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 networks of intermediation such as supply chains, transportation and communication networks and decentralized trading.

We provide a complete characterization of equilibrium prices for arbitrary 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.

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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 on 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 from London to see the Louvre in Paris, using the Eurostar. The first leg of the journey is from Home to St. Pancras Station. There are a number of different service 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 constituted of local transport alternatives in London and in Paris and a common node (the Eurostar Company). Each of the service providers sets a price. The traveler picks the cheapest 'path'. Section 2 develops a number of other applications where 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 and 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 where trade occurs at a high frequency, e.g., over-the-counter financial markets. We study Nash equilibrium 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 in 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).[1] In our benchmark model, the number of intermediaries per se has no impact on the efficiency of trade. This is because the value is perfectly known to all intermediaries. We extend our benchmark model to a setting where 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 length of trading chains, especially the number of critical intermediaries, on prices and the efficiency of trade.

Our finding on the relation between criticality and length of chains on the one hand and market power and revenue sharing on the other hand is consistent with empirical work. In the Net-Neutrality debate, policymakers seek a measure for quantifying network market power.

[1] Double marginalization figured prominently in the Microsoft anti-trust 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).

A network provider's revenue, points of presence, and number of advertised IP addresses are standard metrics, but in a market with over-lapping chains, there is a need to develop more sophisticated metrics based on the topology of the Internet. D'Ignazio and Giovannetti (2006, 2009) study market power in up-stream Internet services. They show that betweenness centrality of a service provider is highly correlated with the traditional Lerner index. We relate betweenness centrality to criticality in section 2 below. In an empirical study of the network of dealers in over the counter markets (OTCs) for municipal bonds, Li and Schürhoff (2012) show that 'centrally located dealers' charge significantly larger spreads than peripheral dealers and that the total cost of dealership is monotonically increasing in the number of dealers intermediating the bond. From a policy perspective, our results suggest that facilitating entry in network segments with critical traders improves efficiency; similarly, entry/mergers that shorten distance between source and destination improve efficiency.

Our model offers a generalization of the classical models of price competition (*a la* Bertrand) and the Nash demand game (Nash, 1950), to a setting with multiple price setting agents where both coordination, competition and double marginalization are important. In the theoretical 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), Manea (2013)) and posted prices (Acemoglu and Ozdagler (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.[2] There are three main difference between our paper and these papers: one, the generality of our network framework (that encompasses all networks and allows for incomplete information), two, our complete characterization of equilibrium and three, the methodological combination of theory and experiments. To the best of our knowledge, the result on role of node criticality in shaping pricing and division of surplus is novel.[3]

In production supply chains and in transportation and communication networks a firm or a

[2]For models where traders choose quantities see Babus and Kondor (2013), Malamud and Rostek (2013) and Nava (2010). Our paper also broadly relates to Ostrovsky (2008) that extends the study of pairwise stability developed in the matching literature to more general environments of trade as such supply chains. Our focus on how the structure of supply chains affect market power is very different from the questions studies in Ostrovsky (2008).

[3]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 fully connectivity across adjacent layers; this rules out 'critical' traders.

consumer will choose the cheapest path. In agriculture supply chains and financial brokerage chains the current owner of an object sells to the highest bidder downstream; he/she will typically not have any interest in the cost of the entire path. Appendix II relates our model of simultaneous posted price to the sequential auction model in Kotowski and Leister (2012) and to the simultaneous Bid-Ask model in Gale and Kariv (2009). There we show how our equilibrium characterization result with posted prices and cheapest cost routing (Theorem 1) is informative – and broadly similar – to the outcome generated in these trading protocols.

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), and Vega-Redondo(2007). The problem of 'key players' has traditionally been studied in terms of maximal independent sets, Bonacich centrality, eigenvector and degree centrality, see e.g., Ballester et al. (2006), Bramoulle and Kranton (2007), De Marzo et al. (2003), Elliot and Golub (2013), Galeotti et al. (2010), 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.[4]

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 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 existing literature, e.g., Roth and Murnighan (1982), Roth (1995), and Fischer et al. (2006).[5] 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

[4]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, while all nodes are critical. Our theory and experiments suggest that all the four intermediaries set the same price.

[5]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 to Easley and Keinberg (2010) for a survey of this work.

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 Appendix I. Supplementary material is presented in Appendices II-IV. The paper also uses Online Appendices for sample instructions of experiments and further data analysis.[6]

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 $\{i_1, ..., i_l\}$ such that $g_{\mathcal{S}i_1} = g_{i_1 i_2} = ... = g_{i_l \mathcal{D}} = 1$. The set of paths is denoted by $\mathcal{Q}$. Every node i is called an *intermediary*; let $\mathcal{N} = \{1, 2, 3..., n\}$, $n \geq 1$, 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 $p = \{p_1, p_2, ..., p_n\}$ denote the price profile. The network g and the price profile p define a cost for every path q between $\mathcal{S}$ and $\mathcal{D}$:

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

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. We assume that v is known and it is normalized to be equal to $v = 1$. Section 4 studies the case where intermediaries have incomplete information about v.

Given g and p, let $\mathcal{Q}^* = \{q \in \mathcal{Q} : c(q, p) = c(p), c(p) \leq 1\}$ be the set of feasible least cost paths. Given network g and price profile p, the payoff to intermediary $i \in \mathcal{N}$ is:

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

[6]http://www.homepages.ucl.ac.uk/~uctpsc0/Research/CGG_I_OnlineAppendices.pdf

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

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 p^* is *efficient* if $c(p^*) \leq 1$. Otherwise, the equilibrium is *inefficient*.

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.[7] 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.

Remark: Our model extends naturally 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. We have also assumed that only intermediaries set prices: the source and destination are price takers. We can easily accommodate price setting by source-destination; in that case our characterization result, Theorem 1, applies to the surplus net of the prices that the source-destination pair set.

The model offers a general framework to study the relation between networks and 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 (that include air lines, shipping, Internet, cable TV). Traditionally, these sectors have been heavily regulated or were under public sector control. The large scale privatization in the UK in the early 1980's was a precursor for 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.

2. Supply chains: Consider a Sony Vaio Laptop. It usually has an Intel processor, the hard drive is from Seagate Technology, Hitachi, Fujitsu or Toshiba, the RAM is from Infineon or Elpida, the wireless chipset is from Atheros or Intel, the optical drive is from Hitachi or

[7]We consider all paths and not just the shortest paths; in this, we follow Borgatti and Everett (2005).

Matsushita, the graphics card is from Intel, NVIDIA or AMD. The speakers may be from HP or is from Sony. The different intermediate input suppliers set prices; 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) showed that production supply chains increasingly traverse the world and decisively shape the pattern and volume of trade. The scale of this transformation calls for a general theory of pricing in supply chains.

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) have argued that the level of bribes should be viewed as a function of the 'market power' of officials. In some contexts there is a single line of officials (or committees) who 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 enquiry into the ways 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 sell the beans onward to one of the small number of exporting trading firms. The exporters sell to dealers/brokers, who in turn sell to roasters (like Nestle). Nestle then sells 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, e.g., 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. But by the 1990's, it was felt that state agencies discouraged innovation and the entry of new intermediaries, leading to a very inefficient system (see e.g., Bayley, (2002), 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. This 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 (there are around 700 firms trading in municipal bonds in any given month). Bonds move from the municipality through an average of 6 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 the network shapes pricing margins and the 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 does not have any interest in the cost of the entire path.

