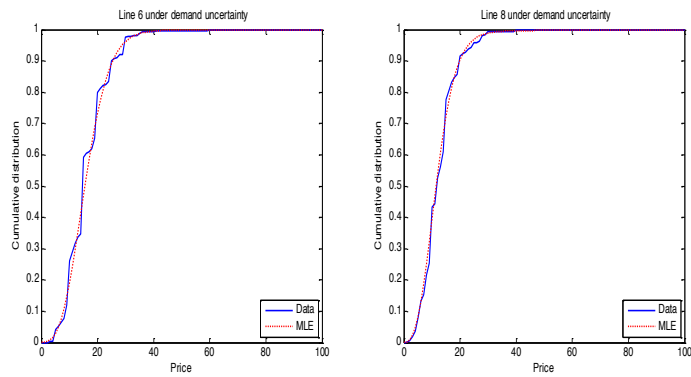


Figure 9: Comparison: predicted vs observed prices with uncertain demand

## Sample Instructions

### Ring 6 network in the benchmark design

This is an experiment in the economics of decision-making. A research foundation has provided funds for conducting this research. Your earnings will depend on your decisions, on the decisions of the other participants in the experiments, and partly on chance. If you follow the instructions and make careful decisions, you may earn a considerable amount of money.

At this point, check the name of the computer you are using as it appears on the top left of the monitor. At the end of the experiment, we will call your computer name to pay your earnings. At this time, you will receive £5 as a participation fee (simply for showing up on time). Details of how you will make decisions will be provided below.

During the experiment we will speak in terms of experimental tokens instead of pounds. Your earnings will be calculated in terms of tokens and then exchanged at the end of the experiment into pounds at the following rate:

$$60 \text{ Tokens} = 1 \text{ Pound}$$

In this experiment, you will participate in 60 independent and identical (of the same form) rounds. In each round you will be assigned to a position in a six-person trading network for a commodity. You will be asked to choose an intermediation price that you will earn in case a seller and a buyer trade a commodity through you.

### A round

We now describe in detail the process that will be repeated in all 60 rounds.

At the start of each round, you will be assigned with equal probability to one of the six network positions labeled *A*, *B*, *C*, *D*, *E*, or *F*. An equal number of the participants in the room will be designated in each of the six network positions. Your type (*A*, *B*, *C*, *D*, *E* or *F*) in each round depends solely upon chance and is independent of the types assigned to you in any of the other rounds.

The network and your type will be displayed at the left hand side of the screen (see Attachment 1). A line segment between any two types indicates that the two types are connected and that the commodity can be delivered between the two types.

Note that in the network used in this experiment,

- type-*A* participants can deliver the commodity either to type-*B* or type-*F*,
- type-*B* participants can deliver the commodity either to type-*A* or type-*C*,
- type-*C* participants can deliver the commodity either to type-*B* or type-*D*,
- type-*D* participants can deliver the commodity either to type-*C* or type-*E*,
- type-*E* participants can deliver the commodity either to type-*D* or type-*F*,
- and type-*F* participants can deliver the commodity either to type-*E* or type-*A*.

Next, the computer randomly forms six-person groups by selecting one participant of type-*A*, one of type-*B*, one of type-*C*, one of type-*D*, one of type-*E*, and one of type-*F* per group. The groups formed in each round depend solely upon chance and are independent of the groups formed in any of the other rounds.

After everyone is assigned to one type in one group, the computer will randomly select a pair of two non-adjacent types (no direct line segment between them) as a buyer-seller pair to trade the commodity. This is called a trading pair. Any pair of two non-adjacent types will be equally likely to be selected. Between two non-adjacent types in any trading pair, there will be at least one intermediary through which the commodity has to be delivered. Two participants in the selected trading pair will be highlighted in green color (see Attachment 1).

Once all participants in each group has been informed of the selection of a trading pair, each participant playing an intermediary role is asked to submit an intermediation price that will be charged if the trade occurs through the participant. Each participant can choose any real number (up to two decimal places) between 0 and 100. You will simply need to type the number you wish to choose in the number box at the bottom left of the screen and click the OK button. Note that if you are selected in a trading pair, you will not need to choose an intermediation price. Thus, you will not have a choice (see Attachment 2).

