Trading in Networks: Theory and Experiment

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Abstract

Intermediation is a prominent feature of production and exchange. Two features of intermediation are salient: coordination among traders between the 'source' and the 'destination' and competition between alternative combinations of intermediaries. We develop a general model of posted prices in networks to study these forces and we test its predictions in experiments.

Our theoretical analysis provides a complete characterization of equilibrium. Both efficient as well as inefficient equilibrium exist. Surplus division is extremal: either original buyer and eventual seller retain entire surplus *or* the intermediaries extract all surplus. Betweenness centrality of intermediaries determines which of the two outcomes prevails.

Laboratory experiments show that efficiency prevails in almost all cases, subjects coordinate on extreme surplus division: betweenness centrality plays a key role in shaping prices and division of surplus.

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1 Introduction

Intermediation is a prominent feature of economic production and exchange.[1] There are typically multiple intermediaries between the 'source' and the 'destination': so different traders must coordinate their pricing choices. Moreover, there may exist multiple paths between source and destination: so intermediaries must price in the presence of competition. In this paper, our aim is to understand how coordination and competition shape the efficiency of exchange and the division of surplus among the traders.

We propose a model of pricing in networks. There is one buyer, b, and one seller, s, and many potential intermediaries. These traders are located on nodes in a *network*. A link between two nodes means they can engage in direct exchange, whereas the absence of a link means they must seek out paths involving other traders. The need of intermediation may arise from constraints on physical location, moral hazard, search costs, or monitoring costs. We take these restrictions as given. The surplus of trade between buyer and seller is normalized to 1. Potential intermediaries set prices simultaneously. The buyer and seller compare the sum of prices on every path between them and pick the cheapest one. If an intermediary lies on the path picked she earns the posted price; if she does not lie on the path, she earns 0. This formulation of pricing thus combines Bertrand competition and the Nash demand game.[2]

Our first result, Theorem 1, provides a constructive proof for the existence of equilibrium in prices, for all networks. An intermediary has maximum between-ness centrality if she lies on all paths between the buyer and seller; for expositional simplicity we refer to such a trader as *critical*. Consider a profile of prices in which all non-critical traders set prices 0 and the set of critical traders set positive prices that equally divide the surplus. A deviation to a positive price by a non-critical intermediary is not profitable as buyer and seller can circumvent her by using an alternative route. Critical traders cannot increase profits by raising prices as all

[1] Anderson and van Wincoop (2003) present evidence that distribution and retail costs amount to a 55% ad-valorem tax on goods. Spulber (1999) argues that the intermediation sector constitutes about one fourth of the US economy. In the agriculture sector of developing countries, intermediaries earn large rents (Fafchamps and Minten (1999)).

[2] Choice among competing routes comprised of distinct price setting agents is common. Consumers compare costs of alternative delivery channels; in communication networks, multiple service providers set prices and end-users choose which combination of providers to use; transport companies – airlines, shippers and truck companies – choose between alternative routes depending on landing and docking charges and tolls, set by independent entities.

surplus is already being extracted.[3]

An equilibrium is said to be efficient if trade occurs with probability 1. Observe that the equilibrium constructed above is efficient. Do there exist other, possibly inefficient, equilibrium? Consider a ring network with 6 traders and suppose that buyer and seller are 3 links apart. There are three types of equilibrium possible in the ring network. An inefficient equilibrium where all intermediaries set price 1; an efficient equilibrium where all intermediaries set price 0, and another equilibrium where intermediaries along one path set price 1, while the two intermediaries along the other path set price 1/2 each. Figure 1 illustrates these outcomes. This example highlights the importance of coordination among intermediaries and motivates a closer exploration of strategic pricing behavior in networks.

- Figure 1 here -

Theorem 2 provides a complete characterization of pricing equilibrium in networks. In particular, it shows that if trade occurs then either intermediaries extract all surplus or buyer and seller get to keep the entire surplus. We then turn to understanding the network features that support the two outcomes, respectively.

Proposition 1 shows that between-ness centrality is the key to this issue: if there exists a critical trader then all surplus must go to the intermediaries.[4]

While our theory provides strong predictions, there are questions that theory cannot answer, mainly due to the multiplicity of equilibrium. How likely is it that we observe efficient outcomes? If trade occurs, which of the two extremal surplus allocations arise? How does the presence of critical intermediaries shape the division of surplus among the different intermediaries? We use a laboratory experiment to address these issues.

Our experiment consists of 6 treatments with different networks (see Figure 2 in Section 3). The first four networks involve *Ring* networks of varying size: 4, 6, 8, and 10 traders. Rings have always two competing paths connecting buyer and seller and no intermediary is critical. As we increase ring size, we retain the number of paths and thus the level of competition constant, but the number of intermediaries along a given path grows making the problem of

[3]Centrality is a key concept in the study of networks; for a well known exposition, see Freeman (1979). Criticality is also related to the notion of unilateral market power, as defined by Holt (1989): a seller has unilateral market power if he can increase his payoff by raising prices given that all other sellers charge the competitive price. This definition of market power is based on the 1984 US Department of Justice horizontal merger guidelines.

[4]We note that in the ring network, there are no critical traders; yet there is an equilibrium in which all surplus accrues to intermediaries. Thus criticality is sufficient, but not necessary, for intermediation rents.

coordination among intermediaries harder. The goal of the experiment is to test the prospects of successful coordination among intermediaries.

The remaining two networks introduce market power in the form of critical traders. These networks are constructed from the Ring 6 network by adding new links and traders. First, we add two traders to each ring node and get the *Ring with hubs*. Then we connect up all pairs of intermediaries on the ring, and get the *Clique with hubs*. In the Clique with hubs, there is only one path between buyer and seller and so only critical traders intermediate trade. The Ring with hubs creates the space for both market power and competition to come into play: in some situations both critical and non-critical traders co-exist while in others, either only critical traders or only non-critical traders are involved in trading.

Our first experimental finding is that the level of efficiency is very high in all network treatments. In ring networks, exchange takes place with probability 1, regardless of the size of ring and of the distance between a buyer and a seller. In Ring with hubs and Clique with hubs the likelihood of trade is around 0.95. Thus, we conclude that subjects are remarkably successful in coordinating on prices that guarantee exchange.

Our second experimental finding is that intermediation costs do take extreme values as predicted by the theory. In ring networks, after some initial learning, intermediation costs are quite low and lie mainly between 5% and 20%, in most cases. By contrast, in the Ring with hubs and the Clique with hubs, with critical intermediaries, intermediation costs are very large: they typically lie between 80% and 100% of the total surplus. These findings suggest that critical traders are 'necessary' and sufficient for surplus extraction by intermediaries. In doing so they enable us to go beyond the theory.

The third experimental finding pertains to the division of surplus among intermediaries in the presence of critical intermediaries. The theory predicts that all surplus must accrue to intermediaries but does not pin down the division between critical and non-critical intermediaries. Our experiment reveals that in the treatments with Rings with Hubs and Clique with hubs, critical intermediaries charge higher prices and obtain higher profits than non-critical intermediaries.

Our paper is a contribution to the study of trading in networks. Trading in networks is a very active field of research; prominent contributions include e.g., Kranton and Minehart (2001), Corominas-Bosch (2004), Charness et al. (2007) and Manea (2010). This work is almost entirely on direct exchange. By contrast, our focus is on intermediation. There is a small body of work on intermediation which includes Condorelli and Galeotti (2010), Goyal and Vega-Redondo (2007) and Nava (2010).[5] The distinctive element in our work is the trading protocol: we study posted prices.

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 players where both coordination and market power are important. This model maps traditional concepts of market power and competition into networks and our analysis illustrates how network structure shapes pricing and the division of surplus in exchange. In the theoretical literature, the closest work is Acemoglu and Ozdagler (2007a, 2007b), Blume et al. (2007) and Gale and Kariv (2009). The main difference between our paper and these papers is the generality of our network framework and the equilibrium characterization results we provide for general networks. In particular, our work brings out the role of betweenness centrality in shaping pricing and division of surplus in networks.[6]

Our experimental findings contribute to a number of major strands of work on markets. Our finding on efficiency of trading 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), among others. Our finding on the decisive role of market power in shaping division of surplus, is to the best of our knowledge, novel.[7] The special case of one critical intermediary can be interpreted as a dictator game; our results on full extraction of surplus in this setting stand in contrast to the general message from the research on dictator games, see Engel (2011) for an overview of these experiments.

The special case of two critical intermediaries in the Clique with Hubs can be interpreted as a symmetric Nash demand game. Our result reveals a high frequency of trade and that equal division of surplus is focal; these results are consistent with existent literature, e.g., Roth and Murnighan (1982) and Fischer et al. (2006).[8] The special case of no critical intermedaries in

[5] Condorelli and Galeotti (2010) study a sequential model of bilateral bargaining with incomplete information. Goyal and Vega-Redondo (2007) have a reduced form model of intermediation and their focus is on the emergence of critical traders in the process of network formation. Nava (2010) studies a model of quantity competition in networks.

[6] So, for instance, Acemoglu and Ozdaglar (2007a, 2007b) consider parallel paths between the source and destination pair. This rules out the existence of 'critical' traders. Similarly, 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 a specific network structure with multiple layers of intermediaries and fully connectivity across these layers; this rules out 'critical' traders and precludes the study of market power.

[7] Earlier work has studied the role of market power in posted price institutions by introducing sellers with capacity constraints. In our context traders' market power results from their structural location in the network. We refer to Holt (1989, 1995) for an overview of these experiments.

[8] See Roth (1995) for a review of experimental studies on bargaining and negotiations.

the Ring 4 represents a duopoly Bertrand competition model. Our result confirms the classical finding that in posted offer markets adjustment to equilibrium prices tends to be from above, see Dufwenberg and Gneezy (2000), Plott (1982) and Holt (1995).[9]

The rest of the paper is organized as follows. In Section 2 we develop the model of trading in networks and provide the theoretical results. In Section 3 we discuss the experimental design, motivated by theory. Section 4 summarizes experimental findings and Section 5 concludes.

2 Theory

2.1 Model

There is a seller, s, and a buyer b, and $\mathcal{N} = \{1, ..., n\}$, $n \geq 1$, potential intermediaries located in a network. Each trader is synonymous with a node; a link between a pair of traders i and j is denoted by $g_{ij} = 1$, while $g_{ij} = 0$ means that i and j are not directly linked. The links between all pairs of traders taken together define an undirected network, which is denoted by $\mathbf{g}$.