This motivates 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 Networks, market power and efficiency

We prove existence and provide a complete characterization of Nash equilibrium. For any given network, there typically exist multiple equilibria, with widely varying pricing, efficiency and division of surplus. We then take the model to the laboratory. The experiments highlight two points: one, the ability of human subjects to coordinate on efficient outcomes, and two, the role of node criticality as an organizing principle 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.

Theorem 1

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

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

1. $c(p^*) = 0$ *is an equilibrium if, and only if, no trader is essential.*
2. $c(p^*) = 1$ *is an equilibrium if, and only if, (i) every trader* $i \in q$, $q \in \mathcal{Q}^*$ *who sets* $p_i^* > 0$ *is essential, and (ii) for every trader* $i \notin q$, $\forall q \in \mathcal{Q}^*$, *if* $i \in q'$ *then* $c_{-i}(q', p^*) \geq 1$.
3. $c(p^*) > 1$ *is an equilibrium, if, and only if,* $c_{-i}(q, p^*) \geq 1$, $\forall\, i \in q$, $\forall q \in \mathcal{Q}$.

The argument for the existence of 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 and so, 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 this case, whenever intermediation costs are larger than zero, an intermediary demanding a positive price gains by undercutting his price. Price competition drives down intermediation costs 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, but 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 6 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.

This multiplicity motivates an exploration of equilibrium refinements. We consider a number of possible refinements – trembling hand perfection, strictness, strong Nash equilibrium, elimination of weakly dominated strategies, and perturbed Nash demand games. We find that in some cases these refinements are too strong, e.g., there do not exist strict or strong Nash equilibrium in some networks. In other cases, the refinement is not effective, e.g., a wide range of outcomes (including those with coordination failure) may be sustained under trembling hand perfection, elimination of weakly dominated strategies, and perturbed bargaining.[8] To gain a deeper understanding of the relation between networks, competition, market power and efficiency, we therefore conduct an experimental investigation of posted prices in networks.

3.1 Posted prices in the Laboratory

3.1.1 Experimental Design

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

The ring networks with 4, 6 and 10 traders allow us to focus on coordination and competition.[9] 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 each. Ring 6 and Ring 10 allow for situations with a higher (and possibly unequal) number of intermediaries on either path.

[8] Goyal and Vega-Redondo (2007) considered a cooperative solution concept – the kernel – in their work. They showed that non-critical traders would earn 0 and critical traders would split the cake 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.

[9] We have also run experiments on a ring network with 8 traders. The results are in line with the one presented in this section and they are not presented to simplify exposition.

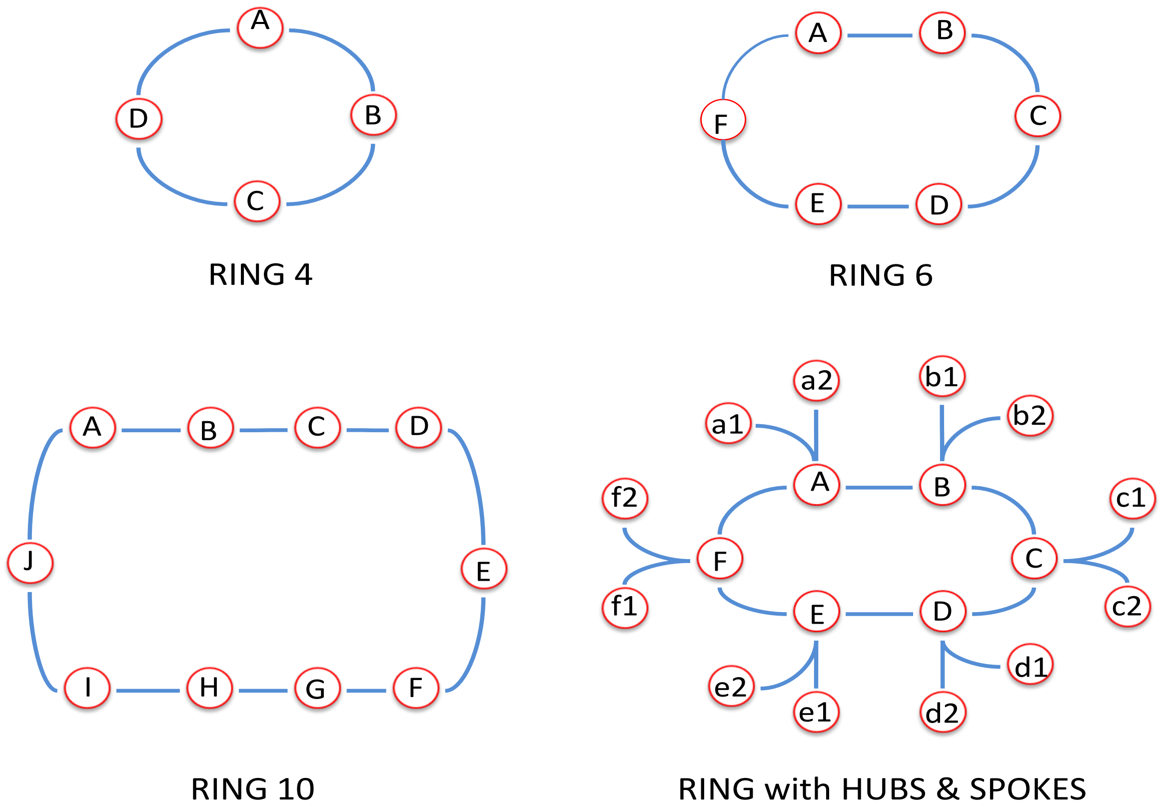

Figure 1: Networks in the benchmark design

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 in 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?*

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 the Ring 4, intermediation

Treatment	Session 1	Session 2	Total
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

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 the intermediaries. 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 UCL undergraduate and master 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 uses one network treatment. We ran 2 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 employ random matching with random assignment of network positions across rounds. In each round of a treatment subjects are assigned with equal probability to one of the possible positions of a network. In Ring n, all nodes are possible positions. In Ring with Hubs and Spokes, each spoke node is a computer-generated agent, and the remaining nodes are all feasible positions for the human subjects. Groups with one subject per intermediary position are then randomly formed. The position of a subject and the groups formed in each round depend solely upon chance and is independent of the subject's position and the groups formed in previous rounds, respectively.

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

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

In each round, earnings are calculated in terms of tokens. For each subject, the earnings in the experiment are the sum of his or her earnings over 60 rounds. At the end of the experiment, subjects are informed of their earnings in tokens. The tokens are exchanged in British pounds with 60 tokens being set equal to £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.

Network	minimum distance of buyer-sell pair				
	All (≥ 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

Finding 1: *The level of efficiency is remarkably high in all networks. Trading in Rings with 4, 6, and 10 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 average intermediation costs, conditional on trading, based on the last 20 rounds, with 95% confidence interval across different trading situations.

In Appendix IV we report the movement across rounds in average intermediation costs across distinct trading situations in Rings and Ring with Hubs and Spokes (see Table 10). Whenever there are no critical traders (resp. there are only critical traders) there is a clear downward trend (resp. upward trend) in the movement of intermediation costs across rounds. When there are both critical and non-critical traders, intermediation costs are stable over time.