A surplus for each trading pair is 100 if trading occurs and zero otherwise. Trading will take place if there is at least one delivery route in which the sum of intermediation prices does not exceed the trading surplus of 100. If there is more than one such route, trading will occur through the route with the *lowest* sum of intermediation prices. If more than one route charges the same lowest sum of prices, one of such routes will be selected with equal probability for trading.

Note that in the network used in this experiment, there are always two possible delivery routes for any trading pair. For instance, if  $(A, E)$  is selected as a trading pair, the commodity can be delivered through  $F$  (route 1), or through  $B, C,$  and  $D$  (route 2). Likewise, if  $(C, F)$  is selected as a trading pair, the commodity can be delivered through  $A$  and  $B$  (route 1), or through  $D$  and  $E$  (route 2).

Once everyone has made a decision, the computer will inform everyone about the choices of intermediation prices made by all the participants in your group, the trading route if trading occurred (highlighted in yellow color), and the earnings for a selected trading pair and intermediaries through which trading occurs (see Attachment 3).

After you observe the results of the first round, press the OK button at the bottom left of the screen to move on to the next round. The second round will start the computer randomly assigning types to all participants and forming new groups of six participants. Note that you can review the outcomes in previous rounds at the top right of the screen (see Attachment 1). This process will be repeated until all the 60 independent and identical rounds are completed. At the end of the last round, you will be informed the experiment has ended.

### Earnings

Your earnings in each round depend on whether you are selected as one participant in the trading pair or as an intermediary. If you are selected in the trading pair, your earnings can be summarized in the following formula.

$$\text{Earnings} = 0.5 \times \{(\text{trading surplus}) - (\text{trading cost})\}$$

Note that the trading surplus is 100 if trading occurs and zero otherwise. The trading cost is the sum of intermediation prices that the trading pair must pay in order to make trading occur. If

trading does not occur, the cost is zero. Two participants in the trading pair share equally the net surplus. Thus, each participant in the pair earns half of the net surplus, as given in the formula.

If you are selected as an intermediary, your earnings are determined by intermediation revenue.

$$\text{Earnings} = (\text{intermediation revenue})$$

Your intermediation revenue is equal to your choice of intermediation price if trading occurs through you. If trading does not happen or does not occur through you, you will receive nothing.

To illustrate the determination of earnings further, let us take the following example. Suppose that  $(A, E)$  was selected as a trading pair. Suppose that  $B$  chose 10,  $C$  chose 40,  $D$  chose 25, and  $F$  chose 80 as their intermediation prices. Then, trading occurs through  $B$ ,  $C$ , and  $D$  because the sum of intermediation prices on this route ( $10 + 40 + 25 = 75$ ) is lower than the price charged by  $F$  (80), and does not exceed the trading surplus. Therefore, earnings six participants received are as follow:

$$\begin{aligned} (A\text{'s earnings}) &= 0.5 \times (100 - 75) = 12.5, \\ (B\text{'s earnings}) &= 10, (C\text{'s earnings}) = 40, (D\text{'s earnings}) = 25 \\ (E\text{'s earnings}) &= 0.5 \times (100 - 75) = 12.5, \\ (F\text{'s earnings}) &= 0. \end{aligned}$$

Let us take another example. Suppose that  $(B, E)$  was selected as a trading pair. Suppose that  $A$  chose 30,  $C$  chose 40,  $D$  chose 65, and  $F$  chose 80 as their intermediation prices. In this case, because each route of intermediaries charges the sum of prices exceeding the trading surplus – the sum of prices by  $A$  and  $F$  is 110 and the sum of prices by  $C$  and  $D$  is 105, trading cannot occur. Therefore, each participant's earnings are simply zero.

Your final earnings in the experiment will be the sum of your earnings over the 60 rounds. At the end of the experiment, the tokens will be converted into money. You will receive your payment as you leave the experiment.

