Trading in Networks: Theory and Experiment

Syngjoo Choi [*] Andrea Galeotti [†] Sanjeev Goyal [‡]

April 1, 2013

Abstract

Intermediation is a prominent feature of economic 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 simple model to study these forces and we test the theoretical predictions in experiments.

Our theoretical analysis yields a complete characterization of pricing equilibrium in networks. There exist both efficient and inefficient equilibria, suggesting a key role of coordination among intermediaries. Strategic interaction leads to either buyer and seller retaining all surplus or intermediaries extracting all surplus. We develop conditions on network structure under which these different extremal outcomes arise, respectively.

Laboratory experiments show that efficiency prevails in almost all cases: so traders are successful in coordination. Subjects coordinate on extreme surplus division. Finally, experiments highlight the role of network structure in determining pricing and the division of surplus among intermediaries.

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

Keywords: Intermediation, market power, competition, coordination.

[*]Department of Economics, University College London. Email: syngjoo.choi@ucl.co.uk

[†]Department of Economic, University of Essex. Email: agaleo@essex.ac.uk

[‡]Faculty of Economics and Christ's College, University of Cambridge. Email: sg472@cam.ac.uk

We thank Gary Charness, Matt Elliott, Marcel Fafchamps, Jacob Goeree, Francesco Nava, Volcker Nocke, Hamid Sabourian, Xiaojian Zhao, and seminar participants at Université Autonoma de Barcelona, CIRANO 2012 Conference (Montreal), Networks Conference in Cambridge, Essex, HKUST, Vienna and Zurich for helpful comments.

1 Introduction

Intermediation is a prominent feature of economic production and exchange. In their survey of international trade, 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 intermediation sector constitutes about one fourth of the US economy. In markets for agricultural goods in developing countries local producers access only a limited number of intermediaries and products are exchanged between intermediaries en route from local producers to end users, e.g., Fafchamps and Minten (1999). Intermediation is also a defining feature of financial markets, channelling funds from ultimate lenders to ultimate borrowers. Interconnection among financial intermediaries has been a central issue in understanding financial contagion and the fragility of financial markets, e.g., Allen and Gale (2000).

Two features of intermediated exchange appear to be salient. There are multiple intermediaries between the 'source' and the 'destination'. So different intermediaries need to coordinate their actions to ensure that exchange does take place. The second feature is *market power*: there may exist multiple paths between source and destination and some intermediaries may lie on more (or all) paths as compared to others.[1] Our aim in this paper is to understand how coordination and competition among intermediaries affect the efficiency of exchange and the division of surplus among the traders. We address these questions through a combination of theory and experiments.

We consider a setting with many traders, some of whom can interact directly with each other, but others can only undertake exchange via other traders. The restrictions on who can trade with whom may arise from physical location, moral hazard, search costs, or monitoring costs. We take these restrictions as exogenous and model them in terms of the structure of a network among traders. A trader is synonymous with a node. 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. We allow for all possible networks, subject to the caveat that there exists at least one path between every pair of traders.

At the start, a buyer and seller is announced and the surplus of the exchange is normalized to 1. All traders other than buyer and seller are intermediaries and each posts an intermediation price. The buyer and seller compare the sum of prices on every path between them and

[1] Consider bread: grain moves to a mill and then to a bakery before arriving at the breakfast table. There are several mills and bakeries so the grain can travel along one out of many competing paths. Similarly, most communication networks transmit information from a source to a destination through multiple interconnected service providers.

pick the cheapest one, provided that it does not exceed the surplus of exchange. If a trader lies on the path picked she earns the price posted; if she does not lie on the path, she earns 0. We study the Nash equilibrium of this game.

An equilibrium is said to be efficient if trade occurs with probability 1. Theorem 1 establishes existence of efficient equilibrium, for all networks and for all possible buyer-seller pairs. The proof is constructive and exploits the notion of *critical* intermediaries. An intermediary is critical for buyer b and seller s in a network if she lies on all paths between them. Observe that, if there is no critical intermediary, then there is an equilibrium in which all traders set price 0. A deviation to a positive price by an intermediary leads b and s to circumvent that trader and use an alternative path. As no intermediary is critical, such a path always exists. If, on the other hand, one or more intermediaries are critical, then consider a profile in which critical intermediaries set positive prices which sum to the surplus of exchange, and all non-critical traders set price 0. In this case, if a critical intermediary charges a higher price the total intermediation costs will exceed the total value of exchange causing a breakdown of exchange. If the intermediary lowers the price exchange will still occur, but the intermediary's profits are lower. Non-critical intermediaries cannot increase profits by charging a positive price as b and s can circumvent them.

We then investigate the possibility of inefficient equilibrium and study the division of surplus between different traders. Theorem 2 provides a complete characterization of equilibrium. In particular, it proves that equilibrium intermediation costs are either in excess of 1 (in which case no exchange occurs and the outcome is inefficient), or they take on value 1 or 0. So in every efficient equilibrium either intermediaries extract all surplus or buyer and seller get to keep the entire surplus.

This characterization of equilibrium highlights the importance of network structure as well as strategic consideration in shaping competition and market power. In particular, our theory identifies *essentiality* as a key property of giving rise to market power and thus making full surplus extraction possible in equilibrium. An intermediary is essential between a buyer and a seller under a profile of prices if that intermediary belongs to every least cost path through which trade can take place. This concept relies not only on structural properties of network but also on strategies chosen by intermediaries. Coordination among traders is key in understanding such strategic consideration.

The following example illustrates the key role of coordination among intermediaries. To see this, consider a ring network with 6 traders and suppose that buyer and seller are 3 links apart. The three types of equilibrium identified in Theorem 2 all exist in this ring network.

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, while the intermediaries along the other path set price 1/2 each. Figure 1 illustrates these outcomes. This example motivates a closer examination of the relation between network structure and the nature of equilibrium. Are there networks for which we can rule out inefficient equilibrium? What are the properties of networks that shape the division of surplus between buyer and seller, on the one hand, and the intermediaries, on the other hand?

- Figure 1 here -

Proposition 1 addresses these questions. It shows that an inefficient equilibrium exists if, and only if, for every path between the buyer and seller the distance is greater than 2. It also shows that, in an efficient equilibrium, if one or more intermediaries are critical then intermediaries extract all surplus. If, on the other hand, there are at least two distinct paths each containing a single intermediary then buyer and seller retain the entire surplus.

To summarize, our theoretical analysis brings out three points. One, coordination among intermediaries is key to the efficiency of exchange. Two, 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. Three, if buyer and seller undertake exchange in the presence of critical traders then intermediaries extract the entire surplus.

While theory provides strong predictions, there are questions that theory alone cannot answer, mainly due to the multiplicity of equilibrium. How likely is it that we observe efficient outcomes? When trade takes place, are trading outcomes indeed extremal? How does the presence of critical traders shape the division of surplus between traders, buyer and seller and critical and non-critical intermediaries? We use a laboratory experiment to address these issues.

Our experiment consists of six 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 subjects. In each ring network, there are always two competing paths connecting buyer and seller and no intermediary is critical. Ring 4 represents a classic duopoly Bertrand competition model: two intermediaries sitting on opposite sides compete for trade one-to-one. As we increase ring size n, we keep the number of paths and thus the level of competition constant, but the number of intermediaries along a given path grows. This intuitively makes the problem of coordination among intermediaries harder, although the equilibrium analysis is silent on this. In this sense, this part of the design intends to put coordination among intermediaries to the test.

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 Clique with hubs, there is only one path between any pair of buyer and a seller. On the other hand, the Ring with hubs generates a variety of trading situations; in some both critical and non-critical traders co-exist while in others, either only critical traders or only non-critical traders are involved in trading. Thus, Clique with hubs is an exemplar of a network of pure market power while the Ring with hubs creates the space for both market power and competition to come into play.