In Ring 4, intermediation costs are around 5 percent of the surplus. In the other rings, intermediation costs vary between 10 and 20 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

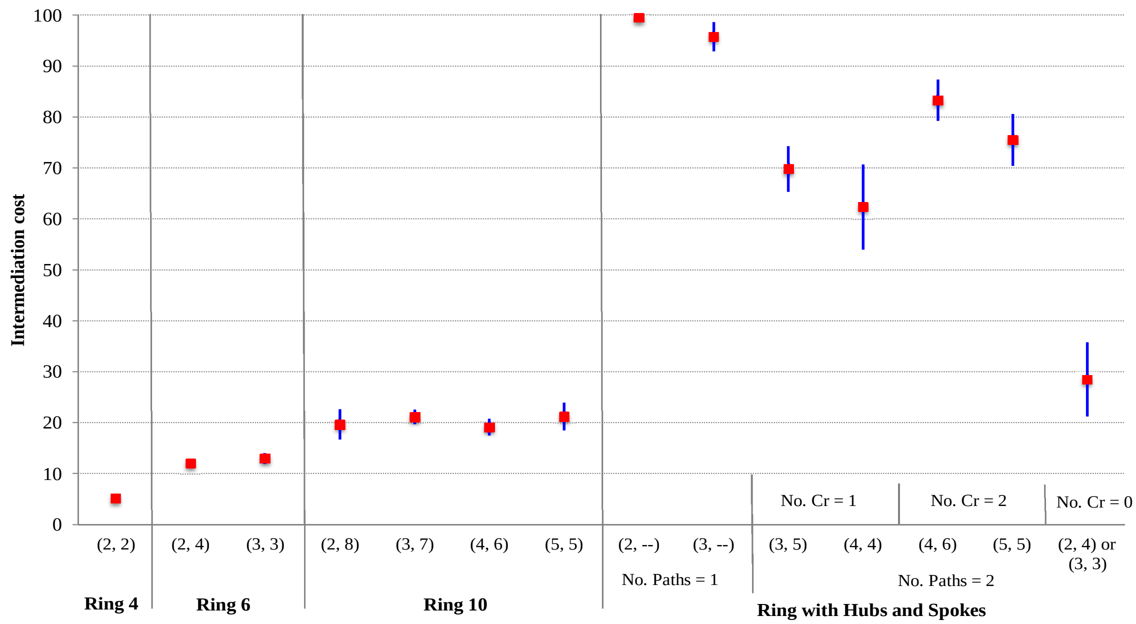

Figure 2: Costs of intermediation

(for a survey, see Engel (2011)). We found a surplus extraction of 99%, which is much higher than the one 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.[10]

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% of the surplus, and they share it roughly equally (refer to Table 11). These findings are consistent with the findings 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, intermediation cost ranges between 62% and 83%. In the case without critical intermediaries, this cost falls sharply to around 28%, 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 4,6, and 10 traders, intermediation costs are small (ranging from 5% to 20%). In the Ring with Hubs and Spokes, with critical traders,*

[10]We also note that in our design, in some situations, both $\mathcal{S}$ and $\mathcal{D}$ are computer generated agents, while in others one of them is a human subject. We found 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 subjects in our experiment.

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 beween buyer and seller.

Table 3: Surplus division among intermediaries

intermediation costs are large (60% to over 95%).

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 is grouped into the blocks of 20 rounds, due to small samples). The number within parentheses is the number of group observations. Looking at the last 20 rounds, we observe that 67% to 80% 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 as compared to 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.[11] In Appendix IV, Table 11 reports average prices charged across rounds by intermediaries in Rings and Ring with

[11] Our design employs random matching with random assignment to limit repeated games effects and allows subjects to learn how to play against random opponents over rounds. We have conducted session-level analysis and found little variation of subjects' pricing behavior across sessions. For instance, in the case of $(\#Cr, \#Paths, d(q), d(q')) = (1, 2, 3, 5)$ of the Ring with Hubs and Spokes, we found that average prices for critical trader, non-critical trader on the shorter path, and non-critical trader on the longer path are 54, 26, and 11 in the first session, and 46, 25, and 8 in the second session. Hence, it is less likely that subjects have developed within-session norm varying much across sessions.

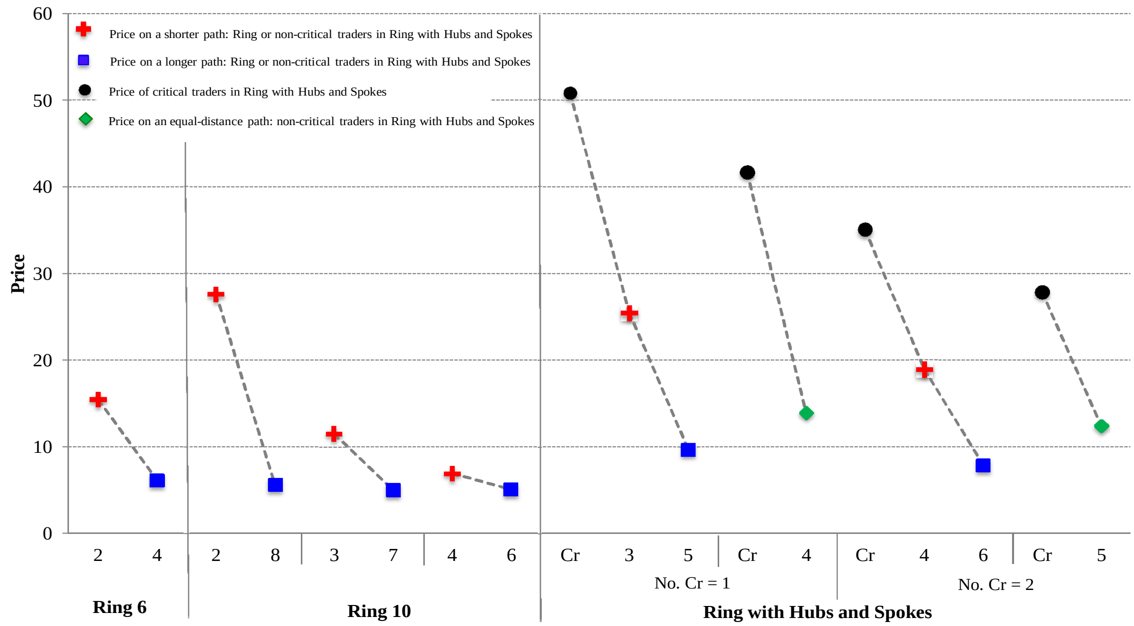

Figure 3: Competition among intermediaries

Hubs and Spokes, respectively. In the Ring with 6 and 10 traders, there is a tight competition between paths. Intermediaries on a longer path chose, on average, prices somewhere between 5 and 10, independently of the distances of the two paths across all ring networks. Responding strategically to this, intermediaries on a shorter path chose higher prices that are proportionate to the difference in distance between 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 instance, when there is one critical intermediary and the two competing paths are of distance 3 and 5, 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 8. Similar behavior is observed in the other cases. This demonstrates the strong impact of network criticality on pricing behavior and the division of surplus.

This evidence suggests that subjects are strategically sophisticated in their choice of prices. While intermediation costs do take on extreme values, they depart significantly from the theoretical predictions. In Section 5 we show that observed departures from equilibrium pricing and surplus extraction are consistent with a model of noisy best response with risk

Network	(d(q), d(q'))	|cost1 - 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 absolute differences of 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

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. This is 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 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.

We now assume that the surplus v is unknown; it has a distribution $F(.)$ on the interval $[0,1]$ (with a continuously differentiable density $f(.)$). Given g and p, define Q^v to be the set of feasible least cost paths, for a realized value v. Given network g and price profile p, the payoff to an intermediary i, for every realized value v, is

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

where η_i^v is the number of paths in $\mathcal{Q}^v$ that contain intermediary i. Finally, given network g

and price profile p, the expected payoff to intermediary i is:

$$\Pi_i(p) = E_v[\pi_i(p, v)]. \tag{3}$$

An equilibrium is efficient (resp. inefficient) if trade occurs (resp. does not occur) regardless of the realization of v. Clearly, an equilibrium is efficient (resp. inefficient) if, and only if, the associated intermediation cost is zero (resp. larger than 1). An equilibrium is partially efficient if it is neither inefficient nor efficient. Define $h(x) = f(x)/[1 - F(x)]$ to be the hazard rate.