### Rules

Please do not talk with anyone during the experiment. We ask everyone to remain silent until the end of the last round.

Your participation in the experiment and any information about your earnings will be kept strictly confidential. Your payments receipt is the only place in which your name is recorded.

If there are no further questions, you are ready to start. An instructor will activate your program.

# Attachment 1

Round

2 of 60

Round	Your type	Trading pair	Price A	Price B	Price C	Price D	Price E	Price F	Earnings
1	F	(B, E)	63.00	--	45.00	25.00	--	43.00	0.00

You are a type-A participant

(F, B) is chosen as a trading pair in this round

Please enter your price:

## Attachment 2

Round

2 of 60

```
graph TD; A((A)) --- B((B)); B --- C((C)); C --- D((D)); D --- E((E)); E --- F((F)); F --- A;
```

Round	Your type	Trading pair	Price A	Price B	Price C	Price D	Price E	Price F	Earnings
1	E	(B, E)	63.00	--	45.00	25.00	--	43.00	15.00

You are a type-F participant

(F, B) is chosen as a trading pair in this round

You do not have to make a pricing choice in this round.

OK



## Attachment 3

Round

2 of 60

```
graph TD; A((A)) --- B((B)); B --- C((C)); C --- D((D)); D --- E((E)); E --- F((F)); F --- A;
```

Participant	Price	Trading	Buyer/Seller earnings	Intermediary Earnings
A	56.00	Yes	0.00	56.00
B	--	Yes	22.00	0.00
C	23.00	No	0.00	0.00
D	25.00	No	0.00	0.00
E	54.00	No	0.00	0.00
F	--	Yes	22.00	0.00

You are a type-A participant

(F, B) is chosen as a trading pair in this round

OK

## **Sample instructions: Ring 6 network with demand uncertainty**

This is an experiment in the economics of decision-making. A research foundation has provided funds for conducting this research. Your earnings will depend on your decisions, on the decisions of the other participants in the experiments, and on chance. If you follow the instructions and make careful decisions, you may earn a considerable amount of money.

At this point, check the number of the computer you are using as it appears on the cubicle. At the end of the experiment, we will use your computer number to pay your earnings. At this time, you will receive £5 as a participation fee (simply for showing up on time). Details of how you will make decisions will be provided below.

During the experiment we will speak in terms of experimental tokens instead of pounds. Your earnings will be calculated in terms of tokens and then exchanged at the end of the experiment into pounds at the following rate:

$$30 \text{ Tokens} = 1 \text{ Pound}$$

In this experiment, you will participate in 60 independent and identical (of the same form) rounds. In each round you will be assigned to a position in a six-person trading network for a commodity with uncertain valuation. You will be asked to choose an intermediation price that you will earn in case a seller and a buyer trade a commodity through you.

### A round

We now describe in detail the process that will be repeated in all 60 rounds.

At the start of each round, you will be assigned with equal probability to one of the six network positions labeled *A*, *B*, *C*, *D*, *E*, or *F*. An equal number of the participants in the room will be designated in each of the six network positions. Your type (*A*, *B*, *C*, *D*, *E* or *F*) in each round depends solely upon chance and is independent of the types assigned to you in any of the other rounds.

The network and your type will be displayed at the left hand side of the screen (see Attachment 1). A line segment between any two types indicates that the two types are connected and that the commodity can be delivered between the two types.

Note that in the network used in this experiment,

- type-*A* participants can deliver the commodity either to type-*B* or type-*F*,
- type-*B* participants can deliver the commodity either to type-*A* or type-*C*,
- type-*C* participants can deliver the commodity either to type-*B* or type-*D*,
- type-*D* participants can deliver the commodity either to type-*C* or type-*E*,
- type-*E* participants can deliver the commodity either to type-*D* or type-*F*,
- and type-*F* participants can deliver the commodity either to type-*E* or type-*A*.

Next, the computer randomly forms six-person groups by selecting one participant of type-*A*, one of type-*B*, one of type-*C*, one of type-*D*, one of type-*E*, and one of type-*F* per group. The groups formed in each round depend solely upon chance and are independent of the groups formed in any of the other rounds.