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, quite high as well. Thus, we conclude that subjects are remarkably successful in coordinating price choices 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. In Ring with hubs and Clique with hubs, if trading is mediated via critical intermediaries, then intermediation costs are very large, between 80% and 100% of the total surplus. If no critical intermediary is involved in exchange, the costs are close to the low-cost outcome in ring networks. Finally, we investigate subjects' pricing behavior to understand further the division of surplus among traders. In ring networks, average prices are positive but quite low; intermediaries on a longer path charge lower prices than those on a shorter path. This results in tight competition between two paths and exchange takes the longer route in roughly one third of the cases! In Rings with Hubs and Clique with hubs, critical intermediaries charge higher prices than non-critical intermediaries leading to unequal division of surplus between the two. If there are multiple critical traders then they charge similar prices.

Our paper is a contribution to the study of trading in networks. Trading in networks is a very active field of research; prominent early contributions include e.g., Kranton and Minehart (2001), Corominas-Bosch (2004) 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).[2] The distinctive element in our work is the trading protocol: we study posted prices.

Thus 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), Blume et al. (2007) and Gale and Kariv (2007). 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.[3]

Our experimental findings contribute to a number of major strands of work. 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 Charness and Rabin (2002) and Gale and Kariv (2007), among others. Our finding on the decisive role of market power in shaping division of surplus, is to the best of our knowledge, novel. 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 sharp contrast to the work on dictator games. For an overview of these experiments, see Engel (2011). 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).[4] Finally, our finding on the division of surplus between critical and non-critical intermediaries appear to be novel.

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,

[2]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.

[3]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 (2007) 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.

[4]We refer to Roth (1995) for a review of experimental studies of bargaining and negotiations.

motivated by theory. Section 4 summarizes experimental findings and Section 5 concludes.

2 Theory

2.1 Model

There are $\mathcal{N} = \{1, ..., n\}$, $n \geq 3$, traders 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 $\mathbf{g}$.

At the start, *one* pair of traders is chosen at random to be buyer (b) and seller (s). We refer to traders other than buyer and seller as intermediaries. 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 $i \in \mathcal{N} \setminus \{b, s\}$ posts an 'intermediation price' $p_i \geq 0$. Intermediaries post prices simultaneously. Let $\mathbf{p}$ denote the intermediation price profile.

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 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 $d(s, b|q)$. 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 $\mathcal{Q}^* = \{q \in \mathcal{Q} : c(q, \mathbf{p}) = c^*(\mathbf{p})\}$.

Under intermediation prices $\mathbf{p}$, an exchange between buyer and seller (b, s) occurs in network $\mathbf{g}$ either when $g_{sb} = 1$ or when $g_{sb} = 0$ 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 $i \in \mathcal{N} \setminus \{b, s\}$ is therefore

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

where η_i is the number of paths in $\mathcal{Q}^*$ that contain trader i.[5]

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 $i \in \mathcal{N} \setminus \{s, b\}$. We focus on pure strategy equilibrium. An equilibrium in which (b, s) do not undertake exchange is called *inefficient*. An equilibrium with exchange realizes the full surplus and is *efficient*.

Our framework permits a simple formulation of structural market power. An intermediary i is *critical* vis-a-vis a pair of buyer and seller (b, s) in network $\mathbf{g}$ if intermediary i lies on every path between (b, s) in network $\mathbf{g}$. Define $\mathcal{C} = \{i \in N : i \in q, \forall q \in \mathcal{Q}\}$ as the set of critical traders. We will use the term leaf to denote a node in a network that has a single link.

Remark: The aggregate surplus obtained by buyer and seller is 0 if exchange does not occur and $1 - c^*(\mathbf{p})$ if exchange occurs. Clearly, our theoretical results do not require any assumption of how this surplus is shared between buyer and seller. When we implement our experiment, we will impose that buyer and seller split equally their aggregate surplus.

2.2 Results

Our first result establishes existence of an efficient equilibrium for arbitrary networks and any pair of buyer and seller.

Theorem 1 *For every network* $\mathbf{g}$ *and every pair of buyer and seller* (b, s) *there exists an efficient equilibrium.*

Proof of Theorem 1. Exchange occurs if $g_{bs} = 1$; so consider that $g_{bs} = 0$. Suppose that $|\mathcal{Q}| = 1$; consider $\mathbf{p}^*$ such that $c(q, \mathbf{p}^*) = 1$, for $q \in \mathcal{Q}$. No intermediary on the unique path q can hope to increase payoffs by raising his price as this will render exchange infeasible. Lowering price keeps the probability of exchange unchanged at 1, but yields lower payoff upon exchange. Next, suppose that $|\mathcal{Q}| > 1$. If the set of critical traders is empty, $\mathcal{C} = \emptyset$, define a

[5] Throughout, we omit mentioning network $\mathbf{g}$ and pair of buyer and seller, for expositional simplicity. See remark 1 for a clarification of the expected payoffs to buyer and seller.

price profile $\mathbf{p}^*$ such that $p_i^* = 0$ for all $i \in \mathcal{N} \setminus \{b, s\}$. Note that no intermediary can earn positive profits by deviating and setting a positive price. This is because, 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. Finally, if $\mathcal{C} \neq \emptyset$, then define 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. ■

We have established that, irrespective of the size and complexity 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 the first question. 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 $\mathbf{p}$.[6] Given a network $\mathbf{g}$, a pair (b, s), and a price profile $\mathbf{p}$, for a path $q \in \mathcal{Q}$ 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)*, in an equilibrium,* p^**, the intermediation cost* $c^*(\mathbf{p}^*) = 0$*,* $c^*(\mathbf{p}^*) = 1$ *or* $c^*(\mathbf{p}^*) > 1$*. Moreover,*

1. $c^*(\mathbf{p}^*) = 0$ *is an equilibrium if, and only if, no intermediary is essential under* $\mathbf{p}^*$*.*

2. $c^*(\mathbf{p}^*) = 1$ *is an equilibrium 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. $c^*(\mathbf{p}^*) > 1$ *is an equilibrium if and only if* $c_{-j}(q, \mathbf{p}^*) \geq 1$ *for every intermediary* $j \in q$ *and* $q \in \mathcal{Q}$*.*

[6] Essentiality is 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.

The proof of Theorem 2 is presented in Appendix I. Here we sketch the intuition for the result and provide economic interpretations of the result.

We first argue that $c^*(\mathbf{p}^*) \in (0,1)$ cannot be an equilibrium. Suppose otherwise. Consider a trader on a least cost path who charges a strictly positive price. If he is essential, he can raise price slightly, maintain trade (as the sum of prices remains below 1) and strictly raise profits. If he is not essential, it means that there is another least cost path to which he does not belong and that the probability that he is used in exchange is at most 1/2. Lowering his price slightly will then make the trade occur through him with probability 1. Thus, this deviation is strictly profitable. Hence, any equilibrium price profile p^*, must have $c^*(p^*) = 0, 1$ or greater than 1.

Now consider part 1 of theorem, price p^* equilibrium with $c^*(\mathbf{p}^*) = 0$. First consider sufficiency. Fix a trader. As he is not essential under $\mathbf{p}^*$, there is a competing path at cost 0, excluding this trader. So there is no profitable deviation for him. Next consider necessity: if there is an essential trader under $\mathbf{p}^*$, he can raise his price slightly while guaranteeing that exchange takes place through him. Thus there exists a profitable deviation. Hence, $c^*(\mathbf{p}^*) = 0$ cannot be an equilibrium, if there is an essential trader.

Next consider equilibrium p^* with $c^*(\mathbf{p}^*) = 1$. In such an equilibrium, every trader i on a least cost path ($i \in q$, $q \in \mathcal{Q}^*$) that charges a strictly positive price is essential, and every trader j on a non-least cost path is unable to find a profitable deviation, because the other traders on the same path mis-coordinate by charging too high prices ($c_{-j}(q, \mathbf{p}^*) \geq 1$). The role of essentiality for positive price traders follows from the proof of part 1 above. The proof is completed by noting that if there is a trader j on a non-least cost path q with $c_{-j}(q, \mathbf{p}^*) < 1$, he can always find a positive price that would make him an essential player and thus yield him a positive payoff.

Part 3 of the theorem highlights the role of coordination failure among intermediaries on all paths is a creating a breakdown of trade.