The value of exchange between seller and buyer is (normalized to) 1. The value of exchange, the network and the identity of the buyer and seller is common knowledge among the traders. Every intermediary $i \in \mathcal{N}$ simultaneously posts an 'intermediation price' $p_i \geq 0$. Let $\mathbf{p} = (p_1, p_2, ..., p_n)$ denote the intermediation price profile.[10]

The seller and buyer successfully carry out an exchange if either they have a direct link in the network $\mathbf{g}$ *or* if they can 'reach' each other in the network at an intermediation cost that does not exceed the value of exchange 1. The intermediation cost is defined as the sum of prices charged by the intermediaries connecting buyer and seller.

Formally, a path in $\mathbf{g}$ connecting (b, s) is a sequence of distinct traders $q = \{s, i_1, ..., i_l, b\}$ so that $g_{si_1} = g_{i_1 i_2} = ... = g_{i_l b} = 1$. Let $\mathcal{Q}$ be the set of paths in $\mathbf{g}$ between s and b. The distance between s and b along path q is the number of edges in q, and it is denoted by

[9] Our paper also relates to the sociological literature on social exchange. We share with this literature the underlying question 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 the results are quite different. We refer to Easley and Keinberg (2010) for a survey of this work.

[10] An alternative interpretation of the model is that each path between 'origin' and 'destination' represents a bundle of complementary intermediate goods. The paths are perfect substitutes; there is a consumer with inelastic demand. The price of the final good is then given by the sum of prices of the intermediate goods in a bundle. A special case of this model – with two paths consisting of two intermediate goods each – has been studied by Bornstein and Gneezy (2002).

$d(s,b|q)$. A network in which there is a path between any pair of traders is referred to as *connected*. Since a path between buyer and seller is necessary for exchange, it is natural for us to restrict attention to connected networks.

Given $\mathbf{p}$, the intermediation cost of path $q \in \mathcal{Q}$ is

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

Let $c^*(\mathbf{p}) = \min_{q \in \mathcal{Q}} c(q,\mathbf{p})$ be the lowest intermediation cost that the pair (b,s) has to pay for exchange. A *least cost* path is a path that costs $c^*(\mathbf{p})$ and the set of least cost paths is denoted by $\mathcal{Q}^* = \{q \in \mathcal{Q} : c(q,\mathbf{p}) = c^*(\mathbf{p})\}$.

Given a price profile $\mathbf{p}$, an exchange between buyer and seller (b,s) occurs in network $\mathbf{g}$ if $g_{sb} = 1$ or if $g_{sb} = 0$ and $c^*(\mathbf{p}) \leq 1$. In case of multiple least cost paths, $|\mathcal{Q}^*| > 1$, we assume that every such path $q \in \mathcal{Q}^*$ is chosen with equal probability, given by $1/|\mathcal{Q}^*|$. The expected payoff to intermediary $i \in \mathcal{N}$ is therefore

$$\Pi_i(\mathbf{p}|(b,s)) = \begin{cases} 0 & \text{if } i \notin q \text{ for all } q \in \mathcal{Q}^* \text{ or } c^*(\mathbf{p}) > 1 \\ \frac{\eta_i^*}{|\mathcal{Q}^*|} p_i & \text{otherwise,} \end{cases} \tag{1}$$

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

The aggregate surplus obtained by buyer and seller is 0 if exchange does not occur and $1 - c^*(\mathbf{p})$ if exchange occurs. Our theoretical results do not require any assumption of how this surplus is shared between buyer and seller.[11]

A price profile $\mathbf{p}^*$ is a Nash equilibrium whenever $\Pi_i(\mathbf{p}^*|(b,s)) \geq \Pi_i(p_i, \mathbf{p}^*_{-i}|(b,s))$ for all $p_i \geq 0$, and for all $i \in \mathcal{N}$. We focus on pure strategy equilibrium. An equilibrium with exchange realizes the full surplus and is *efficient*. An equilibrium with no exchange is called *inefficient*.

Traders who lie on many paths between the buyer and seller potentially have more opportunities to act as intermediary. We define betweenness centrality of trader $i \in \mathcal{N}$ as the fraction of paths between buyer and seller on which intermediary i lies.[12] Let $\eta_i = |\{q \in \mathcal{Q} | i \in q\}|$ and define betweenness centrality of trader i as

[11] In our experiments, for computation of payoffs and earnings, we will assume that buyer and seller split equally their aggregate surplus.

[12] In our context it is natural to define betweenness centrality with respect to paths connecting buyer and seller, instead of considering all paths. Note that we consider all paths and not just the shortest paths; here we follow a suggestion made in Borgatti and Everett (2005).

$$\mathcal{C}_i^B = \frac{\eta_i}{|Q|}. \tag{2}$$

Thus betweenness centrality of a trader i, $\mathcal{C}_i \in [0,1]$. A trader with $\mathcal{C}_i = 1$ is referred to as *critical*. Define $\mathcal{C} = \{i \in \mathcal{N} : i \in q, \forall q \in \mathcal{Q}\}$ as the set of critical traders.

2.2 Results

Our first result establishes existence of an equilibrium for all networks.

Theorem 1 *For every network* $\mathbf{g}$ *there exists an equilibrium.*

Proof of Theorem 1. The proof is constructive. Suppose the set of critical traders is empty, $\mathcal{C} = \emptyset$: consider a price profile $\mathbf{p}^*$ such that $p_i^* = 0$ for all $i \in \mathcal{N}$. Note that no intermediary can earn positive profits by deviating and setting a positive price. Indeed, since no trader is critical, a positive price will mean that there remains another path between buyer and seller where all traders set price 0. Buyer and seller will use such a zero cost path. If there are critical traders, $\mathcal{C} \neq \emptyset$, 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. ■

Observe that in the equilibrium constructed above the intermediation costs are either 0 or 1: so exchange takes place with probability 1. Theorem 1 thus establishes that, irrespective of the network, it is possible for intermediaries to coordinate on prices that support exchange between the buyer and seller. This result raises two questions. The first question is about the efficiency of trade. Are all equilibrium efficient or does there exist an inefficient equilibrium? The second question is about the division of surplus between different traders. How is the surplus distributed across buyer/seller and the intermediaries?

Our next result provides a complete characterization of equilibrium and addresses these two questions. We say that trader i is *essential* for (b,s) under $\mathbf{p}$ if trader i belongs to every least cost path with $c^*(\mathbf{p}) \leq 1$. Note that essentiality depends both on the network $\mathbf{g}$ and the profile of prices $\mathbf{p}$.[13] Given a network $\mathbf{g}$, a pair (b,s), and a price profile $\mathbf{p}$, for a path $q \in \mathcal{Q}$

[13] Essentiality is related to criticality in the following way: if trader i is critical then he must be essential under $\mathbf{p}$ provided that there is at least one path whose total cost is not higher than 1. On the other hand, criticality is not necessary for being essential: a non-critical trader may be essential due to pricing choices. Figure 1 in the introduction illustrates this possibility. So criticality is a purely structural property but essentiality reflects both structural as well as strategic elements.

define $c_{-j}(q, \mathbf{p}) = \sum_{i \in q, i \neq j} p_i$ as the costs of all intermediaries other than intermediary j.

Theorem 2 *For any network* $\mathbf{g}$ *and every pair of buyer and seller* (b, s)*, an equilibrium* $\mathbf{p}^*$ *is either inefficient* ($c^*(\mathbf{p}^*) > 1$)*, intermediaries extract all the surplus* ($c^*(\mathbf{p}^*) = 1$)*, or buyer and seller retain all the surplus* ($c^*(\mathbf{p}^*) = 0$)*. Moreover,*

1. $\mathbf{p}^*$ *is an equilibrium where buyer and seller retain all the surplus if, and only if, no intermediary is essential under* $\mathbf{p}^*$.
2. $\mathbf{p}^*$ *is an equilibrium where intermediaries extract all the surplus if, and only if, (i) for every intermediary* $i \in q$*,* $q \in \mathcal{Q}^*$ *and* $p_i^* > 0$*, intermediary* i *is essential, and (ii) for every intermediary* $j \in q$ *with* $q \in \mathcal{Q} \setminus \{\mathcal{Q}^*\}$*,* $c_{-j}(q, \mathbf{p}^*) \geq 1$.
3. $\mathbf{p}^*$ *is an inefficient equilibrium, if, and only if,* $c_{-j}(q, \mathbf{p}^*) \geq 1$ *for every intermediary* $j \in q$ *and* $q \in \mathcal{Q}$.

Theorem 2 yields a number of insights. The *first* observation is that in every efficient equilibrium intermediation costs take on extreme values: either intermediaries extract all surplus or buyer and seller get to keep all surplus. The basic intuition is the following. When intermediaries become essential under a network and a profile of prices, they exercise market power. Collectively they must extract full surplus, for otherwise an essential trader could slightly increase his intermediation price while guaranteeing that exchange takes place through him. In contrast, when no intermediary is essential, buyer and seller can always circumvent traders who demand a positive intermediation price. Price competition drives down intermediation costs to zero.

The *second* observation is about the role of coordination among intermediaries. To see this, let us consider a ring network with 6 traders and suppose that buyer and seller are 3 links apart. It is easy to verify that the three types of equilibrium identified by Theorem 2 all exist. In particular, it is an equilibrium for all intermediaries to set price 0, for all of them to set price 1, and for intermediaries along one path to set price 1 whereas the intermediaries along the other path set price 1/2 each. Figure 1 illustrates these outcomes.

This multiplicity of equilibrium naturally motivates an examination of equilibrium refinements. We have considered a number of possible refinements – such as 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 very 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.[14]

Keeping in mind the multiplicity of equilibrium, we now move to a closer examination of the relation between network structure and nature of equilibrium. Are there networks for which we can rule out inefficient equilibrium? Are there properties of networks that determine how surplus is distributed between buyer and seller, on the one hand, and the intermediaries, on the other hand? The following result provides a partial answer to these questions.