After everyone is assigned to one type in one group, the computer will randomly select a pair of two non-adjacent types (no direct line segment between them) as a buyer-seller pair to trade the commodity.

Any pair of two non-adjacent types will be equally likely to be selected. Between two non-adjacent types in any buyer-seller pair, there will be at least one intermediary through which the commodity has to be delivered. Two participants in the selected buyer-seller pair will be highlighted in green color (see Attachment 1).

A trading surplus for a buyer-seller pair is uncertain and will be drawn uniformly from the set of integers ranging from 1 to 100 at the beginning of each round. That is, any number from the set  $\{1, 2, \dots, 100\}$  will be drawn with equal probability to be the value of surplus that a buyer and a seller will share if trading takes place. The draw of this value is independent of the values drawn for any other groups in the current round and any of the other rounds. This will be done by the computer.

Once all participants in each group have been informed of the selection of a buyer-seller pair, each participant playing an intermediary role is asked to submit an intermediation price that will be charged if the trade occurs through the participant. At this time, *none* of participants will be informed of the randomly drawn value of trading surplus. That is, each participant is asked to choose a price without knowing the value of surplus.

Each participant can choose any real number (up to two decimal places) between 0 and 100. You will simply need to type the number you wish to choose in the number box at the bottom left of the screen and click the OK button. Note that if you are selected in a buyer-seller pair, you will not need to choose an intermediation price. Thus, you will not have a choice (see Attachment 2).

The intermediation cost between a buyer and a seller is defined to be the *lowest* sum of intermediation prices of all possible delivery routes between them. Trading will occur through the route with the intermediation cost (the lowest sum of prices) if the cost is not higher than the randomly drawn value of trading surplus. If more than one route charges the same intermediation cost, one of such routes will be selected with equal probability for trading.

Note that in the network used in this experiment, there are always two possible delivery routes for any buyer-seller pair. For instance, if  $(A, E)$  is selected as a buyer-seller pair, the commodity can be delivered through  $F$  (route 1), or through  $B, C,$  and  $D$  (route 2). Likewise, if  $(C, F)$  is selected as a buyer-seller pair, the commodity can be delivered through  $A$  and  $B$  (route 1), or through  $D$  and  $E$  (route 2).

Once everyone has made a decision, the computer will inform everyone about the choices of intermediation prices made by all the participants in your group, the intermediation cost, the value of trading surplus, the trading route if trading occurred (highlighted in yellow color), and the earnings for a selected buyer-seller pair and intermediaries through which trading occurs (see Attachment 3).

After you observe the results of the first round, press the OK button at the bottom left of the screen to move on to the next round. The second round will start the computer randomly assigning types to all participants, forming new groups of six participants, and randomly drawing values of trading surplus for all groups. Note that you can review the outcomes in previous rounds at the top right of the screen (see Attachment 1). This process will be repeated until all the 60 independent and identical rounds are completed. At the end of the last round, you will be informed the experiment has ended.

### Earnings

Your earnings in each round depend on whether you are selected as one participant in the buyer-seller pair or as an intermediary. If you are selected in the buyer-seller pair, your earnings can be summarized in the following formula.

$$\text{Earnings} = 0.5 \times \{(\text{trading surplus}) - (\text{trading cost})\}$$

Note that any integer number between 1 and 100 will be drawn with equal probability to be the value of trading surplus if trading occurs. If trading does not occur, the value of surplus is zero. The trading cost is the intermediation cost that the buyer-seller pair must pay in order to make trading occur. If trading does not occur, the trading cost is zero. Two participants in the buyer-seller pair share equally the net surplus. Thus, each participant in the pair earns half of the net surplus, as given in the formula.

If you are selected as an intermediary, your earnings are determined by intermediation revenue.

$$\text{Earnings} = (\text{intermediation revenue})$$

Your intermediation revenue is equal to your choice of intermediation price if trading occurs through you. If trading does not happen or does not occur through you, you will receive nothing.