This characterization yields a number of insights. The *first* insight 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. When intermediaries become essential under a network and a profile of prices then they exercise market power collectively to extract full surplus. When no intermediary is essential then competition drives down the cost to zero. The *second* insight pertains to the key role of coordination among intermediaries. In order to highlight these insights, 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.[7]

Within the class of efficient equilibrium, we have identified the key role of essentiality in determining the surplus division among traders. Since essentiality involves structural as well as strategic considerations, we 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* $\mathbf{g}$ *and every pair of buyer and seller* (b, s)*, 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, i.e.,* $c^*(\mathbf{p}^*) = 1$ *if* $c^*(\mathbf{p}^*) \leq 1$.

   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, i.e.,* $c^*(\mathbf{p}^*) = 0$.

[7] 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.

Proof: 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. ■

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. It shows that if one or more intermediaries lie on all paths connecting buyer and seller, then the intermediaries must extract all surplus in every efficient equilibrium. By contrast, 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. If buyer and seller exchange via intermediaries who have market power then the intermediaries extract all surplus.

3 From Theory to Experiment

3.1 Design

Our theory predicts that coordination among traders is key in efficiency and that the division of surplus is extremal because (lack of) market power pushes intermediation costs up to the value of exchange (down to zero). It also identifies essentiality as a key (both network-structural and strategic) property of giving rise to market power and thus making full surplus extraction possible in equilibrium. In order to investigate empirical validity of the theory, we utilize a laboratory experiment with a variety of trading networks. The design of the experiment centers around the variations of two distinct forces relating to essentiality: (i) the extent of coordination problem among intermediaries in the absence of critical traders; and (ii) the presence of critical trader. 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 achieved by the introduction of Clique with hubs and Ring with hubs. As illustrated below, the selection of networks is made carefully to address the effects of coordination and market power on trading.

- Figure 2 here -

Coordination. We first take up the issue of coordination by focusing on the class of ring networks in which the number of trading paths is fixed to be 2 – ring networks with $n = 4, 6, 8$ and 10. 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 in which coordination among traders on a path, in the face of competition from the other path, is key to sharing trading surplus. 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 ring networks 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.[8] By comparing such 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

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

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 $n \geq 6$, traders on a longer path need to coordinate in order to win over a single trader on the other shorter path. The larger the distance of a longer path is the bigger the challenge of resolving coordination problems among traders.

Market power. Our second interest is in examining the effects of market power on efficiency and surplus division. For this purpose, we compare three networks in the design – Ring 6, Ring with hubs, and Clique with hubs, as shown in Figure 2. Ring 6 is a case of competition with no market power because none of traders is critical. On the contrary, Clique with hubs is a case of market power with no competition because there is essentially a unique path for any pair of buyer and seller and thus every trader on that path is critical. If there exists only one critical trader in Clique with hubs, it is the problem of pure monopoly. When there are two critical traders on the unique path, the game just amounts to a standard symmetric Nash demand game between the two traders. Thus, Clique with hubs represents a quintessential case of pure market power. On the other hand, Ring with hubs represents an intriguing mixture of both market power and competition. 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). However, since traders A and E lie on both paths, that is, they are critical, they are in a position of exerting market power. The other traders (B, C, D, and F) lie only on one of the paths and thus are not critical. Strategic tension of critical and non-critical traders may have important consequences in pricing behavior and surplus division.

To put these experimental variations in perspective, we summarize the equilibrium analysis of these selected networks. First, let us consider efficiency. An inefficient equilibrium exists if, and only if, the distance of every path between buyer and seller is strictly higher than 2 (Proposition 1). In the class of ring networks, it is the case only in Ring $n \geq 6$ where the minimum distance between buyer and seller is larger than 2. In the market-power design, it is the case if there are at least two intermediaries on each path, regardless of criticality. 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 composition of critical and non-critical traders)?*

We now turn 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 trade takes place the presence of a critical trader then implies that there is 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?*

Our third question relates to the role of distance between buyer and seller in network on pricing and the division of surplus. We expect that longer distance between buyer and seller implies greater strategic uncertainty for traders. Nash equilibrium analysis provides little guidance on this issue: the rings of size 6,8 and 10, all exhibit the same equilibrium patterns. These observations underlie the following general question:

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

Finally, we are interested in examining the division of surplus among intermediaries, especially between critical and non-critical traders. Theory says that if trade occurs and there is a critical trader then intermediaries extract full surplus. However, theory does not pin down the division of surplus among the intermediaries. What role does criticality play in dividing trade surplus? Moreover, how do multiple critical traders divide surplus? These concerns motivate our final question:

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.[9]

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.

[9] 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 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.[10] 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, the focus of our interest lies in the impact of coordination (across ring networks of different size) and market power (across composition of critical and non-critical traders) on efficiency. Theory tells us that there always exists an efficient equilibrium; but in all networks in the experiment, except for Ring 4, there also exist an inefficient equilibrium. 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 -

[10] 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.

Strikingly, 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 where the buyer and seller need to use four intermediaries to transact, and despite this trade occurs all the time. In Ring with hubs and Clique with hubs, the frequency of trade is also very 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 a shorter 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 potential complexity of pricing decision due to the problem of coordination among traders along the same path and competition between paths, traders across all treatments are remarkably successful in coordinating on prices that ensure trade.

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. Theory predicts that if trade occurs, intermediaries get either nothing or extract full surplus. The presence of a critical trader ensures full surplus extraction by intermediaries. However, in ring networks where there is no critical trader, both outcomes of intermediation costs can be sustained in equilibrium. Note that the cost of intermediation represents the aggregate payoffs obtained by intermediaries, while the residual surplus, the value of exchange minus the cost, is the aggregate payoff to buyer and seller. Hence, the description of intermediation costs indicates the division of surplus between intermediaries, on one side, and a pair of buyer and seller, on the other side.

We start by examining the impacts of coordination on intermediation costs in the class of ring networks.

Ring networks. Table 2 reports average intermediation costs across distinct situations of trading across ring networks. Because there are always two competing paths between buyer and seller, we distinguish trading situations with respect to distances of two 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 appear to be 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 later.

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 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 $(d(q), d(q'))$. In Clique with hubs where there always exists (essentially) a single path between buyer and seller, the number of critical intermediaries on a (unique) path is either 1 or 2. Ring with hubs contains many distinct cases of trading, encompassing those in Clique with hubs as well as those in Ring 6 with no critical intermediary. It is also possible to have one or two critical intermediaries and two competing paths in this network. 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. We note that 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.[11]

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 more 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 intermediary dramatically affects trading. This is qualitatively consistent with the key role of criticality on division of surplus as theory predicts, although the data departs quantitatively from the equilibrium prediction of full surplus extraction.

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 very 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

In the previous section we have found that intermediation costs are low in all ring networks and vary across sizes of ring network, and that the presence of critical intermediaries makes most of the surplus go to intermediaries. This motivates a closer examination of individual pricing behavior here. 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

[11] 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.

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 a 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 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. Instead of developing an equilibrium model with strategic uncertainty, we employ a tractable and parsimonious model of noisy behavior.[12] 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. Let $\widetilde{\Pi}_i\left(p|\left(q,q'\right)\right)$ denote individual i's expected payoff of choosing a price p, against opponents' strategies, for $i \in q$. Individual i's pricing behavior is assumed to follow the logistic function:

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

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. We then proceed to estimate, using maximum likelihood estimation, the model of strategic uncertainty with noisy best response in each distinct case of trading in ring networks. Details of the model and the estimation method are provided in Appendix 2.

Table 6 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.[13]

- *Table 6 here* -

First, in all cases, estimated λs are strictly positive and significantly away from zero.[14] This confirms that the empirical distribution of price choice is consistent with the monotonic

[12] 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.

[13] 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.

[14] 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

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 and fitted prices in each case and compare how close these distributions are to each other (these figures are reported in Online Appendix II[15], 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.

Ring with hubs and Clique with hubs. As theory predicts, the presence of critical intermediary has a powerful impact on the division of surplus between a pair of buyer and seller, on the one side, and intermediaries, on the other side. We now turn to the question of surplus division among intermediaries, by examining their pricing behaviors. Table 7 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 7 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 of equal division between two critical intermediary is consistent with the findings in the experimental literature of Nash bargaining (e.g., Roth and Murnighan (1982) and Fischer et al (2006)).

the results. Rather, the significance of λ from zero is more important in confirming the monotonic relation between price choices and payoffs.