Proposition 1 *For every network* $\mathbf{g}$ *the following holds:*

1. *An inefficient equilibrium exists if, and only if, the distance of every path between buyer and seller is strictly higher than two, i.e.,* $d(b, s|q) > 2$, $\forall q \in \mathcal{Q}$.
2. *Consider equilibrium* $\mathbf{p}^*$.
   - 2a. *If one or more intermediaries are critical and the equilibrium is efficient then intermediaries extract all surplus.*
   - 2b. *If there are at least two paths* q *and* q' *between* (b, s) *with distance* $d(b, s|q) = d(b, s|q') = 2$, *then the equilibrium is efficient and there is full extraction of surplus by buyer and seller.*

Part 1 of Proposition 1 establishes that we need two or more intermediaries on every path between buyer and seller to support an inefficient equilibrium. Theorem 1 tells us that there always exists an efficient equilibrium. So, the result clarifies the key role of coordination failure in the breakdown of exchange. Part 2a of Proposition 1 clarifies the property of network structure in establishing market power: if one or more traders has maximum betweenness centrality then intermediaries must extract all surplus in exchange. It is worth noting that while maximal betweenness centrality determines that surplus must accrue to intermediaries, the theory is permissive about the division of surplus among the intermediaries. To see this point, consider the Ring with hubs network presented in Figure 2 and suppose that the seller and buyer are nodes (a_1, d_1). Then there exists an equilibrium in which all surplus accrues to

[14] 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.

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.

Finally, the last part of Proposition 1 brings out the property of network structure in creating market competition, *a la* Bertrand: if two or more traders are sole intermediaries on competing paths connecting buyer and seller then price competition eliminates all intermediation surplus.

Summarizing, our analysis brings out three points:

1. Coordination among intermediaries is key to the efficiency of exchange.
2. Strategic interaction delivers extremal outcomes for intermediation costs and division of surplus: either buyer and seller keep all the value of exchange or the intermediaries extract all surplus.
3. In the presence of traders with maximal betweenness centrality all surplus in an exchange must accrue to the intermediaries.

3 From Theory to Experiment

3.1 Design

The theory is illuminating along a number of dimensions and yields a number of predictions. One goal of the experiment is to investigate if these predictions hold out in practice. There are a number of interesting economic questions on which theory is silent due to the multiplicity of equilibria. The second goal of the experiment is to explore how network structure shapes the ways in which subjects select among the equilibria.

The design of the experiment centers on a number of network architectures. These networks have been picked to highlight the role of two economic forces of interest: coordination and competition. In order to examine the former, we use a class of ring networks with varying size $n = 4, 6, 8$ and 10. The latter is the focus in the Clique with hubs and Ring with hubs. Figure 2 illustrates these networks.

- Figure 2 here -

Coordination. We first take up the issue of coordination by focusing on the class of ring networks with $n = 4, 6, 8, 10$ subjects. We refer to a ring network with n traders as Ring n. By varying the size of ring networks, we create a wide range of trading situations.

For instance, take, as a baseline, Ring 4 where any non-adjacent pair of buyer and seller is equidistant on either path (with the distance of 2). Larger rings contain trading situations of equidistance with more traders: $(d(q), d(q')) = (3, 3)$ in Ring 6; $(4, 4)$ in Ring 8; $(5, 5)$ in Ring 10.[15] By comparing equidistant paths with varying distance, we can examine one type of coordination problem among symmetric traders. Alternatively, we can fix the distance of one path to be 2 (only one trader) and increase the distance of the other path: $(d(q), d(q')) = (2, 2)$ in Ring 4; $(2, 4)$ in Ring 6; $(2, 6)$ in Ring 8; $(2, 8)$ in Ring 10. In Ring $n \geq 6$, intermediaries on a longer path need to coordinate in order to win over a single intermediary on the other path. The larger the distance of a longer path is the bigger the challenge of resolving coordination problems among traders.

Market power. In examining the effects of market power on efficiency and surplus division, we compare three networks in the design – Ring 6, Ring with hubs, and Clique with hubs. No trader is critical in Ring 6, whereas exchange is mediated always by critical traders in the Clique with hubs.

Ring with hubs creates the space for both market power and competition to come into play. For instance, consider a trading situation where two leaf agents, $a1$ and $e1$, are selected as buyer and seller. Two intermediation paths compete: a shorter path (through A, F, and E) and a longer path (through A, B, C, D, and E). Traders A and E lie on both paths, and so are critical. The other traders (B, C, D, and F) lie only on one of the paths and thus are not critical.

To put these experimental variations in perspective, we summarize the equilibrium analysis of these selected networks. First, let us consider efficiency. In Ring 4 every equilibrium is efficient. In every other network an inefficient equilibrium exists whenever there are at least two intermediaries in every path connecting buyer and seller. On the other hand, Theorem 1 demonstrates the existence of efficient equilibrium in any network and any pair of buyer and seller. Thus, theory is silent on which equilibrium – efficient or inefficient – is salient as we vary networks. These observations motivate the following question:

Question 1 *Does the efficiency of trade vary with different levels of coordination (across ring networks of different size) and with different degrees of market power (across differential*

[15] We simplify the notation of distance between buyer b and seller s on a path q with $d(q)$ whenever necessary.

composition of critical and non-critical traders)?

We turn next to the issue of intermediation costs. If trading does take place, theory predicts an extremal division of trade surplus (Theorem 2): either buyer and seller keep all the value of exchange (when no intermediary is essential) or intermediaries extract all trade surplus (when any trader earning positive payoffs is essential). Both types of outcome are possible in every ring network we consider, except for Ring 4 where the intermediation cost of the unique equilibrium is zero. In Clique with hubs and Ring with hubs, if exchange involves critical traders then equilibrium dictates full surplus extraction by intermediaries (Proposition 1). These considerations motivate the following question:

Question 2 *If trade occurs, does absence (presence) of critical traders ensure zero (full) surplus extraction by intermediaries?*

In addition to these first two questions, which are the focus of our analysis, we also analyse in details how the network location of a trader affects his pricing behavior and the rents that he can hope to gain. Nash equilibrium analysis provides little guidance on this issue. In rings, the theory does not predict how the distance between buyer and seller influences traders' pricing behavior and intermediation costs. In Ring with hubs and Clique with hubs when exchange is mediated by critical traders, the theory predicts that intermediaries extract all surplus, but does not pin down the division of surplus among critical intermediaries and whether critical intermediaries should earn more than the other traders. These considerations motivate two auxiliary questions:

Question 3 *How does the distance between buyer and seller influence traders' pricing behavior and intermediation costs?*

Question 4 *Do critical traders acquire higher surplus than non-critical traders? When two critical traders are present, do they share surplus equally?*

3.2 Experimental procedures

We ran the experiment 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 and had no previous experience about this experiment. 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 Online Appendix I.[16]

The experiment utilized six network treatments – Ring $n = 4, 6, 8, 10$, Ring with hubs, and Clique with hubs. We ran 2 sessions for each treatment; so there were a total of 12 sessions. Each session consisted of 60 independent rounds. The number of subjects who participated in a session varies from 16 to 24; a total of 240 subjects participated in the experiment. The table below summarizes the experimental design and the amount of experimental data. The first number in each cell is the number of subjects and the second one is the number of group observations in each treatment.

	Session		
Treatment	1	2	Total
Ring 4	16 / 240	16 / 240	32 / 480
Ring 6	18 / 180	24 / 240	42 / 420
Ring 8	24 / 180	24 / 180	48 / 360
Ring 10	20 / 120	20 / 120	40 / 240
Ring with hubs	18 / 180	24 / 240	42 / 420
Clique with hubs	18 / 180	18 / 180	36 / 360

In each round of a treatment subjects are assigned with equal probability to one of the possible intermediary positions of a network. In each Ring n, all nodes are possible intermediary positions. In Ring with hubs and Clique with hubs, each leaf node is a computer-generated agent, and the remaining nodes are the set of possible intermediary positions. The position of a subject in each round depends solely upon chance and is independent of the subject's position in previous rounds. Groups with one subject per intermediary position are then randomly formed. The groups formed in each round depend solely upon chance and are independent of the groups formed in previous rounds.

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

For each group, a pair of two non-adjacent nodes is randomly selected as buyer, b, and seller, s. Each pair of two non-adjacent nodes is equally likely to be selected. All subjects in each group are informed of the position in the network of the buyer and seller and that the value of exchange is 100 tokens. Then, each subject playing an intermediary role is asked to submit an intermediation price. Each subject chooses a real number (up to two decimal places) between 0 and 100 and types the number in the number box in the computer screen. 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 the surplus 100. If there are multiple least cost paths then one of them is picked at random.

At the end of the round, subjects observe the prices of all the subjects in their groups and the trading outcome, including the earnings for intermediaries and the earnings of the selected buyer-seller pair.[17] After observing the results of the round, subjects moved to the next round. We repeat this process for 60 rounds.

Each round earnings are calculated in terms of tokens. For each subject, the earnings in the experiment is 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.

4 Experimental Results

4.1 Efficiency

We begin the analysis of the experimental data by examining the efficiency of trade in networks. As summarized in Question 1 our interest lies in the impact of coordination and market power on efficiency. Table 1 reports the relative frequency of trade across different treatments, along with the number of group observations in parentheses. We also present data on frequency of trade arranged by minimum distance between buyer and seller.

- Table 1 here -

Trade occurs with probability 1 in ring networks, regardless of the size of ring and the distance between buyer and seller. For example, in Ring 10, we have 35 group observations

[17] We recall that buyer and the seller are allocated each 1/2 of the net surplus, which corresponds to the value of exchange minus the intermediation costs.

where, despite buyer and seller need to use four intermediaries to transact, trade occurs all the time. In Ring with hubs and Clique with hubs, the frequency of trade is also high, around 0.95. So, market power does not cause a significant effect on inefficiency of trading. In both networks, when a single intermediary lies in the shortest path between buyer and seller, trade always occur by default. In cases of multiple intermediaries, there is some inefficiency around 6% to 12%. Overall, despite the need of coordination among traders along the same path, the presence of competition between paths and of market power of some intermediaries, traders across all treatments are remarkably successful in coordinating on prices that ensure exchange.

Finding 1 (efficiency): *The level of efficiency is remarkably high in all networks. Trading in rings occurs with probability 1. In Ring with hubs and Clique with hubs, trading occurs with probability around* 0.95*.*

4.2 Division of surplus

We next move on to Question 2 about intermediation costs. We start by examining the impacts of coordination on intermediation costs in the class of ring networks, and then examine the impact of critical intermediaries on surplus division.

Ring networks. Table 2 reports average intermediation costs across distinct situations of trading across ring networks. We distinguish trading situations with respect to distances of the two competing paths between buyer and seller, denoted by $(d(q), d(q'))$. We also divide the sample data, conditional on each situation of trading, into six blocks of ten rounds: 1-10 rounds, 11-20 rounds, ..., and 51-60 rounds. The number of group observations is reported in parentheses. For example, in the case of $(2, 4)$ of Ring 6 network where the distance of a shorter (longer) path is 2 (4), we have 52 group observations in the first ten rounds with an average intermediation cost, 41.77.