To illustrate the determination of earnings further, let us take the following example. Suppose that  $(A, E)$  was selected as a buyer-seller pair and the value of trading surplus for this pair is drawn to be 60. Suppose that  $B$  chose 10,  $C$  chose 15,  $D$  chose 25, and  $F$  chose 65 as their intermediation prices. Then, trading occurs through  $B$ ,  $C$ , and  $D$  because the sum of intermediation prices on this route ( $10 + 15 + 25 = 50$ ) is lower than the price charged by  $F$  (65), and thus the intermediation cost, 50, does not exceed the trading surplus, 60. Therefore, earnings six participants received are as follow:

$$(A\text{'s earnings}) = 0.5 \times (60 - 50) = 5,$$

$$(B\text{'s earnings}) = 10, (C\text{'s earnings}) = 15, (D\text{'s earnings}) = 25$$

$$(E\text{'s earnings}) = 0.5 \times (60 - 50) = 5,$$

$$(F\text{'s earnings}) = 0.$$

Consider another example in which all is the same as the above example except that the value of surplus is drawn to be 40. Because each route of intermediaries charges the sum of prices exceeding the trading surplus 40, trading cannot occur. Therefore, each participant's earnings are simply zero.

Your final earnings in the experiment will be the sum of your earnings over the 60 rounds. At the end of the experiment, the tokens will be converted into money. You will receive your payment as you leave the experiment.

### Rules

Please do not talk with anyone during the experiment. We ask everyone to remain silent until the end of the last round.

Your participation in the experiment and any information about your earnings will be kept strictly confidential. Your payments receipt is the only place in which your name is recorded.

If there are no further questions, you are ready to start. An instructor will activate your program.

# Attachment 1

Round

2 of 60

Round	Your type	Buyer Seller pair	Value	Price A	Price B	Price C	Price D	Price E	Price F	Earnings
1	D	(B, F)	23	28.00	--	25.00	10.00	8.00	--	0.00

You are a type-C participant

(E, B) is chosen as the buyer/seller pair in this round

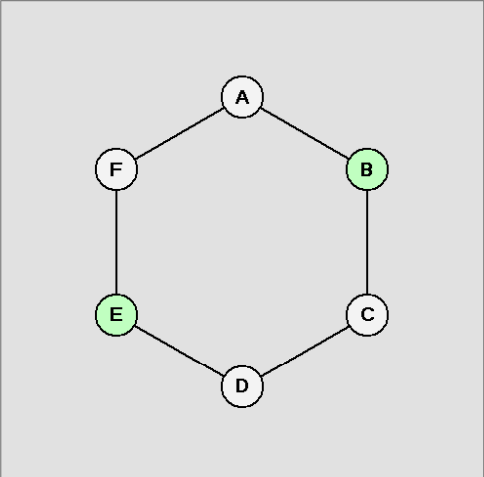
Please enter your price:

OK

## Attachment 2

Round

2 of 60



The graph consists of six nodes arranged in a circle, labeled A through F. Node E is highlighted in green. The nodes are connected in a cycle: A-B, B-C, C-D, D-E, E-F, and F-A.

Round	Your type	Buyer Seller pair	Value	Price A	Price B	Price C	Price D	Price E	Price F	Earnings
1	F	(B, F)	23	28.00	--	25.00	10.00	8.00	--	0.00

You are a type-E participant

(E, B) is chosen as the buyer/seller pair in this round

You do not have to make a pricing choice in this round.

OK

## Attachment 3

Round

2 of 60

Participant	Price	Trading	Buyer/Seller earnings	Intermediary Earnings
A	22.00	No	0.00	0.00
B	-	Yes	29.00	0.00
C	20.00	Yes	0.00	20.00
D	10.00	Yes	0.00	10.00
E	-	Yes	29.00	0.00
F	15.00	No	0.00	0.00

You are a type-C participant

(E, B) is chosen as the buyer/seller pair in this round

The value of trading surplus in this round is 88.

The intermediation cost is 30.

OK