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

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 exploit their market power inherent in their network location and 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, $(1, 2, 3, 5)$, 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 8 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 8 provide clear evidence that 'critical' network location generates large payoff advantages.

- Table 8 here -

We finally remark that there are very few observations on the cases where both buyer and sellers are on the ring in Ring with hubs, that is, where 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.

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 traders set similar prices.*

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 longer 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

Intermediation is a prominent feature of economic 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). How does coordination and competition among intermediaries affect the efficiency of exchange and the division of surplus among the traders? We address these questions through a combination of theory and experiments.

We provide a complete characterization of equilibrium. This characterization allows us to make three general points. One, there exist multiple equilibria exhibiting zero to full efficiency: so coordination among intermediaries is key to the efficiency of exchange. Two, 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. Three, if buyer and seller undertake exchange in the presence of critical traders then intermediaries extract the entire surplus.

Laboratory experiments show that efficiency prevails in almost all cases: so traders coordinate successfully. The division of surplus does take on extremal values; in the absence (presence) of critical intermediaries the seller and buyer retain (give up) most of the surplus. These findings are in line with the theoretical predictions.

Finally, our experiment sheds light on questions relating to division of surplus among intermediaries. We find that network structure determines this division: most of the surplus goes to critical intermediaries very little goes to non-critical intermediaries. Second, in networks with no critical intermediaries (as in a ring), pricing behavior of subjects responds in subtle ways to accommodate the path length of competing paths: intermediaries on shorter paths consequently set higher prices and earn more than their counterparts on longer paths.

In the model studied, traders have complete information on location of buyer and seller and the size of the surplus before they set prices. In on-going companion work, we explore the implications of incomplete information–with regard to location of buyer and seller and with regard to value of surplus– for intermediary behavior and trading outcomes.

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] Allen, F. and D. Gale (2000), Financial Contagion, *Journal of Political Economy*, 108, 1, 1-33.

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

[5] 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.

[6] Charness, G., and M. Rabin (2002) Understanding Social Preferences with Simple Tests, *Quarterly Journal of Economics*, 117, 817-869.

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

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

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

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

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

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

[13] Gale, D., and S. Kariv (2009), Trading in Networks: A Normal Form Game Experiment. *American Economic Journal: Microeconomics.*

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

[15] Inderst, R. and M.Ottaviani (2012), Competition through Commissions and Kickbacks, *American Economic Review*, 102 (2), 780-809.

[16] Judd, S., and M. Kearns (2008), Behavioral Experiments in Networked Trade, *EC 2008*.

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

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

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

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

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

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

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

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

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

Appendix I. Proof of Theorem 2

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.

■

Appendix II. A Model of Strategic Uncertainty with Stochastic Choice

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:

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

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 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:

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

Table 6 reports such ML-estimated λs in different cases arising in ring networks.

Figure 1. Equilibria on a Ring Network

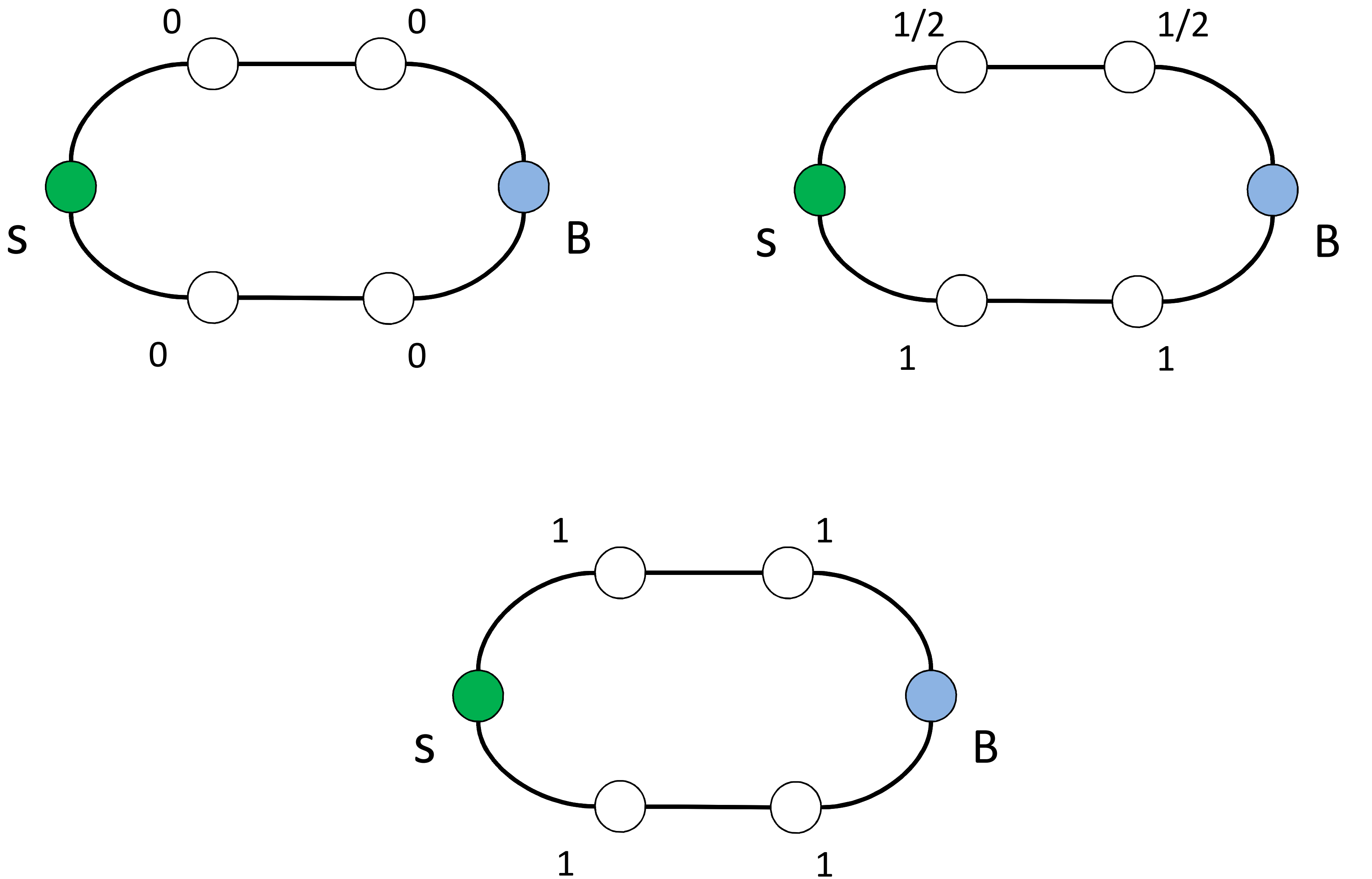
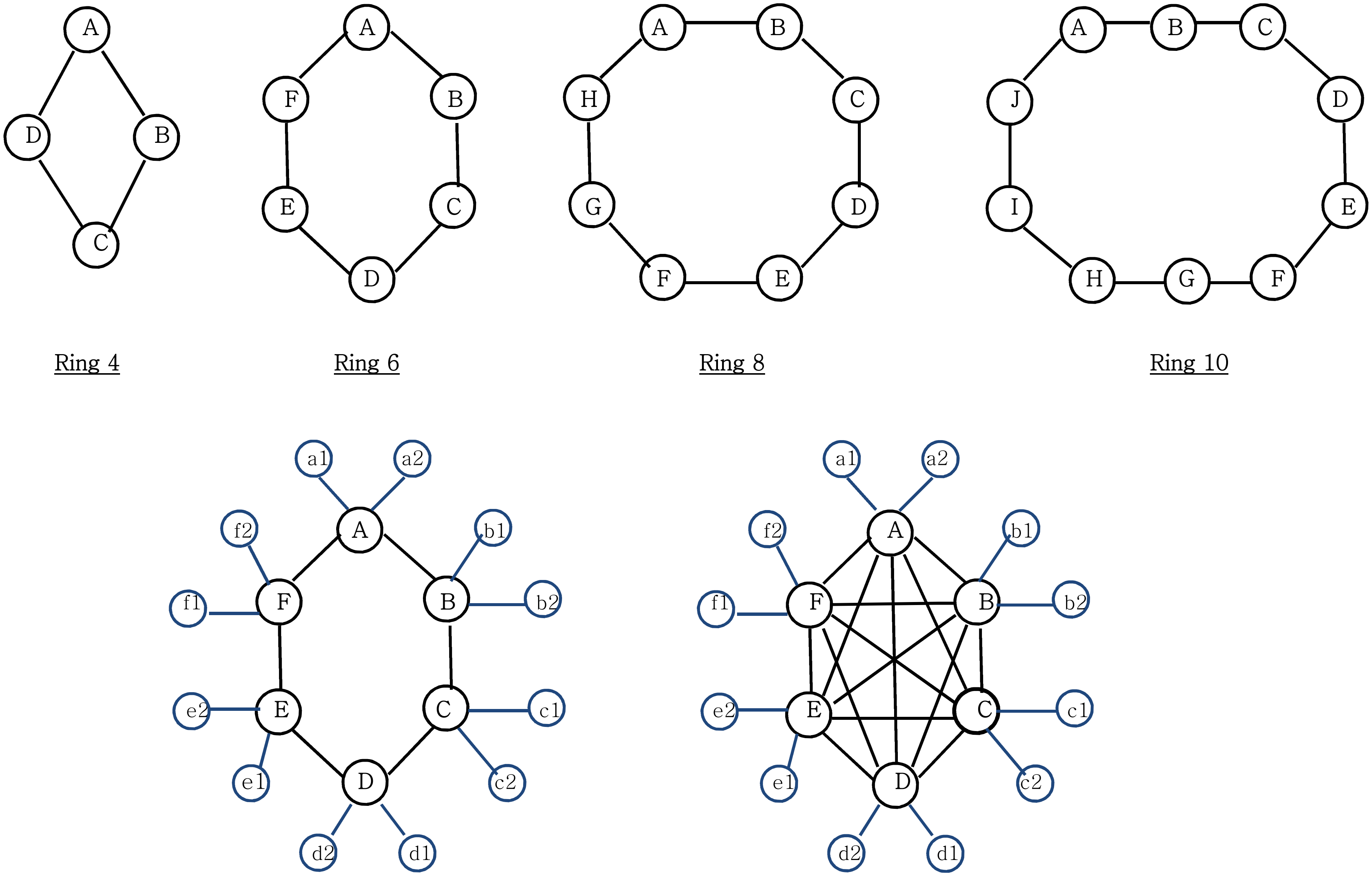