- *Table 2 here* -

There is a clear downward trend in the movement of costs across rounds. Average costs in the initial 10 rounds are around 20 in Ring 4 and hover somewhere between 40 and 50 in the other rings. Intermediation costs go down over rounds and when we look at the last 20 rounds of the data, they are positive but remarkably low. In Ring 4, intermediation costs are around 5 percent of the total value of exchange. In the other rings, intermediation costs vary between 10 and around 20 percent of the value of exchange (except for Ring 8 when the distance between buyer and seller is four where they reach almost 30%). 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. This pattern is particularly stronger in smaller rings.

There are interesting differences of costs across distinct cases of distance within and across networks. In order to investigate more closely the potential effects of distance on trading costs, we present average intermediation costs with 95% confidence interval across different cases of distance in Figure 3.

- *Figure 3 here* -

Our first observation is that if we hold constant a minimum distance between buyer and seller, the size of ring network has an influence on intermediation costs in many cases. By way of illustration, consider the case of minimum distance 2. The average cost of Ring 4 is 5%, which is significantly different from 12% in Ring 6 (p-value for unpaired t-test of comparing two average costs is zero). As we move from $(2, 4)$ in Ring 6 to $(2, 6)$ in Ring 8 and $(2, 8)$ in Ring 10, the costs increase significantly by 12% and 8%, respectively (p-values for t-test are nearly zero). We do not find a significant difference of average costs between $(2, 6)$ of Ring 8 and $(2, 8)$ of Ring 10 (p-value for t-test is around 0.14). Similarly, when we compare the cases of minimum distance 3, the average cost for $(3, 3)$ of Ring 6 is 13% and significantly smaller than those for $(3, 5)$ of Ring 8 and $(3, 7)$ of Ring 10, respectively, 19% and 21% (p-values for t-test are nearly zero).

Our second observation is about within-ring variations of intermediation costs: here we don't find significant differences in costs for Ring 6 and Ring 10. In Ring 8, the average cost in the case of $(3, 5)$ is significantly lower than those in cases of $(2, 6)$ and $(4, 4)$ (p-values for t-test are, respectively, 0.046 and 0.002).

These across-ring and within-ring variations of intermediation costs suggest that subjects' pricing behavior responds to the length of their own path and the length of the competing paths in a subtle manner. We investigate the pricing behavior in greater detail in section 4.3.

We look next into the "competitiveness" of the two paths to enhance our understanding on why the overall intermediation costs in ring networks are so low. For this purpose, we directly compare intermediation costs of two paths by computing (absolute) differences between them. Table 3 reports the sample median of (absolute) differences of costs between two competing paths, again by dividing the sample into six blocks of 10 rounds. The number in parentheses is the relative frequency of trading on a shorter path. The median difference in intermediation costs is less than 8 in all cases, and this difference is stable over time. Considering the problem of coordination among multiple intermediaries on a single path, we view these median differences in costs as quite small and thus that the competition between the two paths is so tight. This tight competition is reflected in another fact about trading: the frequency of trading along the shorter path is lower than 65% in all but one case.

- Table 3 here -

Ring with hubs and Clique with hubs. A trading situation between buyer and seller in Ring with hubs and Clique with hubs can be characterized by (*i*) the number of critical intermediaries ($\#Cr$), (*ii*) the number of intermediation paths ($\#Paths$), and (*iii*) the distance of each path $(d(q), d(q'))$. Table 4 presents average intermediation costs across distinct cases of trading in Ring with hubs and Clique with hubs, $(\#Cr, \#Paths, d(q), d(q'))$, dividing the sample into six blocks of 10 rounds. The number of observations is reported in parentheses.

- Table 4 here -

First, for the single-path cases with either one or two critical traders, intermediaries extract almost the entire surplus. In Ring with hubs, they extract about 99% and 96% of the total surplus in the last 20 rounds when there are one or two critical traders, whereas about 88% and 96% of surplus are taken by intermediaries in Clique with hubs, respectively.

When there is only one critical intermediary, the decision problem is analogous to that of standard dictator game, widely studied in the experimental literature (for a survey, see Engel, 2010). In this case, we found much higher surplus extraction than reported in the experimental literature.[18] There are two main differences between our design and the literature. First, we frame the decision problem as that of posted prices of intermediaries. This may give rise to the feelings of entitlement that are distinct from standard dictator game. Second, in our design there are two recipients – buyer and seller – whereas in the dictator game there is one recipient.[19]

[18]Our work 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).

[19]We also note that in our design, in some situations, both buyer and seller 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 vs. computer issue does not play a major role in explaining the behavior of subjects in our experiment.

When there are two competing paths, trading outcomes are greatly affected. In the cases with critical intermediaries, intermediation cost ranges between 62% and 83% in the last 20 rounds. In the case without no critical intermediary, this cost falls sharply to around 28%, which is comparable to the low-cost outcome found in ring networks. This strongly suggests that, even in case of two competing paths, the presence of critical intermediaries dramatically affects trading. Overall, this is qualitatively consistent with the key role of criticality on division of surplus as theory predicts. We summarize these observations in two findings:

Finding 2A (division of surplus): *(i) In ring networks, intermediation costs are small (ranging from 5% to 30%), while in Clique with hubs and Ring with hubs, if trading is mediated via critical traders, then intermediation costs are large (60% to over 95%).*

Finding 2B (distance and costs): *Distance between buyer and seller has significant impact on intermediation costs: holding constant the minimum distance between buyer and seller, the costs increase in the length of the longer path.*

4.3 Pricing behavior

We now examine individual pricing behavior. Our interest lies in (i) the effects of distance on pricing behavior in ring networks, as addressed in Question 3, and (ii) the pricing behavior of critical and non-critical intermediaries in Ring with hubs and Clique with hubs, as addressed in Question 4.

Ring networks. We first look into subjects' pricing behavior in the ring networks. Table 5 reports average prices charged by intermediaries, conditional on distances of two paths, $(d(q), d(q'))$, and the distance of their own path, along with the number of observations in parentheses. We again partition the sample into six blocks of 10 rounds.

- *Table 5 here* -

Controlling out for potential learning effects across rounds, we focus on the last 20 rounds and present graphically average prices across different trading situations in Figure 4. For the sake of comparison, we also present the resulting intermediation cost for each case.

- *Figure 4 here* -

Subjects lying on a longer path chose on average prices somewhere between 5 and 10 (presented with blue-colored squares), independently of the distances of two paths across all ring networks. Responding strategically to this, subjects lying on a shorter path chose higher prices that are proportionate to the difference of distances between two paths (presented with red-colored cross). For example, in cases where the minimum distance between buyer and seller is 2, subjects on the shorter path in Ring 6 chose on average a price around 15; they charged an average price of around 25 in Ring 8; and in Ring 10 they chose an average price of around 28. In Ring 6 and 8, the average price on the shorter path is proportionate to the number of intermediaries on the longer path and their average prices.

The within-network comparison also reveals similar patterns of strategic competition: average prices charged by subjects lying on competing paths become closer as their respective lengths become similar. For example, within Ring 10 average prices on the shorter path decreases gradually from around 28 in the case of distance 2, to around 12 in the case of distance 3, and to around 6 in the case of distance 4. Due to the tight competition between two paths, the resultant intermediation costs (presented with green-colored circle) often get lower than the sum of average prices charged on the shorter path. This re-confirms the result in Table 3 that trade occurs frequently along the longer path.

All this evidence on pricing behavior suggests that subjects are strategically sophisticated in their choice of prices, while facing some uncertainty about other subjects' behavior. In order to evaluate this further, we consider a simple model of stochastic response under strategic uncertainty about opponents' behavior and fit the model to the data. The analysis and results, presented in Appendix II, confirm that a simple model of strategic uncertainty with noisy response provides a fairly good account of the pricing behavior in ring networks.

Ring with hubs and Clique with hubs. We now turn to the question of surplus division among critical and non-critical intermediaries, by examining their pricing behaviors. Table 6 presents average prices of critical and non-critical intermediaries in Ring with hubs and Clique with hubs, conditional on distinct trading case $(\#Cr, \#Paths, d(q), d(q'))$, partitioning the sample into six blocks of 10 rounds. The number of observations is reported in parentheses.

- Table 6 here -

We first look into the pricing behavior of two critical intermediaries when there is only a single path connecting buyer and seller, $(2, 1, 3, -)$. An average price of each critical intermediary in Ring with hubs (resp. in Clique with hubs) is 45.6 (resp. 46.1) in the first ten rounds and then increases slightly over time to reach 50 in the last 10 rounds (resp. 51). This offers strong evidence that both critical intermediaries successfully coordinate to extract and divide the total surplus equally between them. Bearing in mind that this case of trading is strategically equivalent to Nash demand game with two symmetric players, we conclude that our finding is consistent with the findings in the experimental literature of Nash bargaining (e.g., Roth and Murnighan (1982) and Fischer et al (2006)).

Next we turn to cases in which critical and non-critical intermediaries co-exist in two competing paths. The pricing behavior of critical and non-critical intermediaries is strikingly different: Critical traders post much higher prices than non-critical traders, regardless of the characteristics of the two competing paths. For instance, in the case where there is one critical intermediary and the two competing paths are of distance 3 and 5 (first row of table 6), the critical trader charges, on average, a price close to 50 in the last 20 rounds, non-critical traders lying in the distance-3 path charge a price close to 25 and those in the other longer path post a price around 10. Similar behavior is observed in the other cases.

This indicates strong impacts of network position on pricing behavior and thus surplus division. Table 7 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. Thus, the results in Table 7 provide clear evidence that 'critical' network location generates large payoff advantages.[20]

- Table 7 here -

We summarize our findings on pricing behavior as follows:

Finding 3A (criticality and pricing): *In ring networks, average prices are positive but quite low. In Ring with hubs and Clique with hubs, critical intermediaries charge higher prices than non-critical intermediaries leading to unequal intermediation rents. Multiple critical intermediaries set similar prices.*

[20] There are very few observations on the cases where both buyer and sellers are on the ring in Ring with hubs, and so there is no critical intermediary. We observe that all non-critical traders behave similarly to that of traders in ring networks. In fact, traders on a shorter path set higher prices than those on a longer path and, as a result, traders on both paths compete tightly. However, as compared to ring networks, non-critical intermediaries in this case of Ring with hubs charge higher prices. It may be that subjects have few chances of learning about opponents' behavior in this case, due to the small sampling problem, and experiences in other cases (with critical intermediaries) might spill over and affect the behavior in this case.