The next result proves existence and provides a complete characterization of equilibrium, for all networks. $\mathcal{E}(g, p)$ denotes the set of essential traders, i.e., a set of traders that lies on all paths $q \in \mathcal{Q}^1$.

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. $c(p^*) = 0$ *is an equilibrium if, and only if, no trader is essential.*
2. $c(p^*) \in (0, 1)$ *is an equilibrium if, and only if, (a)* $|\mathcal{E}(g, p^*)| \geq 1$ *and* $\forall i \in \mathcal{E}(g, p^*)$*:*

$$p_i^* = \hat{p} = \frac{1}{h(|\mathcal{E}(g, p^*)|\hat{p})}, \tag{4}$$

(b) for every non-essential trader $i \in q$, $q \in \mathcal{Q}^1$, $p_i^* = 0$. *(c) for all traders* $i \notin q$, $\forall q \in \mathcal{Q}^1$, *if* $i \in q'$ *then* $c_{-i}(q', p^*) \geq |\mathcal{E}(g, p^*)|\hat{p}$.

3. $c(p^*) > 1$ *is an equilibrium, if, and only if,* $c_{-i}(q, p^*) \geq 1$, $\forall i \in q$, $\forall q \in \mathcal{Q}$.

Theorem 2 brings out two important implications of pricing in networks under uncertain demand.[12] The first is that lack of criticality is necessary and sufficient for the existence 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 which solves condition (4). As $c(p^*) \in (0, 1)$, intermediaries always share surplus with $\mathcal{S}/\mathcal{D}$.

[12] 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.

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* p^* *and* p' *are two partially efficient equilibria, with* $|\mathcal{E}^*| > |\mathcal{E}'|$ *essential traders, respectively. Then:*

1. *Price for essential traders under* p^* *is strictly lower than the price under* p'*.*
2. $c(p^*) > c(p')$*. Hence,* p^* *is less efficient.*
3. *The sum of intermediaries payoffs and sum of* $\mathcal{S}/\mathcal{D}$*'s payoffs are both lower 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 number of essential traders and prices and intermediation costs (refer to Theorem 1).

To summarize, the theoretical analysis of pricing under uncertain demand tells us that there exist multiple equilibria with widely varying pricing, division of surplus and efficiency. This is similar to the situation under known demand.[13] Uncertain demand does, however, have powerful effects on pricing: in equilibrium with trading activity, all essential traders set equal prices; these prices are falling and the intermediation costs are increasing in the number of essential traders.

4.1 Uncertain Demand in the Laboratory

4.1.1 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 $4, 6, 10$ and the Ring with Hubs and Spokes, we also consider Line networks with 6 and 8 traders.[14] Figure 4 presents these networks.

Recall that in ring networks there always exists an efficient equilibrium, but in rings with 6 and 10 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

[13]For instance, natural variants of the three equilibria in a ring network with 6 traders identified in section 3 also exist under uncertain demand.

[14]In the Line network with 6 and 8 traders, the pair $\mathcal{S}$ and $\mathcal{D}$ are always the two end nodes and computer-generated agents.

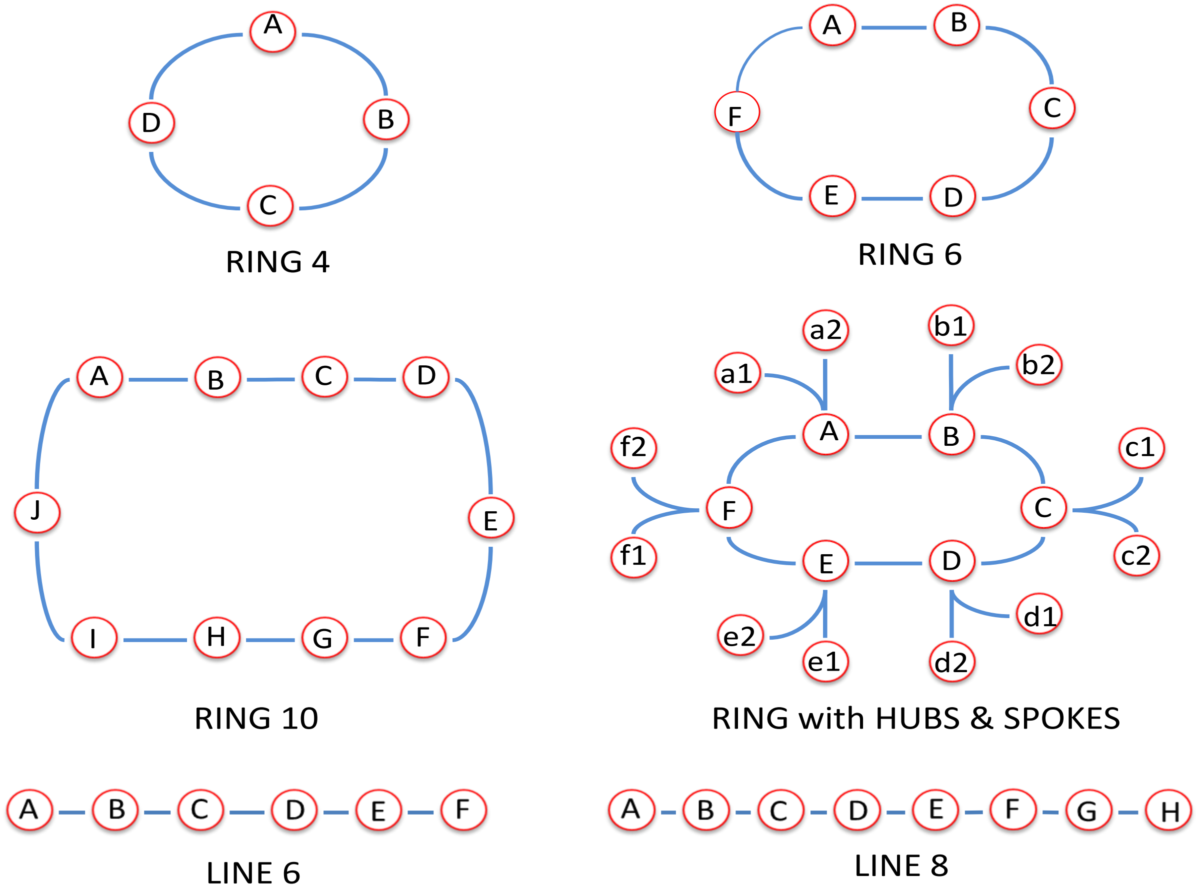

Figure 4: Networks in uncertain demand case

exist, but there exists a partially efficient equilibrium. 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 number of critical traders?*

4.1.2 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

Treatment	Session 1	2	3	4	Total
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 5: Treatments with uncertain demand

experiment were recruited from the ESSEXLab pool consisting undergraduate and masters students across all disciplines at the University of Essex. The experimental procedures follow the one we have discussed 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 5 summarizes the experimental design and treatments. In each cell we report number of subjects / number of group observations in a session.