Figure 2. Trading Networks



Ring 4 Ring 6 Ring 8 Ring 10

Ring with hubs Clique with hubs

Figure 3. Intermediation Costs in Ring Networks

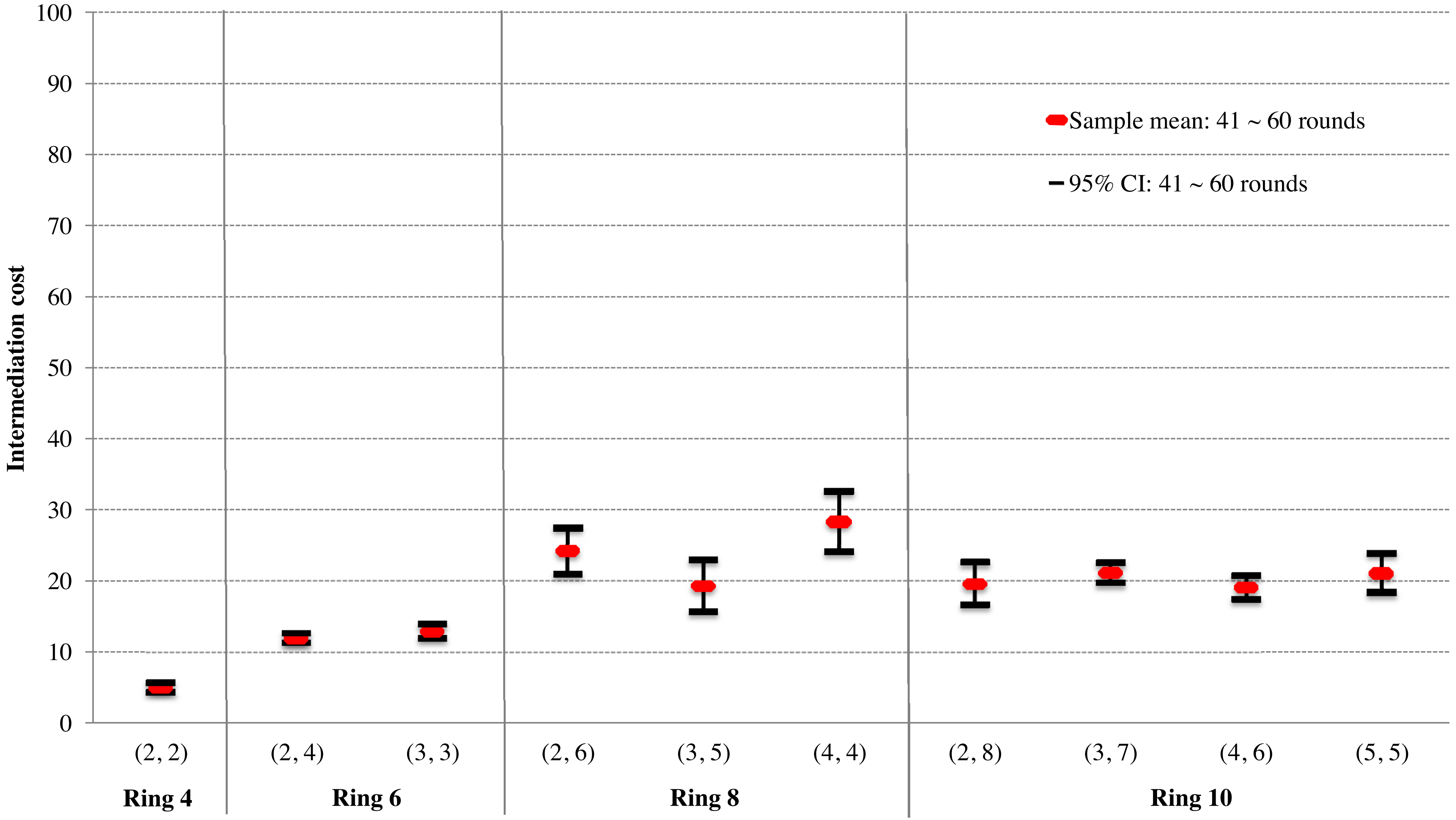


Figure 4. Average Prices across Distances: last 20 rounds

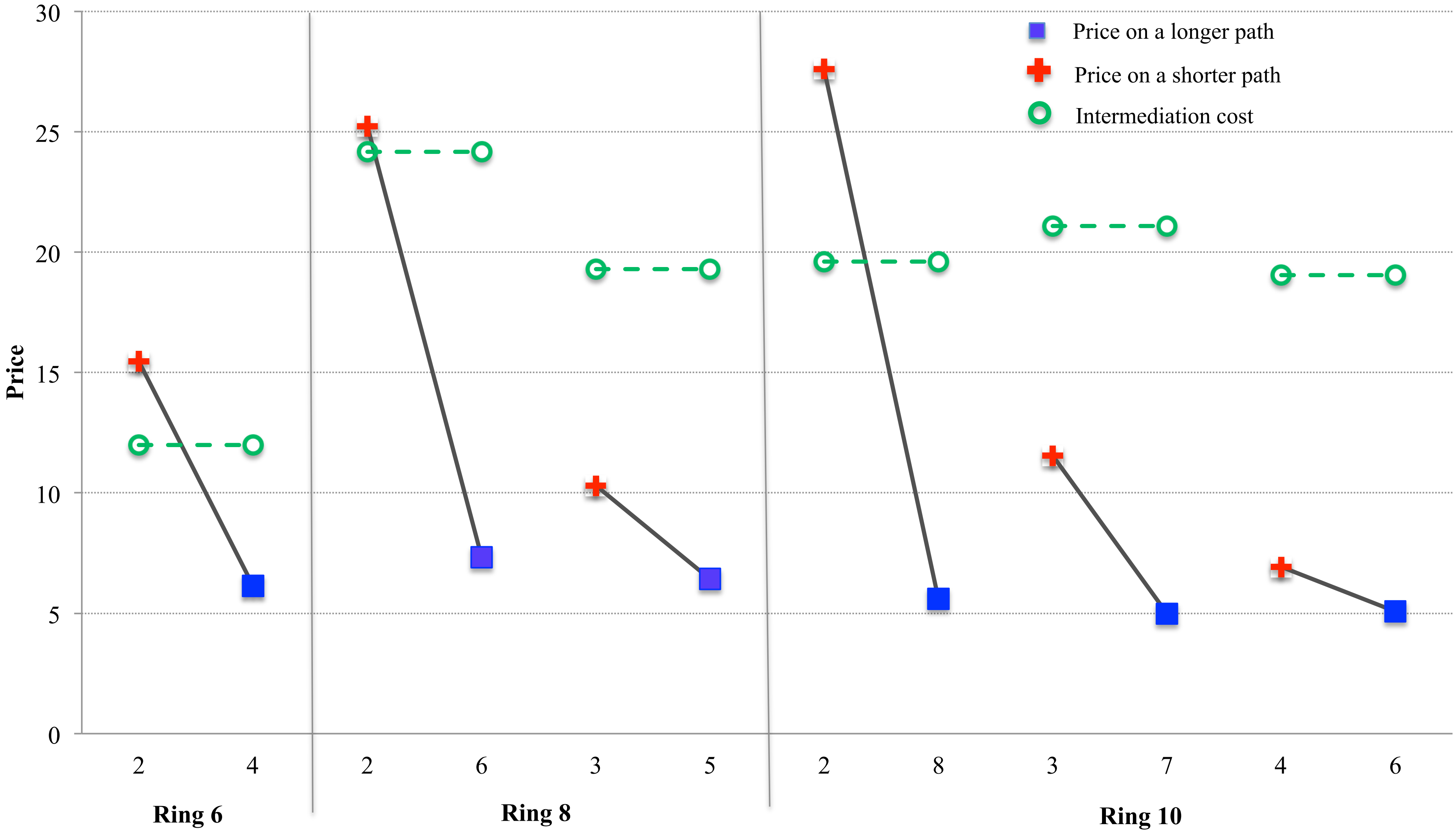


Table 1. Frequency of Trading

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.

<u>Table 2. Intermediation Costs in Ring Networks</u>

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.

<u>Table 5. Pricing Behavior in Ring Networks</u>

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. Model of Strategic Uncertainty: Optimality and Estimation

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

Table 7. 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 8. Fraction of Intermediation Costs by Critial Intermediaries in Ring with Hubs
(conditional on trading)

Network	(#Cr,#Paths, d(q),d(q'))	Rounds 1 ~ 20	Rounds 21 ~ 41	Rounds 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.

Online Appendix I: Sample Instructions

Ring 6 network

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

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

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

60 Tokens = 1 Pound

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

A round

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

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

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

Note that in the network used in this experiment,

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

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

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

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

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

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

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

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

Earnings

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

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

Note that the trading surplus is 100 if trading occurs and zero otherwise. The trading cost is the sum of intermediation prices that the trading pair must pay in order to make trading occur. If trading does not occur, the cost is zero. Two participants in the trading pair share equally the net surplus. Thus, each participant in the pair earns half of the net surplus, as given in the formula.

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

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

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

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

$$(A\text{'s earnings}) = 0.5\times(100 - 75) = 12.5,$$

$$(B\text{'s earnings}) = 10, (C\text{'s earnings}) = 40, (D\text{'s earnings}) = 25$$