Finding 3B (distance and pricing): *Relative length of two paths affect prices: intermediaries on a longer path set lower prices as compared to intermediaries on a shorter path. This results in tight competition between two paths and trade takes place along the longer path in almost one third of the cases.*

5 Conclusion

We have examined, through a combination of theory and experiments, how coordination and competition among intermediaries affect the efficiency of exchange and the division of surplus among traders. Our model maps traditional concepts of market power, competition and coordination into networks.

Our theoretical analysis shows that efficient equilibrium always exists; but efficiency is not guaranteed, as inefficient equilibria are also common. The experiments show that subjects almost always select efficient outcomes. The theory predicts that the division of surplus takes extreme forms: either all surplus stays with the buyer and seller or all surplus is extracted by the intermediaries. The experiments show that the division of surplus is (close to) extremal. Moreover, they point to the key role of betweenness centrality as an organizing principle. Surplus goes to the intermediaries if and only if there exist traders with maximal betweenness centrality. Experiments also reveal that betweenness centrality is a key determinant of pricing behavior and earning power among intermediaries.

We have assumed that intermediaries have complete information on the value of exchange between buyer and seller. In on-going work, we explore the implications of demand uncertainty: when intermediaries post their price they do not know the exact value of exchange (Choi, Galeotti and Goyal (2013)). We have developed a complete characterization of pricing in this model. A positive price equilibrium exists and in such an equilibrium traders set equal positive prices. These prices are falling while the total intermediation costs are rising in the number of active traders. The notion of betweenness centrality and the presence of critical traders remain key to understanding pricing and surplus division in the new model. Finally, in a positive price equilibrium, trade occurs with positive probability but not always: the extent of inefficiency and the surplus extraction by intermediaries depends on the 'distance' between the buyer and seller. These results relate closely to the large body of work on double marginalization.

References

[1] Acemoglu, D. and A. Ozdaglar (2007a), Competition in Parallel-Serial Networks. *IEEE Journal on selected areas in communications.*

[2] Acemoglu, D. and A. Ozdaglar (2007b), Competition and Efficiency in Congested Markets, *Mathematics of Operations Research*, 32, 1, 1-31.

[3] Anderson, J. and E van Wincoop (2004), Trade Costs, *Journal of Economic Literature*, 42, 3, 691-751.

[4] Blume, L., D. Easley, J. Kleinberg and E. Tardos (2007), Trading Networks with Price-Setting Agents, in *Proceedings of the 8th ACM conference on Electronic commerce EC 2007* New York, NY, USA.

[5] Borgatti, S. P. and M. Everett (2005), A Graph-Theoretic Perspective on Centrality, *Social Networks*, 28, 466–484.

[6] Bornstein, Gary, and U. Gneezy (2002), Price competition between teams, *Experimental Economics*, 5:29-38.

[7] Charness, G., M. Corominas-Bosch and G. Frechette (2007), Bargaining and Network Structure: an Experiment, *Journal of Economic Theory*, 136.

[8] Cheery, T.L., P. Frykblom and J. F. Shogren (2002), Hardnose the Dictator, *American Economic Review*, 92, 4, 1218-1221.

[9] Choi, S., A. Galeotti and S. Goyal (2013), Trading in Networks II: incomplete information. *mimeo.*

[10] Corominas-Bosch, M. (2004), Bargaining in a Network of Buyers and Sellers, *Journal of Economic Theory*, 115, 35-77.

[11] Condorelli, D. and A. Galeotti (2011), Bilateral Trading in Networks. *Mimeo.*

[12] Dwefenberg, M. and U. Gneezy (2000), Price Competition and Market Concentration: An Experimental Study, *International Journal of Industrial Organization*, 18, 7-22.

[13] Easley, D. and J. Keinberg (2010), *Networks, Crowds and Markets.* Cambridge University Press.

[14] Engel, C (2010), Dictator Games: a Meta Study. *Preprint 2010/07*, Max Planck Institute Bonn.

[15] Fafchamps, M. and B. Minten (1999), Relationships and Traders in Madagascar, *The Journal of Development Studies*, 35, 6, 1-35.

[16] Freeman, L. C. (1979), Centrality in social networks: Conceptual clarification, *Social Networks*, 1, 3, 215–239.

[17] Fisher S., W. Guth, W. Muller and A. Stiehler (2006) From Ultimatum to Nash Bargaining: Theory and Experimental evidence, *Experimental Economics*, 9, 17-33.

[18] Gale, D. and S. Kariv (2009), Trading in Networks: A Normal Form Game Experiment. *American Economic Journal: Microeconomics*, 1, 2, 114-32.

[19] Goyal, S. and F. Vega-Redondo (2007), Structural Holes in Social Networks, *Journal of Economic Theory*, 137, 460-492.

[20] Holt, C. A. (1989), The exercise of market power in laboratory experiments. *Journal of Law and Economics,* 32:107-130.

[21] Holt, C. A. (1995), Industrial organization: a survey of laboratory research, *Handbook of Experimental Economics.*.

[22] Kranton, R. and D. Minehart (2001), A Theory of Buyer-Seller Networks, *American Economic Review*, 91, 485-508.

[23] Manea, M. (2010), Bargaining in Stationary Networks, *American Economic Review*, 101, 5, 2042-2080.

[24] McKelvey, R. D. and T. R. Palfrey (1995), Quantal Response Equilibria for Normal Form Games, *Games and Economic Behavior*, 10, 6-38.

[25] Nava, F. (2010), Flow Competition in Networked Markets. *Mimeo.* LSE.

[26] Nash, J. (1950). The Bargaining Problem. *Econometrica* 18, 2: 155–162.

[27] Plott, C.R. (1982), Industrial organization theory and experimental economics, *Journal of Economic Literature,* 20:1485-1527.

[28] Roth, A. E. (1995). Bargaining Experiments. In John H. Kagel and Alvin E. Roth (Eds), *The handbook of experimental economics*. Princeton University Press.

[29] Roth, A. E. and J.K. Murnighan (1982), The Role of Information in Bargaining: an Experimental Study. *Econometrica*, 50, 1982, 1123-1142

[30] Rubinstein, A. and A. Wolinsky (1987), Middlemen, *Quarterly Journal of Economics*, 102 (3), 581-594.

[31] Smith, V. L (1962), An Experimental Study of Competitive Market Behavior, *Journal of Political Economy*, 70(2), 111-137.

[32] Spulber, D. (1999), *Market Microstructure: Intermediaries and the Theory of the Firm.*

Appendix I. Proof of Theorem 2 and Proposition 1.

Proof of Theorem 2. We first show that $c^*(\mathbf{p}^*) \in (0,1)$ 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 $c^*(\mathbf{p}^*) > 0$. 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; hence, exchange will take place with probability 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 lowest 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 $c^*(\mathbf{p}^*) = 0$. 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 $\mathbf{p}$, 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 $\mathbf{p}^*$ is an equilibrium.
   We now establish necessity. Suppose there is a trader i who is essential under $\mathbf{p}^*$. As $c^*(\mathbf{p}^*) = 0$, essential trader i can raise his price slightly, still ensure that exchange takes place through him, and thereby he strictly raises his payoffs. So $\mathbf{p}^*$ is not an equilibrium.

2. Assume $c^*(\mathbf{p}^*) = 1$. 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 $l \in q$, with $q \notin \mathcal{Q}^*$. This trader earns 0 in $\mathbf{p}^*$. A deviation to a lower positive price leaves the trade probability via l at 0, as $c_{-l}(q, \mathbf{p}^*) \geq 1$. We have shown that $\mathbf{p}^*$ 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 $k \in q$, with $q \notin \mathcal{Q}^*$ and suppose $c_{-k}(q, \mathbf{p}^*) < 1$. Under $\mathbf{p}^*$, the payoff to k is 0. But since $c^*(\mathbf{p}^*) = 1$, there is a price $p_k = 1 - c_{-k}(q, \mathbf{p}^*) - \epsilon$ 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 $c^*(\mathbf{p}^*) > 1$. We first establish sufficiency. All traders earn 0 under profile $\mathbf{p}^*$. Consider $j \in q$ with price p_j^*. It can be checked that no deviation to another price can generate positive payoffs given that $c_{-j}(q, \mathbf{p}^*) \geq 1$. 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 such that $c_{-j}(q, \mathbf{p}^*) < 1$. Then there is a price $p_j = 1 - c^*_{-j}(\mathbf{p}^*) - \epsilon$, for some $\epsilon > 0$ such that trade takes place via trader j with probability 1. This constitutes a profitable deviation.

■

Proof Proposition 1: Part 1. First consider sufficiency. Set prices of all intermediaries at 1. Given that $d(b, s|q) > 2$, there are always at least 2 traders in any path $q \in \mathcal{Q}$. This is an equilibrium, from part 3 of Theorem 2. Next, we establish necessity. If $d(b, s|q) = 2$ then there exists a path in $\mathbf{g}$ between b and s, with only one intermediary, say, i. If $c^*(\mathbf{p}^*) > 1$ then there is no trade and all paths between the buyer and seller cost more than 1 and all traders makes zero payoffs. However, by setting a positive price $p \leq 1$ intermediary i ensures exchange and earns positive payoff.

We now consider part 2a. If the equilibrium is efficient then $c^*(\mathbf{p}^*) \leq 1$. If $c^*(\mathbf{p}^*) = 0$ then any intermediary $k \in \mathcal{C}$ can raise price slightly, retain probability one of exchange, and so increase his payoff. From Theorem 2 it then follows that $c^*(\mathbf{p}^*) = 1$.

Finally, consider part 2b. From part 1 we know that equilibrium is efficient. Suppose $c^*(\mathbf{p}^*) = 1$; for this to be an equilibrium it must be the case that intermediaries who lie on distance 2 paths set price 1. This also implies that each of those intermediaries earns at most $1/2$. But this is clearly sub-optimal. An intermediary on a path of distance 2 can strictly raise payoffs by slightly lowering his price as this guarantees that he is on the trading path, and ensures a payoff close to 1. ■

Appendix II. A Model of Strategic Uncertainty with Stochastic Choice

We employ a tractable and parsimonious model of noisy behavior to account for pricing behavior in rings.[21] The model is built on a set of structural assumptions: First, we assume that individuals on a given path q against a competing path q' use a symmetric strategy, described by the distribution of price choice. Second, we assume that an individual subject has correct beliefs about opponents' strategies. Third, each individual is assumed to choose a price to maximize his expected payoffs against opponents' strategies. In the exercise of fitting the model to the data, we introduce the possibility of noisy best response, using a conventional logistic choice function. For practical purpose, we discretize the action space to be the set of integer numbers, ranging from 0 to 100.