4.1.3 Findings

We start with an examination of efficiency of trade. Table 6 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 6 and subsequently, 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 a significant impact on efficiency. In the Ring network with 10 traders, 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 fixed distance, the frequency of trade in a ring network and in a line network is very different. The frequency of trade in Ring with Hubs and Spokes lies somewhere between that in rings and 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.[15] We

[15]In Appendix IV we report average intermediation costs (see Table 12) and average prices for network

Network	#Paths	minimum distance between buyer and seller						
		All (≥ 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 6: Frequency of trade

calculate the frequency of trade in ring networks after pooling all the observations in rings with 4, 6 and 10 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 lines 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 the 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 sample average in the last 20 rounds. First, we look at the pricing behavior in Ring networks and Ring with Hubs and Spokes. This is presented in Figure 6. Similarly to our benchmark experiment, there is clear evidence that subjects responded strategically to the distances of two paths: intermediaries on a shorter path chose higher prices that appear proportionate to the difference in distance between two paths. As a consequence, also under demand uncertainty trade occurs often along the longer path. In contrast with the result in our benchmark experiment, in Ring with Hubs and Spokes we found that critical intermediaries chose similar prices to non-critical traders

location (see Table 13) over time and across treatments.

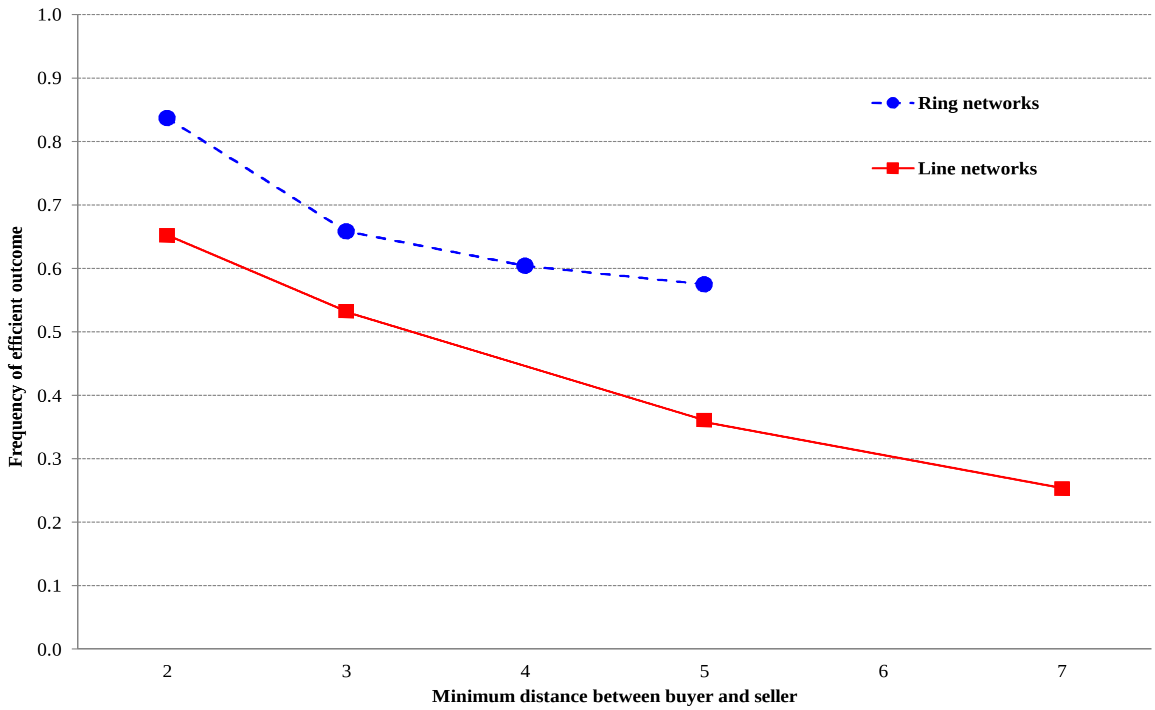

Figure 5: Efficiency and distance

on a shorter path.

Next, we examine the pricing behavior in Line networks. Theorem 2 (in a partially efficient equilibrium) predicts the declining patterns of prices in 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; 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 under-price 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 7 reports the average prices across positions. We also report p-values of pairwise t-test for the null hypothesis of the equivalence of prices between any two positions in each Line network. Average prices are quite similar across trading positions. We cannot reject the null hypothesis for each pair of trading positions at an usual significant level.