$$(E\text{'s earnings}) = 0.5\times(100 - 75) = 12.5,$$

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

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

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

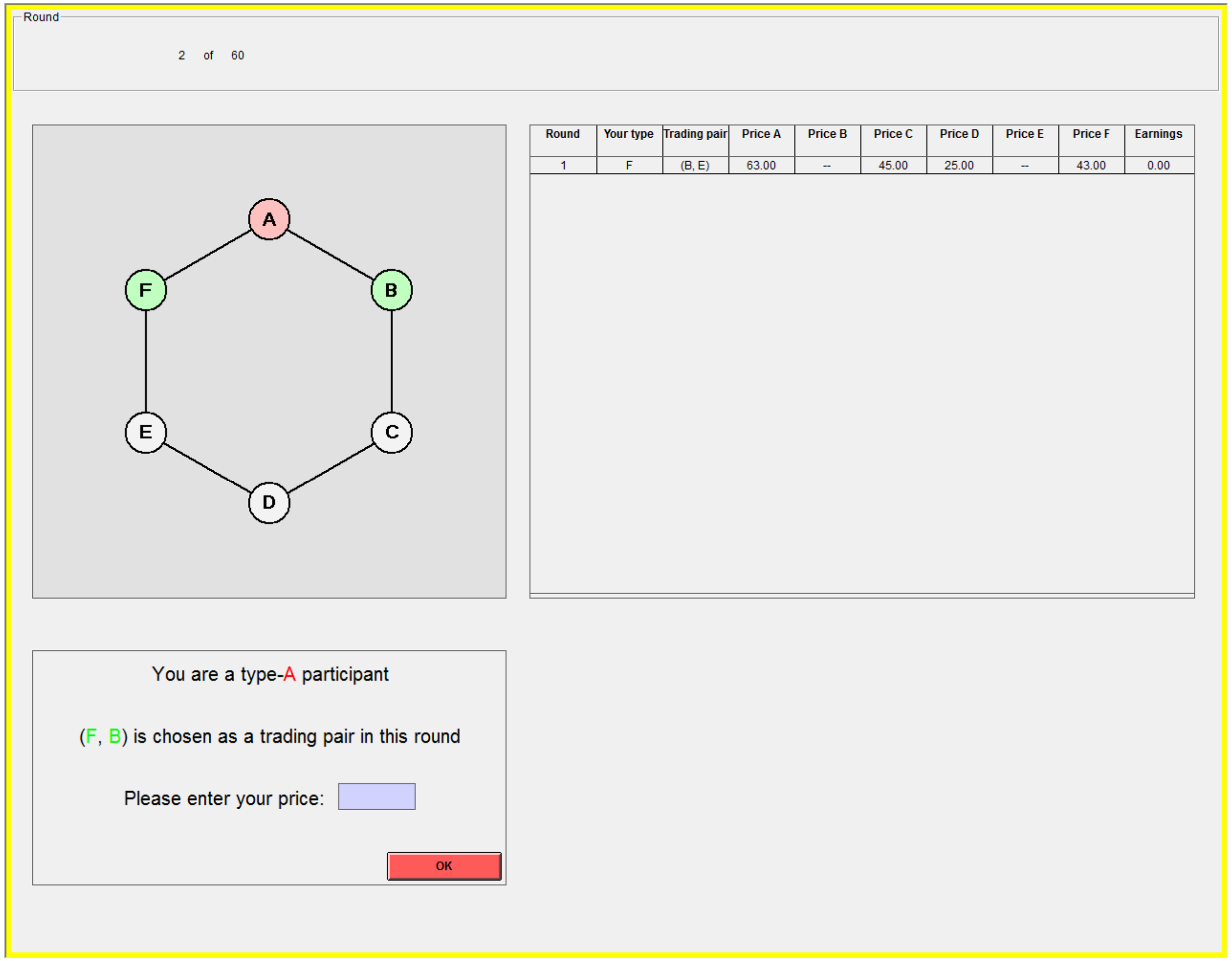
Rules

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

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

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

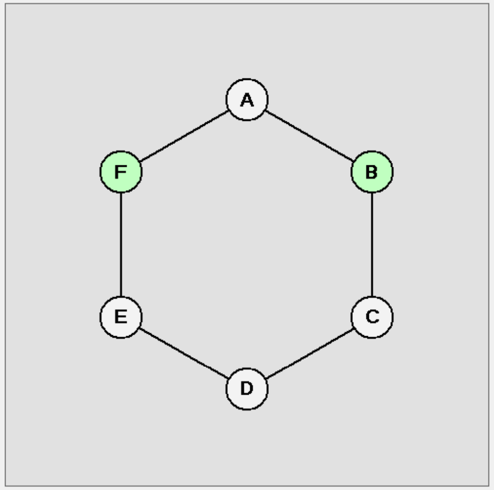
Attachment 1



Attachment 2

Round

2 of 60



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

You are a type-F participant

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

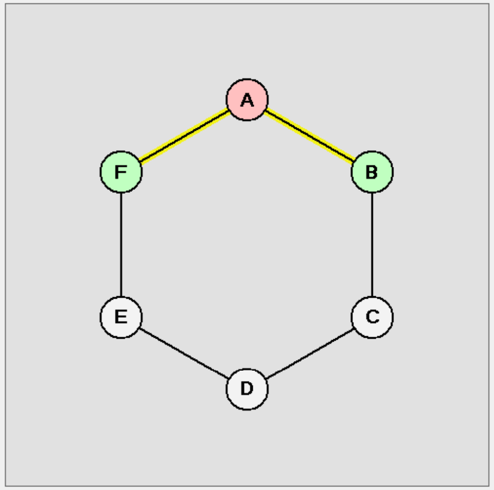
You do not have to make a pricing choice in this round.

OK

Attachment 3

Round

2 of 60



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

You are a type-A participant

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

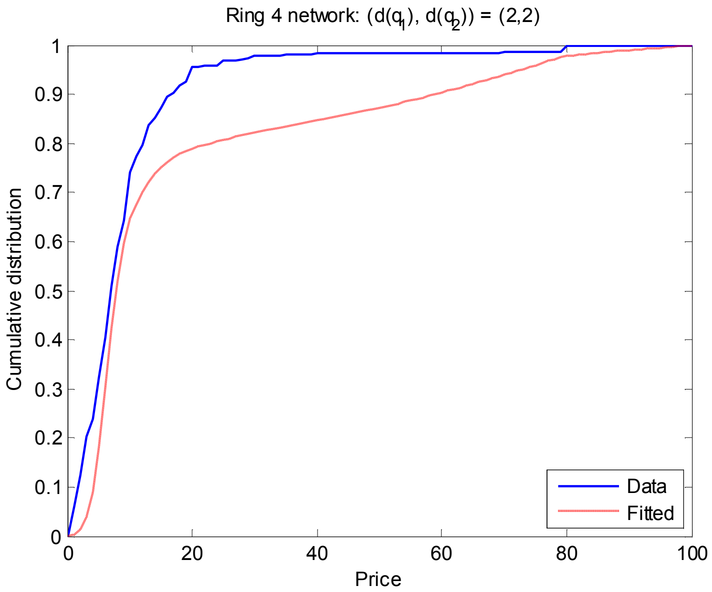
OK

Online Appendix II

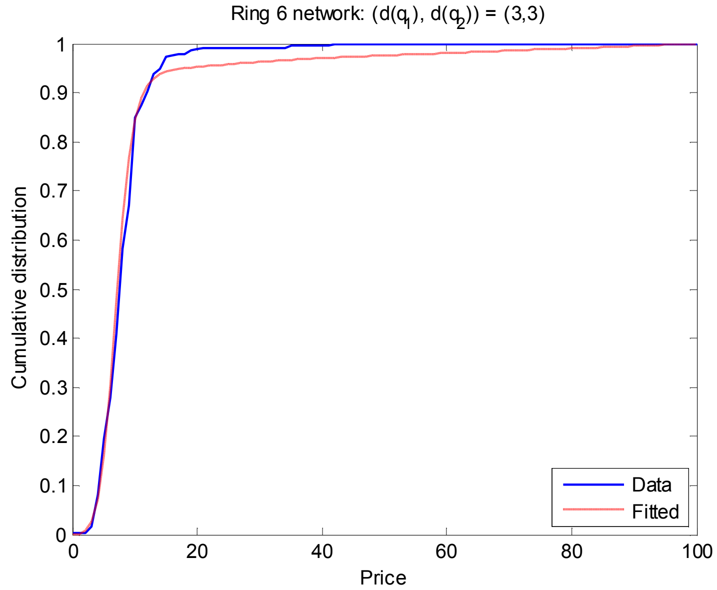
Goodness of Fit of the Model of Strategic Uncertainty with Stochastic Choice