Formally, we first describe a model of strategic uncertainty without decision error. Consider intermediary i on a path q with a competing path q' in Ring n network. This intermediary faces uncertainty about the behavior of other intermediaries in the ring network, which is represented by his probabilistic beliefs about others' behavior: let $\widehat{F}_j$ denote intermediary i's belief about j's price choice for $i, j \in q$, and $\widehat{F}_k$ denote i's belief about k's price choice for $k \in q'$. Given his beliefs about others' pricing behavior, the individual can compute expected payoffs for any price choice, p_i:

$$\widetilde{\Pi}_i\left(p_i|\left(q, q'\right)\right) = p_i \times \underset{\substack{j\in q, j\neq i \\ k \in q'}}{\int \cdots \int} \left\{ \begin{array}{c} \Pr\left(p_i + \sum_{j\in q, j\neq i} p_j < \sum_{k \in q'} p_k\right) p_i \\ + \Pr\left(p_i + \sum_{j \in q, j\neq i} p_j = \sum_{k\in q'} p_k\right)/2 \end{array} \right\} d\widehat{F}_j \cdots d\widehat{F}_k$$

Individual i chooses his price p_i to maximize associated expected payoffs, given his beliefs:

$$\max_{p_i \in \{0,1,2,\ldots,100\}} \widetilde{\Pi}_i\left(p_i|\left(q, q'\right)\right)$$

Second, in order to fit the model to the data, we extend the model of strategic uncertainty with probabilistic choice. We assume a conventional logistic function to model stochastic

[21] We have also tried to develop a stochastic equilibrium model such as Quantal response equilibrium (QRE) model, proposed by McKelvey and Palfrey (1995). We were unable to derive the QRE strategy due to the continuous action space and the asymmetry of multiple players in different network positions. Moreover, the numerical approach of solving equilibrium conditions is very demanding. This practical challenge leads us to adopt a non-equilibrium model of strategic uncertainty.

choice:

$$\Pr\left\{p_i = s|\left(q,q'\right)\right\} = \frac{\exp\left(\lambda\widetilde{\Pi}_i\left(s|\left(q,q'\right)\right)\right)}{\sum_{t=0}^{100}\exp\left(\lambda\widetilde{\Pi}_i\left(t|\left(q,q'\right)\right)\right)},$$

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 order to proceed further with the experimental data, we assume that each individual intermediary has rational beliefs about other players' behavior, consistent with empirical distributions of their price choices. For practical purposes, we assume that intermediaries on a given path employ a symmetric strategy.

We use the maximum likelihood estimation (MLE) method to estimate the payoff-sensitivity parameter in the model of strategic uncertainty with stochastic choice. Let the data consist of $\{p_j\}_{j=1}^n$ for all $j \in q$ and $\{p_k\}_{k=1}^m$ for all $k \in q'$. Using this data, we first construct empirical distributions of players on paths q and q', $\widehat{F}_j$ and $\widehat{F}_k$, respectively, for $j \in q$ and $k \in q'$, and then compute expected payoffs $\widetilde{\Pi}_i\left(p_i|\left(q,q'\right)\right)$ for intermediary $i \in q$. We can then choose λ to maximize the following log-likelihood function:

$$\mathcal{L}\left(\lambda; \{p_j\}_{j=1}^n, \{p_k\}_{k=1}^m\right) = \sum_{i=1}^n \left\{\sum_{t=0}^{100} 1\{p_i = t\} \times \log\left(\Pr\left\{p_i = t|\left(q,q'\right)\right\}\right)\right\}.$$

Table 8 presents the estimation results of this model with the samples of last 40 rounds and last 30 rounds, respectively, along with the best response level of price choice (without decision error) and the sample average price from the data, for comparison.[22]

- Table 8 here -

First, in all cases, estimated λs are strictly positive and significantly away from zero.[23] This confirms that the empirical distribution of price choice is consistent with the monotonic relation between choice probability and payoffs imposed by the model. In order to assess the goodness of fit of the model, we draw the cumulative distributions of observed prices

[22] In the distance case of $(2,8)$ in Ring 10, we eliminated one sample of price 100. Due to the small sample problem, the inclusion of this outlier price distorts the working of the model for both traders on two paths in this case.

[23] The value of λ depends on the scaling of payoffs. If payoffs are scaled down by a factor k, the value of λ is scaled up by the same factor. In this sense, the magnitude of λ value has little relevance in interpreting the results. Rather, the significance of λ from zero is more important in confirming the monotonic relation between price choices and payoffs.

and fitted prices in each case and compare how close these distributions are to each other (these figures are reported in Online Appendix II[24], in the interest of space). In most of the cases, the cumulative distributions of observed and fitted prices appear quite close to each other. Second, we calculate best-response prices (without decision error) against opponents' strategies. The best-response prices are quite close to average prices observed in the data. Furthermore, the model confirms that it is optimal to choose a low but positive price in each case of ring networks, given others' behavior. Therefore, we conclude that the model of strategic uncertainty with noisy response provides a fairly good account of the pricing behavior in ring networks.