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

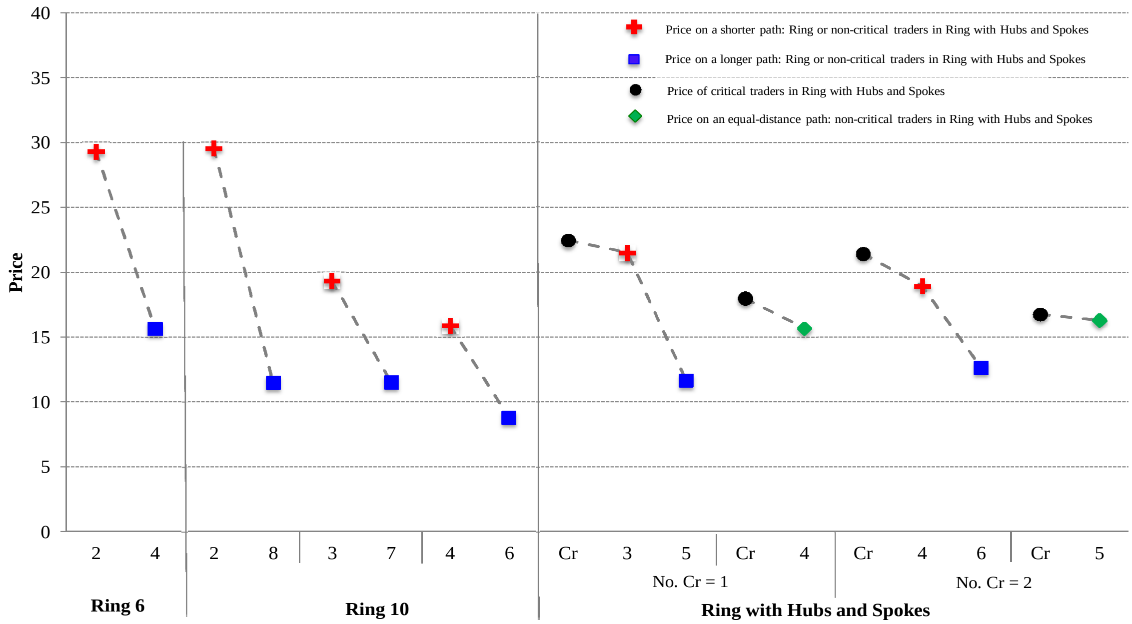

Figure 6: Pricing behavior in Rings and Ring with Hubs and Spokes

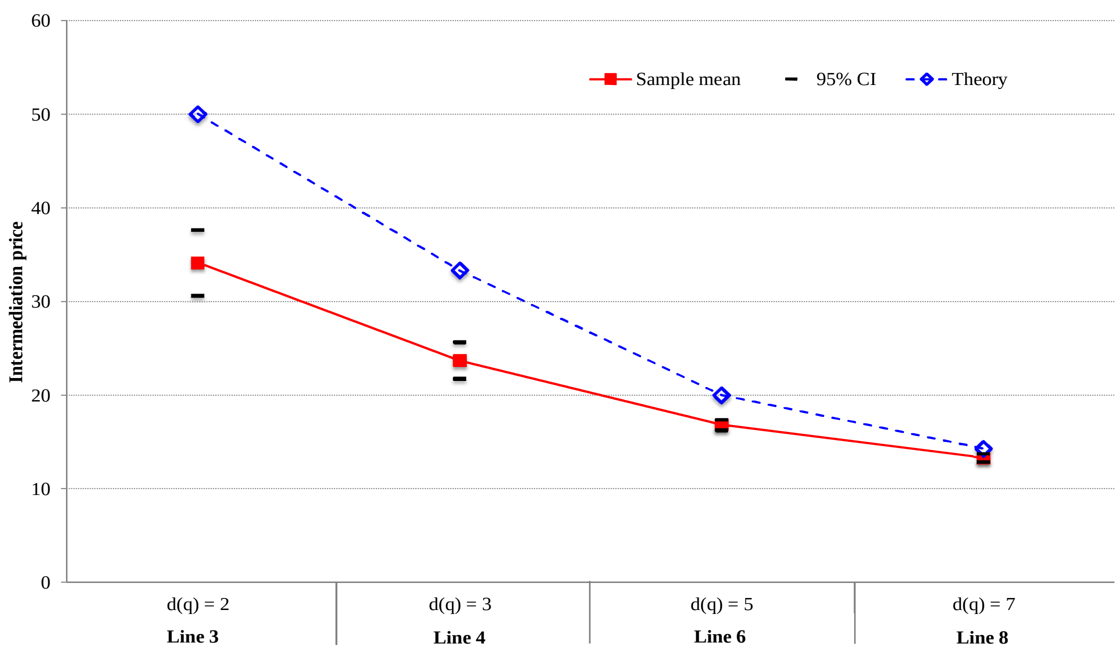

Figure 7: Pricing behavior in Line networks

A. Average prices across trading positions

Networks	d(q)	A	B	C	D	E	F
Line	5	17.01	16.60	16.65	17.10		
	7	13.83	12.62	13.28	13.61	13.34	13.24

B. pairwise t-tests for equivalence of prices in Line 6 network (p-value)

	A	B	C	D
A	--	0.59	0.64	0.91
B		--	0.95	0.57
C			--	0.61
D				--

C. pairwise t-tests for equivalence of prices in Line 8 network (p-value)

	A	B	C	D	E	F
A	--	0.14	0.52	0.82	0.55	0.49
B		--	0.38	0.24	0.32	0.41
C			--	0.70	0.93	0.96
D				--	0.75	0.66
E					--	0.89
F						--

Table 7: Prices across positions in Line networks

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 in distance, as theory predicts. However, average prices are lower than equilibrium prices; the gap between them shrinks with distance.*

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: one, intermediation costs depart from both 0 and 100, and two, in the uncertain demand case prices set by critical traders are systematically lower than 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)) as well as in a non-strategic environment (e.g., Holt and Laury (2002)). We explore the effects of risk-aversion in our setting, first theoretically and then estimate a model of risk

		Equilibrium	
Networks	Average prices	$\rho = 0$	$\rho = 0.5$
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 8: Risk Aversion and Prices in Line Networks

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 coefficient. In a Line network with η 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 ρ.[16]

In order to get a sense of how risk aversion comes into play, Table 8 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 makes two key assumptions. First, 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.[17] 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 λ approaches 0 choice behavior becomes purely

[16] The derivation of the equilibrium with risk aversion follows along the lines of the proof of Theorem 2; the details are omitted.

[17] For instance, in Ring 10 network where $\mathcal{S}$ and $\mathcal{D}$ are B and H, intermediary A forms beliefs about the behaviors of two distinct traders–trader on the shorter path and 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.

random, while as λ goes to the infinity, the individual chooses a best response with certainty.[18] Further details of the model are given in Appendix III.

We combine the model of strategic uncertainty with risk aversion by assuming the above power utility function and estimate the payoff-sensitivity parameters (λs) and the CRRA coefficients (ρs). 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 where 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 9 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 observe choices to their nearest integer. We report the estimated ρ and λs 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 exhibit 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.[19]

Second, Table 9 shows that the estimated λs are large and significant for all trading situations, suggesting that the subjects in the experiments responded 'optimally' against others' pricing.

Third, the estimated model replicates closely 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

[18] We have tried to develop a stochastic equilibrium model such as Quantal Response equilibrium (QRE), proposed by McKelvey and Palfrey (1995). Solving such an equilibrium is complicated because it 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.

[19] 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: ρ (St. Err.) & Log likelihood	λ (St. Err.)	(sample mean - predicted mean) [95% CI]	Benchmark experiment: ρ (St. Err.) & Log likelihood	λ (St. Err.)	(sample mean - predicted mean) [95% CI]
Ring 4	(2, 2)	2	0.667 (0.018) & -9860.7	10.30 (0.72)	-9.26 [-10.12, -8.30]	0.461 (0.062) & -6482.5	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]
	(3, 3)	3		14.76 (1.00)	0.56 [-0.54, 1.50]		35.01 (6.99)	-2.59 [-4.57, -1.81]
Ring 10	(2, 8)	2		9.06 (2.03)	2.07 [-0.92, 4.33]		14.78 (5.72)	-1.36 [-18.91, 4.53]
		8		269.12 (76.88)	-1.03 [-2.48, 0.07]		149.00 (51.75)	-4.80 [-13.40, -0.60]
	(3, 7)	3		16.56 (1.91)	-1.82 [-4.42, 0.15]		12.62 (1.06)	-8.35 [-11.96, -4.68]
		7		115.79 (23.69)	0.13 [-0.80, 0.89]		103.96 (27.32)	-1.06 [-2.39, -0.15]
	(4, 6)	4		15.63 (1.11)	-4.10 [-6.49, -1.97]		7.49 (0.48)	-19.42 [-23.08, -13.89]
		6		54.61 (7.30)	-0.06 [-1.83, 1.19]		103.55 (29.98)	-0.39 [-3.58, 0.28]
	(5, 5)	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	0.578 (0.023) & -5054.3	38.84 (6.18)	-3.86 [-5.99, -1.88]	0.480 (0.078) & -2036.3	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]
	(1, 2, 4, 4)	Critical		17.09 (4.51)	-8.97 [-12.56, -5.63]		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]
	(2, 2, 4, 6)	Critical		27.44 (3.68)	-2.07 [-3.68, -0.59]		16.60 (3.65)	0.20 [-2.88, 3.54]
		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	0.608 (0.010) & -8034.1	16.71 (2.95)	1.10 [-1.12, 3.17]			
	(2,1,3,--)	Critical		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		69.72 (2.75)	0.20 [-0.16, 0.57]			

Table 9: Estimation of strategic uncertainty model with risk aversion

of cases, we cannot reject the null hypothesis for the equivalence of empirical and predicted average prices at 5% significance level.

Finally, we plot the predicted distribution of prices and the observed prices, to get a further 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 Appendix IV present a selective set of these plots from both experiments.[20]

6 Conclusion

We propose a general model of posted prices in networks of intermediaries. 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.

In this paper, we assumed that intermediaries know the origin and destination of trades, when they set prices. 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, irrespective of where they started or where they are subsequently planning to go. This motivates the study of pricing in a model where the network origin and destination of trades is 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, a $\mathcal{S}/\mathcal{D}$ pair is picked at random from the set of all traders. As before, a feasible least cost path is picked. 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.

[20] The full set of these plots are presented in Online Appendix II.

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.