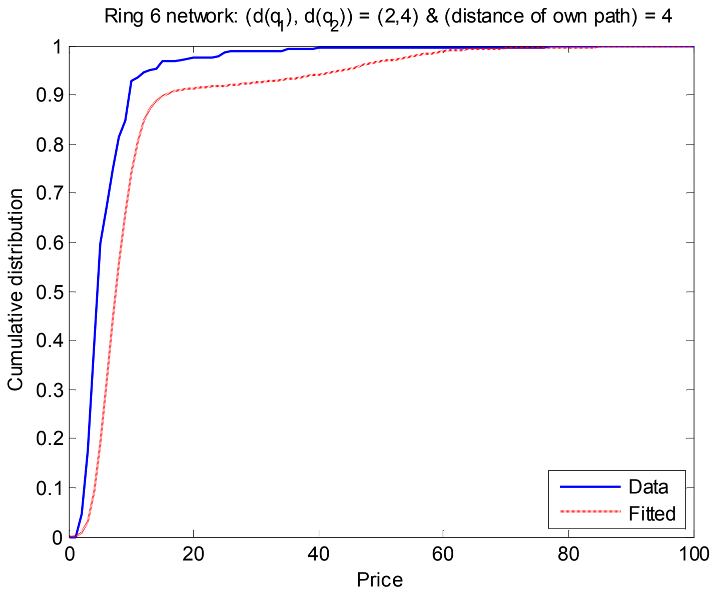
1. Sample data: 21 ~ 60 rounds

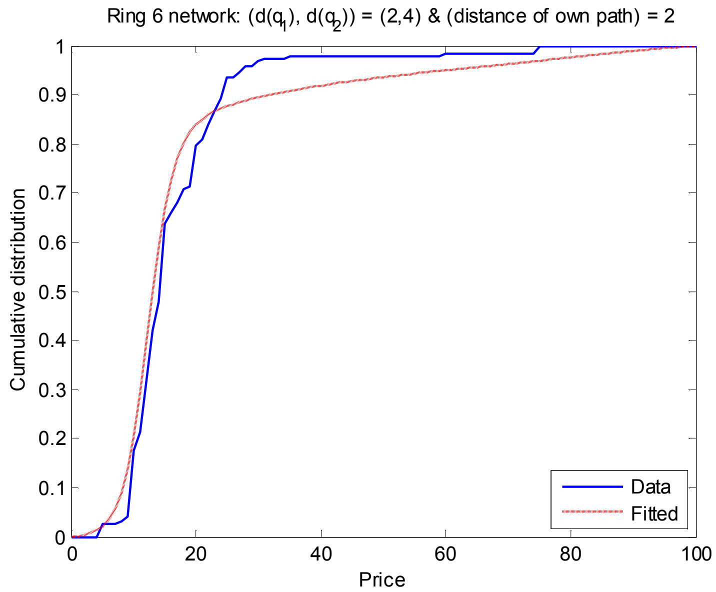
Ring 4 network



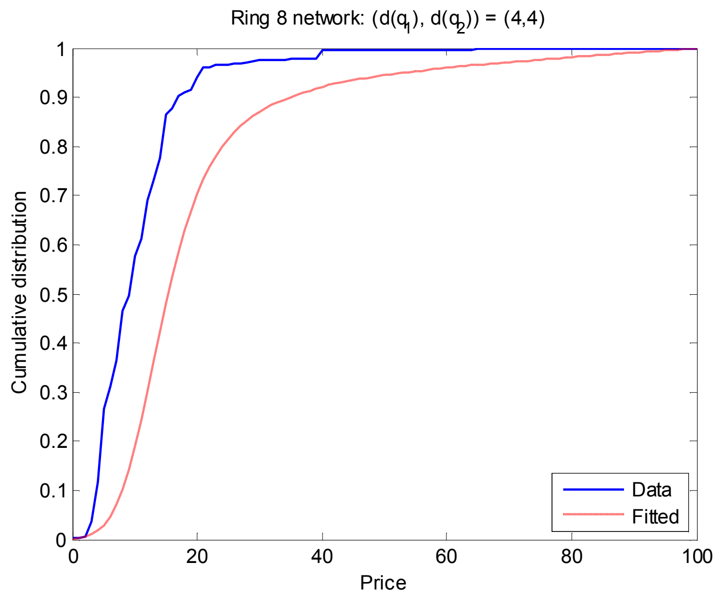
Ring 6 network

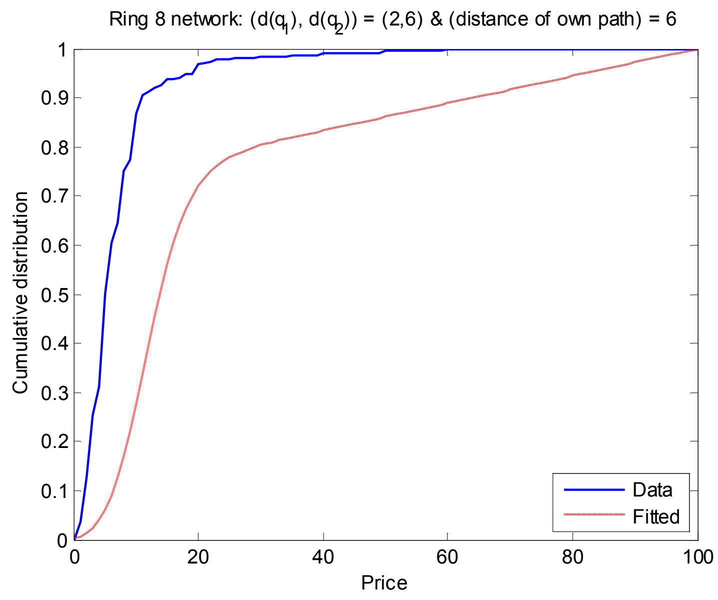