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

Figure 1. Equilibria on a Ring Network

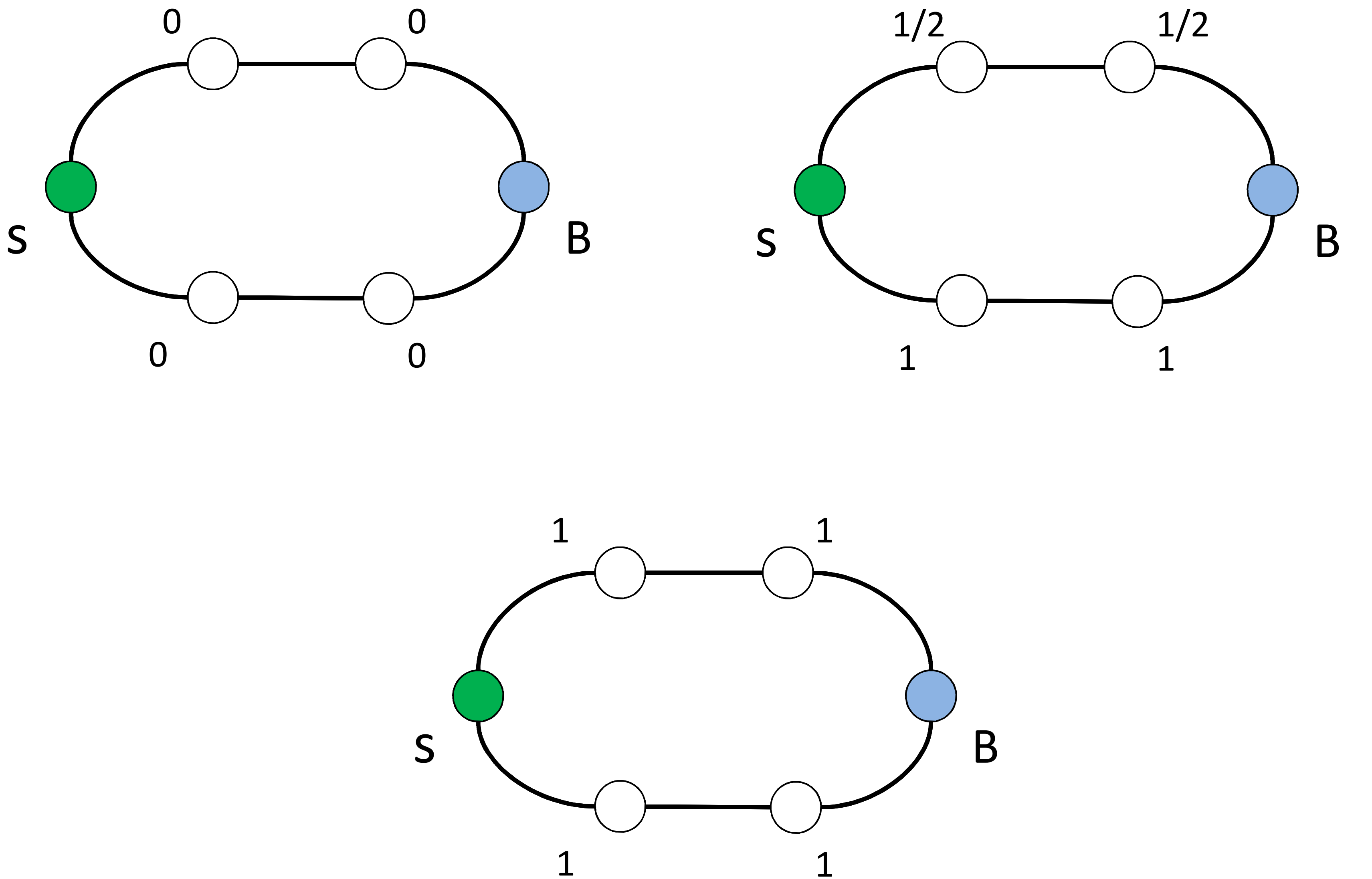


Figure 2. Trading Networks

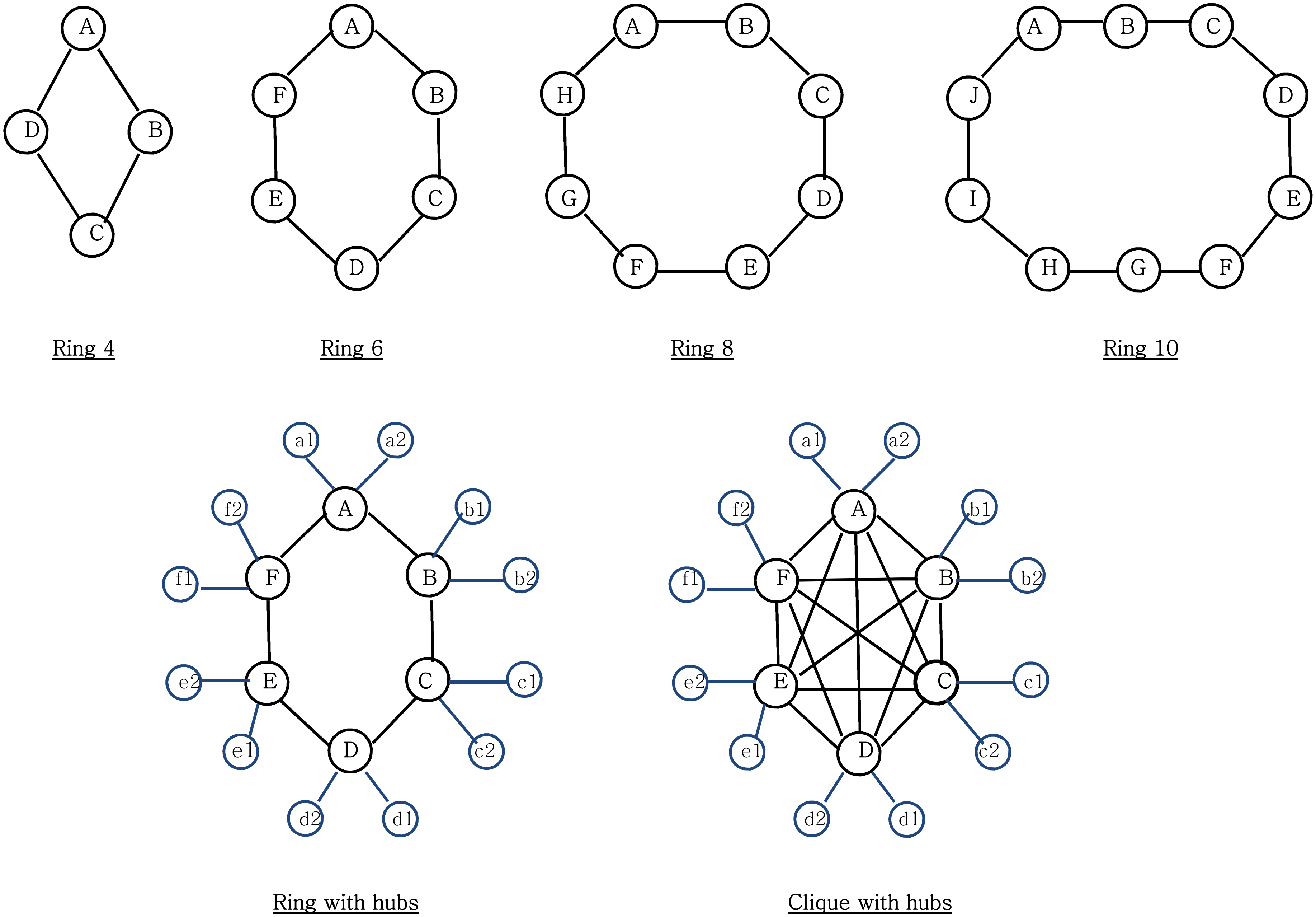


Figure 3. Intermediation Costs in Ring Networks

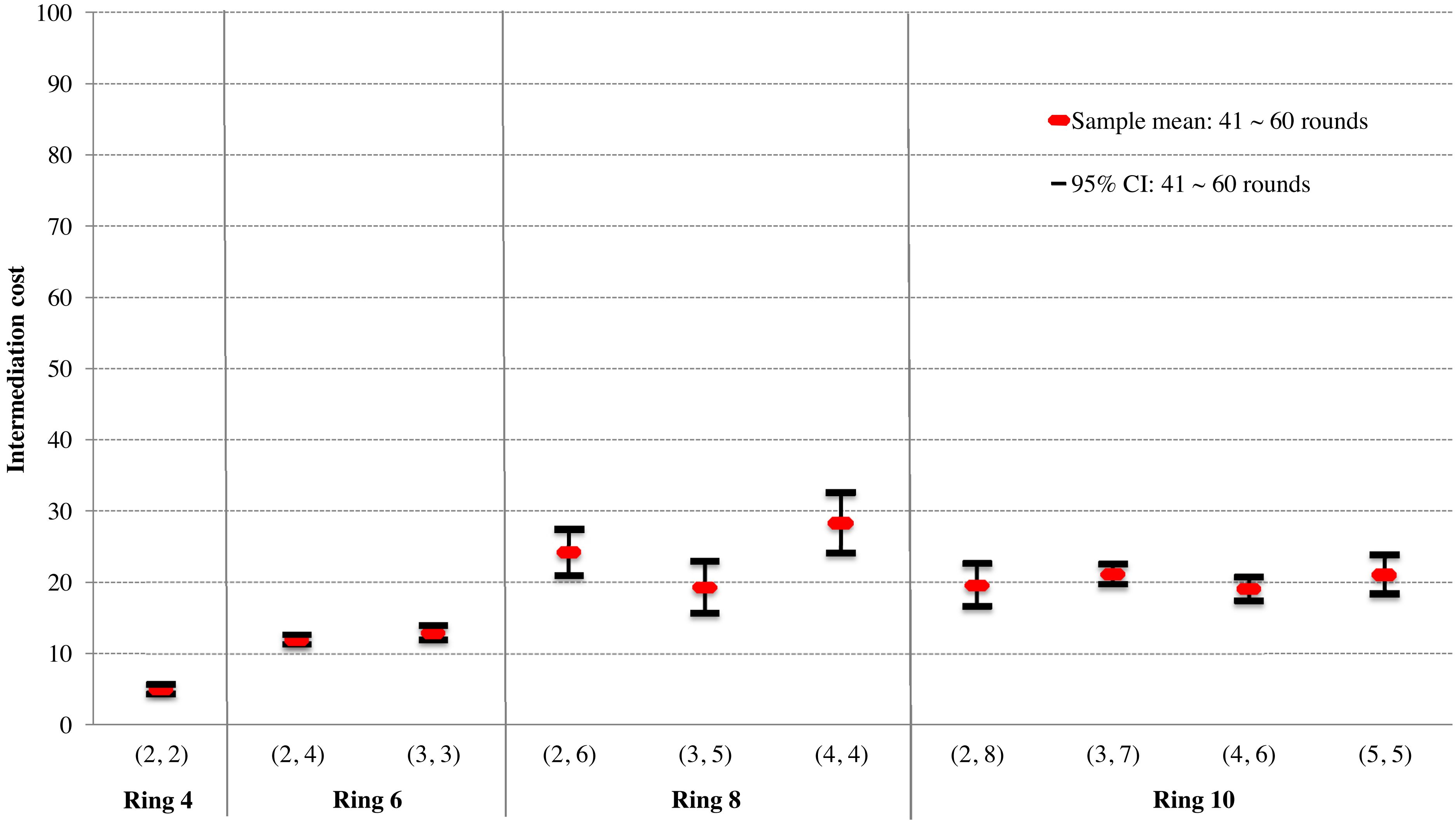
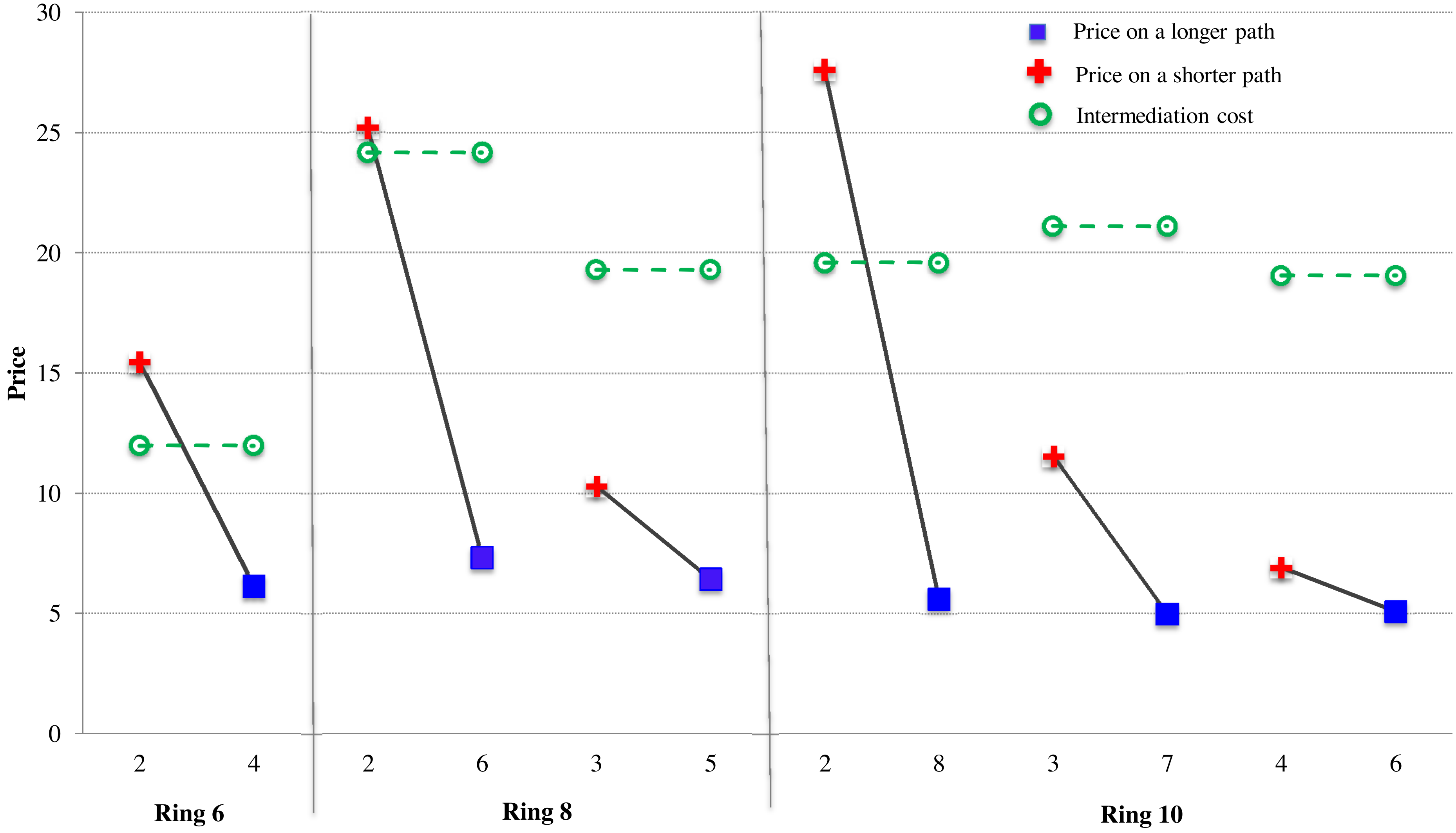