$\blacksquare$

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 η 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., $|\mathcal{E}(g, p^*)| \geq 1$, 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

$$p_i^* = \arg\max p_i[1 - F(p_i + c_{-i}^*(p^*)]. \tag{5}$$

It is easy to see that $p_i^* \in \left(0, 1 - c_{-i}^*(p^*)\right)$; 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 $p_i^* \in \left(0, \frac{1}{|\mathcal{E}(g,p^*)|}\right)$. So equilibrium price is given by

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

The existence of such a $p^* \in \left(0, \frac{1}{|\mathcal{E}(g,p^*)|}\right)$ 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 $c_{-i}(q'^*) < |\mathcal{E}(g, p^*)|p^*$ for some path q' such that $i \in q'$. Then player i can charge a price $p = |\mathcal{E}(g, p^*)|p^* - c_{-i}(q'^*) - \epsilon > 0$ 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:

$$p_i^* = \frac{1}{h(\eta p_i^*)} \tag{6}$$

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

Part 1. Implicitly differentiating (6) and simplifying yields:

$$\frac{dp^*}{d\eta} = -\frac{h'(\eta p_i^*)}{h^2(\eta p_i^*) + h'(\eta p_i^*)} < 0, \tag{7}$$

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

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

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

where the the second equality follows by substituting the expression for $\frac{dp^*}{d\eta}$ from above, and the inequality follows from the assumption of increasing hazard rate.

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

$$\sum_{i\in\mathcal{N}} \Pi_i(p^*) = \eta p^*[1 - F(\eta p^*)], \tag{8}$$

and

$$\frac{d\sum \Pi_i(p^*)}{d\eta p^*} = [1 - F(\eta p^*)] - \eta p^* f(\eta p^*) = [1 - F(\eta p^*)](1 - \eta) \leq 1, \tag{9}$$

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

$$\begin{aligned}\Pi_{\mathcal{S}}(p^*) + \Pi_{\mathcal{D}}(p^*) &= [1 - F(\eta p_i^*)]\,[E[v|v \geq \eta p_i^*] - \eta p_i^*] \qquad (10) \\ &= \int_{\eta p_i^*}^1 xf(x)dx - \eta p^*[1 - F(\eta p_i^*)] \qquad (11)\end{aligned}$$

and therefore

$$\frac{d[\Pi_{\mathcal{S}}(p^*) + \Pi_{\mathcal{D}}(p^*)]}{d\eta p^*} = -[1 - F(\eta p_i^*)] < 0. \tag{12}$$

■

Appendix II: 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 ($\mathcal{S}$ and $\mathcal{D}$ 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 $\{i_1, ..., i_n\}$, where $g_{\mathcal{S}i_1} = g_{i_1 i_2} = ... = g_{i_n \mathcal{D}} = 1$. Consider the following bid-ask profile:

A. Strategy of traders in q^*: $a_{i_x} = b_{i_{x+1}}$ for all $x = 1, ..., n-1$, and $a_{i_n} = 1$, and $b_{i_x} = 1 - \sum_{j = i_x, ..., i_n} p_j^*$ for all $x = 1, ..., n$.

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

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

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 $x = 1, \ldots, n$. 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 $x = 1...n$. 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 $x = 1...n$. 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 $p_{i_1} = ... = p_{i_x} = 0$. This holds because $i_1, \ldots, i_x$ 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 $g_{ji_x} = 1$ for at least two $x = 1...n$. 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/η (because $\mathcal{S}$ picks an intermediary with equal probability across all the η 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-pricemodel.

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

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 $\ell \in 2, ..., L$ 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.[21]

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 ℓ as the profit 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

[21]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 $p = 1$

multipartite network, has critical intermediaries if, and only if, $n_\ell = 1$ for some $\ell \in \{1, ..., L\}$. When there are critical intermediaries, let ℓ^* be the largest index such that $n_{\ell^*} = 1$, i.e., the intermediary in layer ℓ^* 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 $(n_1, ..., n_L)$ 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 $\ell \in \{\ell^*, ..., L\}$ to bids v and each intermediary in layer $\ell \in \{1, ..., \ell^* - 1\}$ bids 0 is an equilibrium. In this equilibrium critical intermediary in layer ℓ^* 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 $\ell \in \{\ell^*, ..., L-1\}$. Now consider the auction run by intermediary in layer $\ell^* - 1$. Note that, since intermediary in ℓ^* 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.

Appendix III: 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 behaviors. 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

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

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

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

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

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

In estimating the model of strategic uncertainty with the experimental data,[22] we assume that intermediary i makes a stochastic choice, modelled by a conventional logistic function:

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

where λ is a payoff-sensitivity parameter in choice function. If λ goes to zero, the pricing choice becomes purely random. If λ 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 ρ 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, $k_1, ..., k_m$, 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

[22] 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:

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

The set of parameters, $(\rho, \lambda_{k_1}, ..., \lambda_{k_m})$, are chosen to maximize the log-likelihood function. Table 10 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.

Appendix IV: 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 10 and Table 11) and for the experiment with demand uncertainty (Table 12 and Table 13). 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
Ring 4	(0, 2, 2, 2)	19.76	12.77	7.80	6.04	4.81	5.36
		(80)	(80)	(80)	(80)	(80)	(80)
Ring 6	(0, 2, 2, 4)	41.77	24.62	18.44	14.08	11.96	12.01
		(52)	(49)	(50)	(44)	(44)	(50)
	(0, 2, 3, 3)	39.05	22.92	17.54	14.99	12.92	13.00
		(18)	(21)	(20)	(26)	(26)	(20)
Ring 10	(0, 2, 2, 8)	40.40	30.51	22.36	20.35	17.60	20.71
		(5)	(11)	(11)	(8)	(5)	(9)
	(0, 2, 3, 7)	41.85	29.66	26.44	22.20	20.11	22.09
		(17)	(14)	(15)	(13)	(14)	(14)
	(0, 2, 4, 6)	41.41	29.31	23.53	22.01	20.07	17.54
		(11)	(11)	(10)	(12)	(15)	(10)
	(0, 2, 5, 5)	43.32	30.73	24.44	20.76	24.54	18.20
		(7)	(4)	(4)	(7)	(6)	(7)
Ring with hubs	(1, 1, 2, --)	89.19	98.09	98.06	99.20	99.67	99.31
		(15)	(22)	(17)	(15)	(15)	(16)
	(2, 1, 3, --)	87.35	85.00	92.85	97.59	95.00	96.88
		(14)	(5)	(18)	(13)	(12)	(8)
	(1, 2, 3, 5)	66.09	73.44	74.59	74.28	73.50	66.31
		(11)	(9)	(11)	(15)	(12)	(13)
	(1, 2, 4, 4)	76.35	71.41	66.43	59.33	58.00	65.17
		(7)	(9)	(7)	(6)	(4)	(6)
	(2, 2, 4, 6)	86.06	87.51	86.90	85.53	84.94	81.82
		(7)	(9)	(7)	(12)	(11)	(13)
	(2, 2, 5, 5)	90.19	84.12	76.83	81.00	71.57	82.25
		(5)	(3)	(3)	(5)	(7)	(4)
	(0, 2, 2, 4) or (0, 2, 3, 3)	40.60	47.00	46.50	31.33	32.33	25.56
		(5)	(5)	(4)	(3)	(6)	(8)

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 beween buyer and seller.

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

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 beween buyer and seller.

Table 11: 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	(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 beween buyer and seller.