Figure 4. Average Prices across Distances: last 20 rounds



<u>Table 1. Frequency of Trading</u>

Network	minimum distance of buyer-sell pair				
	All ($\geq$ 2)	2	3	4	5
Ring 4	1.00 (480)	1.00 (480)	--	--	--
Ring 6	1.00 (420)	1.00 (289)	1.00 (131)	--	--
Ring 8	1.00 (360)	1.00 (128)	1.00 (143)	1.00 (89)	--
Ring 10	1.00 (240)	1.00 (49)	1.00 (87)	1.00 (69)	1.00 (35)
Ring with hubs	0.95 (420)	1.00 (126)	0.94 (155)	0.90 (109)	0.90 (30)
Clique with hubs	0.94 (360)	1.00 (171)	0.88 (189)	--	--

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

Table 2. Intermediation Costs in Ring Networks

Network	(d(q),d(q'))	Rounds					
		1 ~ 10	11 ~ 20	21 ~ 30	31 ~ 40	41 ~ 50	51 ~ 60
Ring 4	(2, 2)	19.76	12.77	7.80	6.04	4.81	5.36
		(80)	(80)	(80)	(80)	(80)	(80)
Ring 6	(2, 4)	41.77	24.62	18.44	14.08	11.96	12.01
		(52)	(49)	(50)	(44)	(44)	(50)
	(3, 3)	39.05	22.92	17.54	14.99	12.92	13.00
		(18)	(21)	(20)	(26)	(26)	(20)
Ring 8	(2, 6)	45.05	33.50	28.37	28.89	26.80	21.87
		(19)	(23)	(24)	(17)	(21)	(24)
	(3, 5)	46.92	35.27	31.68	27.05	20.11	18.28
		(30)	(21)	(25)	(29)	(21)	(17)
	(4, 4)	47.44	39.75	28.08	24.52	26.82	29.80
		(11)	(16)	(11)	(14)	(18)	(19)
Ring 10	(2, 8)	40.40	30.51	22.36	20.35	17.60	20.71
		(5)	(11)	(11)	(8)	(5)	(9)
	(3, 7)	41.85	29.66	26.44	22.20	20.11	22.09
		(17)	(14)	(15)	(13)	(14)	(14)
	(4, 6)	41.41	29.31	23.53	22.01	20.07	17.54
		(11)	(11)	(10)	(12)	(15)	(10)
	(5, 5)	43.32	30.73	24.44	20.76	24.54	18.20
		(7)	(4)	(4)	(7)	(6)	(7)

Note: The number in a cell is the sample average. The number of observations is reported in parentheses. d(q) denotes the distance of path q between b and s.

Table 3. Competition between Two Paths in Ring Networks

(absolute difference of costs & frequency of trading on a shorter route)

Network	(d(q), d(q'))	Rounds						
		1 ~ 10	11 ~ 20	21 ~ 30	31 ~ 40	41 ~ 50	51 ~ 60	All
Ring 4	(2, 2)	7.08	2.40	3.05	2.79	3.43	4.69	3.93
		--	--	--	--	--	--	--
Ring 6	(2, 4)	10.00	8.00	3.50	4.51	3.76	4.93	6.00
		(0.58)	(0.63)	(0.64)	(0.68)	(0.57)	(0.72)	(0.64)
	(3, 3)	12.50	8.98	4.00	3.00	4.01	4.51	4.81
		--	--	--	--	--	--	--
Ring 8	(2, 6)	7.99	8.13	6.58	4.02	5.12	3.62	6.71
		(0.53)	(0.48)	(0.67)	(0.53)	(0.67)	(0.71)	(0.60)
	(3, 5)	8.99	4.00	3.75	5.05	4.05	2.26	5.00
		(0.57)	(0.67)	(0.64)	(0.55)	(0.57)	(0.65)	(0.60)
	(4, 4)	8.09	3.90	6.30	3.13	3.53	8.00	6.00
		--	--	--	--	--	--	--
Ring 10	(2, 8)	6.00	7.00	7.55	4.16	13.29	17.36	7.00
		(0.80)	(0.82)	(0.73)	(0.75)	(0.40)	(0.78)	(0.73)
	(3, 7)	9.00	5.17	3.66	4.01	4.88	9.50	5.00
		(0.59)	(0.79)	(0.53)	(0.54)	(0.71)	(0.64)	(0.63)
	(4, 6)	10.50	7.81	7.72	2.76	6.61	8.94	7.69
		(0.27)	(0.64)	(0.40)	(0.42)	(0.60)	(0.80)	(0.52)
	(5, 5)	15.72	12.74	8.15	4.99	3.01	8.02	7.21
		--	--	--	--	--	--	--

Note: The number in a cell is the sample median of differences of intermediation costs of two paths. The number in parentheses is the frequency of trading on a shorter path of intermediation. d(q) denotes the distance of path q between b and s.

Table 4. Intermediation Costs in Ring with Hubs and Clique with Hubs
(conditional on trading)

Network	(#Cr,#Paths, d(q),d(q'))	Rounds					
		1 ~ 10	11 ~ 20	21 ~ 30	31 ~ 40	41 ~ 50	51 ~ 60
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)
Clique with hubs	(1, 1, 2, --)	78.07	81.59	89.21	80.78	86.92	89.30
		(28)	(29)	(27)	(27)	(33)	(27)
	(2, 1, 3, --)	84.08	91.52	90.04	93.88	94.73	97.93
		(25)	(25)	(30)	(32)	(26)	(29)

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 5. Pricing Behavior in Ring Networks

Network	(d(q),d(q'))	Distance of own path	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 8	(2, 6)	2	50.16	37.61	30.25	30.05	28.50	22.37
			(19)	(23)	(24)	(17)	(21)	(24)
		6	10.55	8.99	7.15	7.19	7.56	7.33
			(95)	(115)	(120)	(85)	(105)	(120)
	(3, 5)	3	25.00	18.01	16.85	14.62	10.64	9.86
			(60)	(42)	(50)	(58)	(42)	(34)
		5	14.11	9.81	9.09	9.13	7.32	6.43
			(120)	(84)	(100)	(116)	(84)	(68)
	(4, 4)	4	17.70	14.37	11.06	9.54	10.65	11.40
			(66)	(96)	(66)	(84)	(108)	(114)
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)

Note: The number in a cell is the sample average. The number of observations is reported in parentheses. d(q) is the distance of path q between b and s.

Table 6. Pricing Behavior of Critical and Non-critical Intermediaries in Ring and Clique with Hubs

Network	(#Cr,#Paths, d(q),d(q'))	Type of Intermediary	Rounds 1 ~ 10	11 ~ 20	21 ~ 30	31 ~ 40	41 ~ 50	51 ~ 60
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)
		Non Critical in shortest path	36.67	40.36	33.59	32.09	26.31	24.62
			(12)	(11)	(11)	(15)	(13)	(13)
		Non Critical in longest path	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)
		Non Critical in shortest path	29.98	27.78	23.07	24.58	20.46	17.46
			(10)	(11)	(10)	(12)	(13)	(13)
		Non Critical in longest path	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)
Clique with hubs	(2, 1, 3, --)	Critical	46.08	48.92	46.46	47.11	47.76	50.82
			(64)	(62)	(66)	(66)	(54)	(66)

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 7. Fraction of Intermediation Costs by Critial Intermediaries in Ring with Hubs

(conditional on trading)

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

Note: 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 8. Model of Strategic Uncertainty: Optimality and Estimation

Network	(d(q),d(q'))	Distance of own path	Data: 21 ~ 60 rounds: BR / Sample mean (# of obs)	Data: 21 ~ 60 rounds: λ (std. err.) / Likelihood value	Data: 31 ~ 60 rounds: BR / Sample mean (# of obs)	Data: 31 ~ 60 rounds: λ (std. err.) / Likelihood value
Ring 4	(2, 2)	2	6	1.25 (0.09)	6	1.668 (0.245)
			9.58 (640)	-2198.57	9.65 (480)	-1225.6
Ring 6	(2, 4)	2	13	0.441 (0.03)	11	0.539 (0.027)
			16.81 (188)	-624.06	15.59 (138)	-427.17
		4	7	3.166 (0.075)	5	5.932 (0.137)
			6.55 (564)	-1633.8	6.21 (414)	-1117.7
	(3, 3)	3	7	1.42 (0.005)	7	1.504 (0.002)
			8.49 (368)	-951.1	8.07 (288)	-731.29
Ring 8	(2, 6)	2	24	0.146 (0.001)	24	0.154 (0.027)
			27.58 (86)	-358.31	26.55 (62)	-259.61
		6	12	1.024 (0.01)	12	1.012 (0.028)
			7.35 (430)	-1652.7	7.41 (310)	-1214.2
	(3, 5)	3	15	0.599 (0.085)	15	0.620 (0.008)
			13.48 (184)	-671.41	12.21 (134)	-510.06
		5	10	1.256 (0.005)	10	1.333 (0.057)
			8.23 (368)	-1297.8	7.9 (268)	-964.56
	(4, 4)	4	14	0.784 (0.002)	14	0.749 (0.072)
			10.73 (372)	-1362.6	10.64 (306)	-1142.4
Ring 10	(2, 8)	2	20	0.352 (0.045)	18	0.443 (0.061)
			22.72 (32)	-121.1	21.67 (21)	-87.67
		8	7	2.678 (0.006)	6	3.016 (0.211)
			5.38 (231)	-816.6	5.83 (154)	-540.44
	(3, 7)	3	12	1.072 (0.071)	12	1.101 (0.243)
			12.44 (112)	-307.5	11.79 (82)	-224.29
		7	6	2.769 (0.078)	6	2.982 (0.038)
			5.09 (336)	-958.94	4.91 (246)	-728.63
	(4, 6)	4	9	1.165 (0.095)	9	1.132 (0.030)
			7.79 (141)	-379.57	7.45 (111)	-301.76
		6	6	3.990 (0.237)	5	4.635 (0.049)
			5.13 (235)	-560.6	5.02 (185)	-423.16
	(5, 5)	5	8	1.646 (0.037)	8	1.654 (0.100)
			6.35 (192)	-555.88	6.18 (160)	-464.29

Note: BR respresents an optimal price in the model of strategic uncertainty with no decision error. The second column in each data reports an estimated value of λ, its standard error, and the log-likelihood value at the optimum.