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

Table 13: Pricing behavior in the uncertain demand case

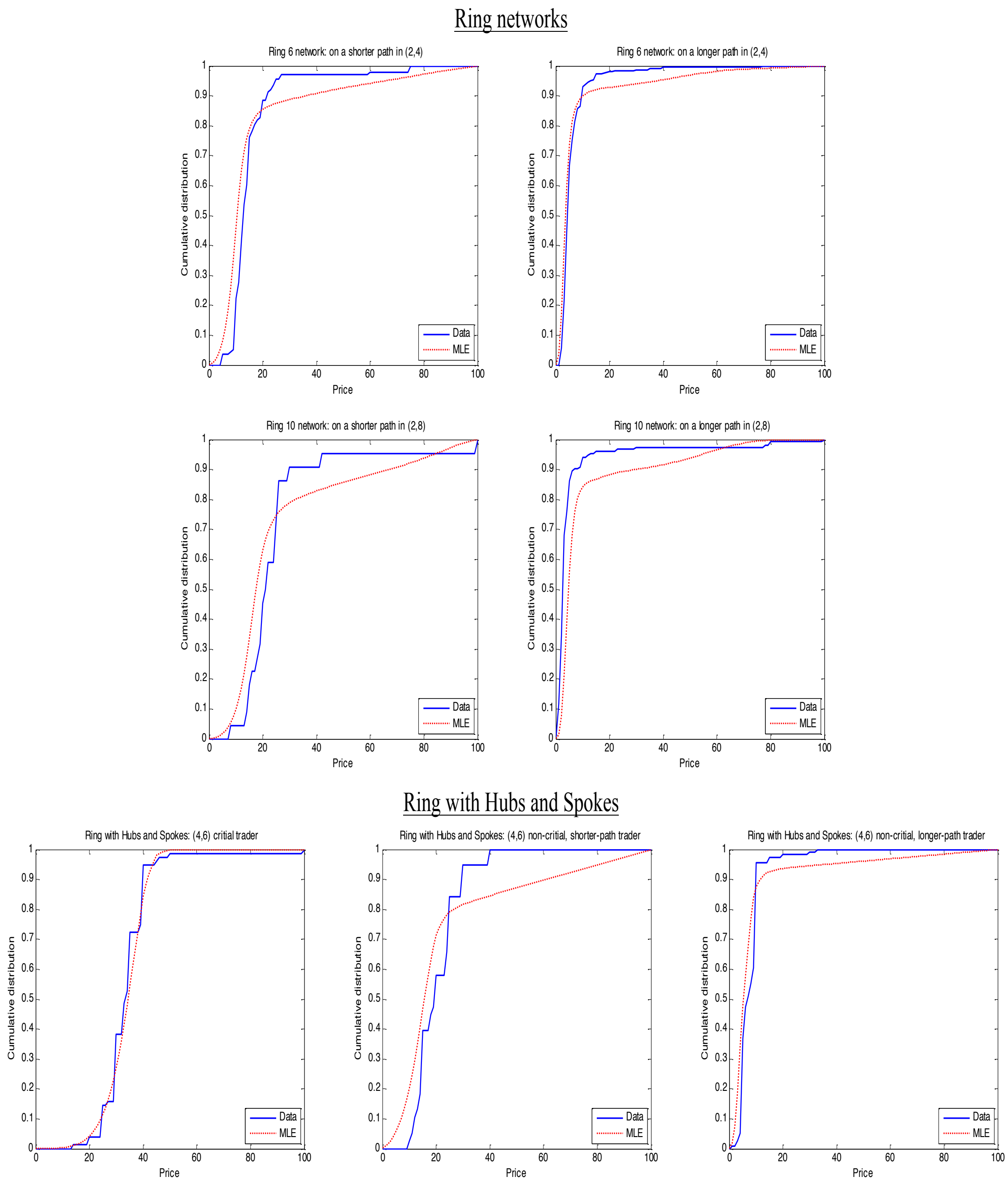

Figure 8: Comparison: predicted vs observed prices in benchmark model

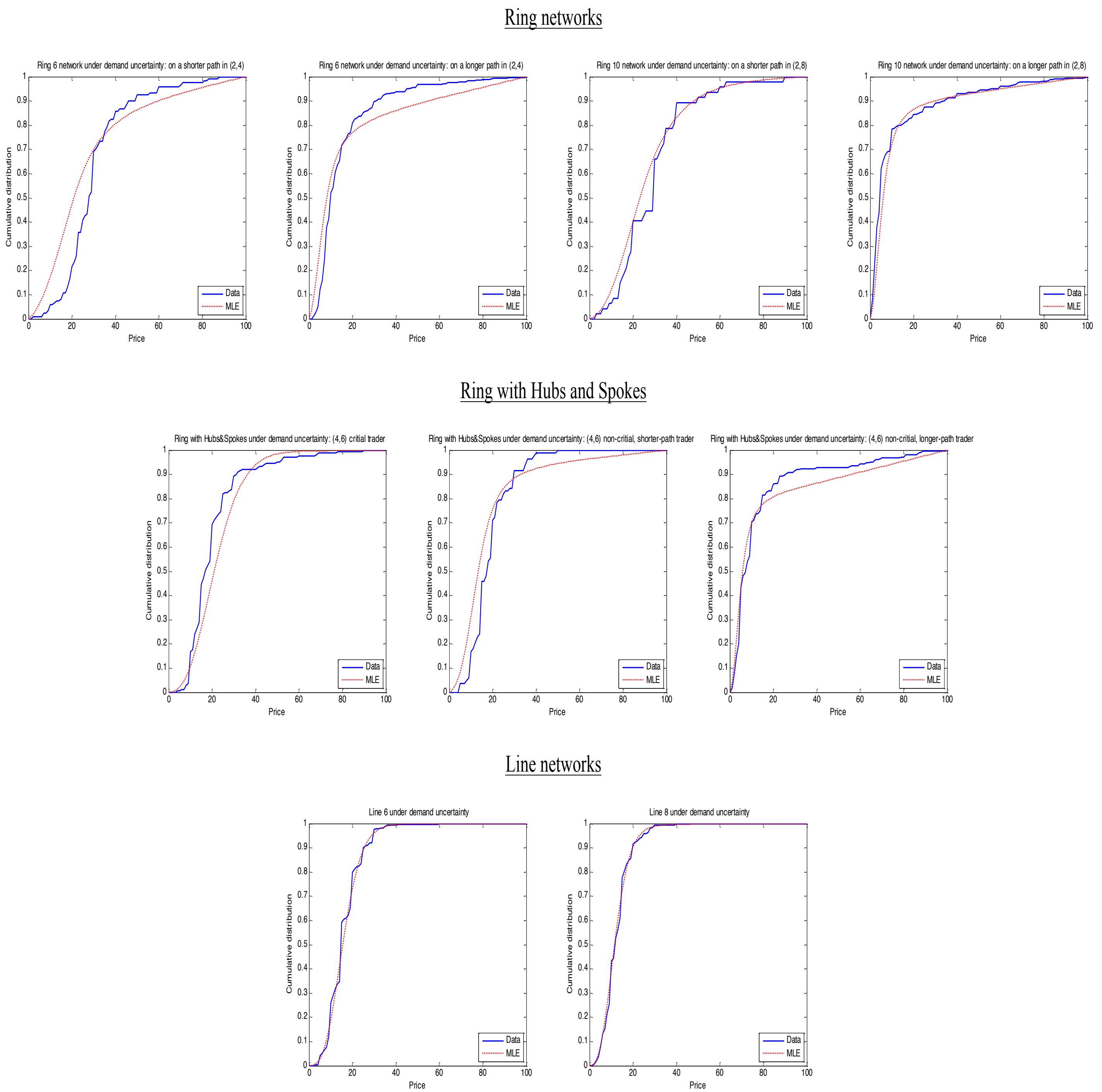

Figure 9: Comparison: predicted vs observed prices with uncertain demand

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