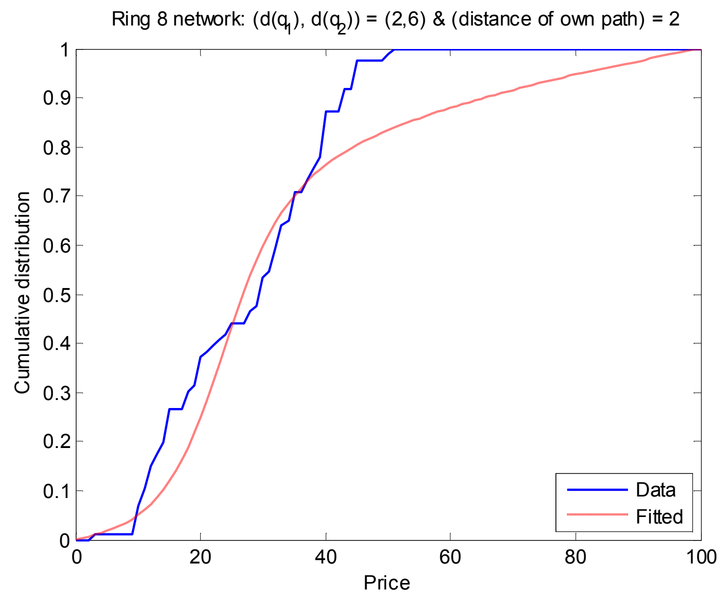


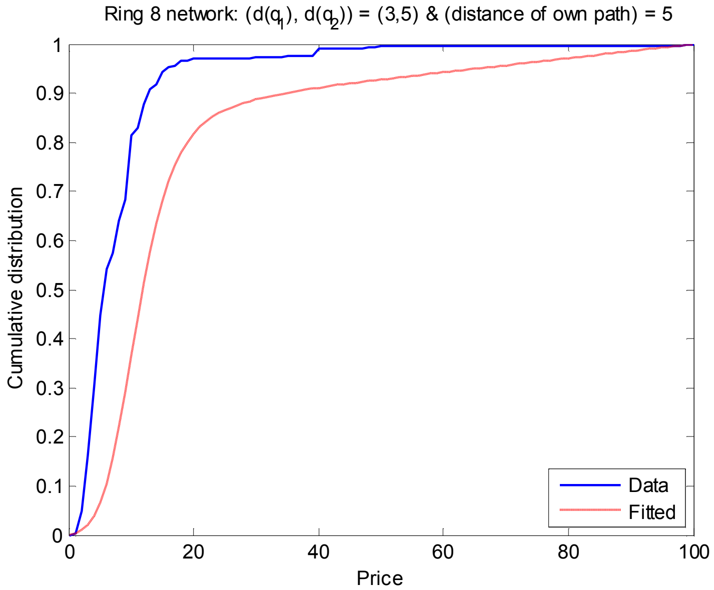


Ring 8 network

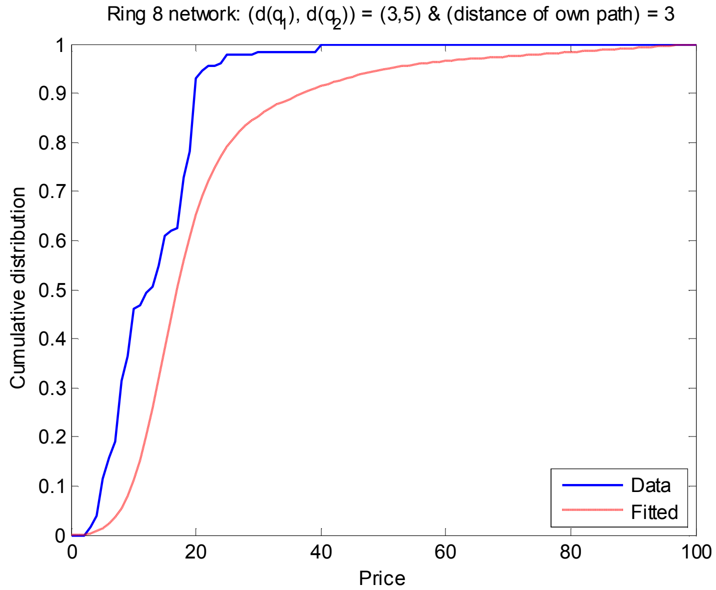






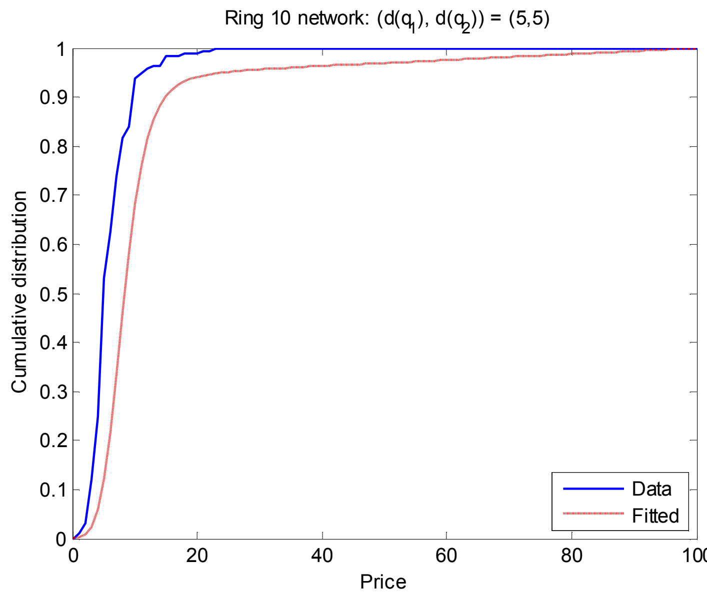


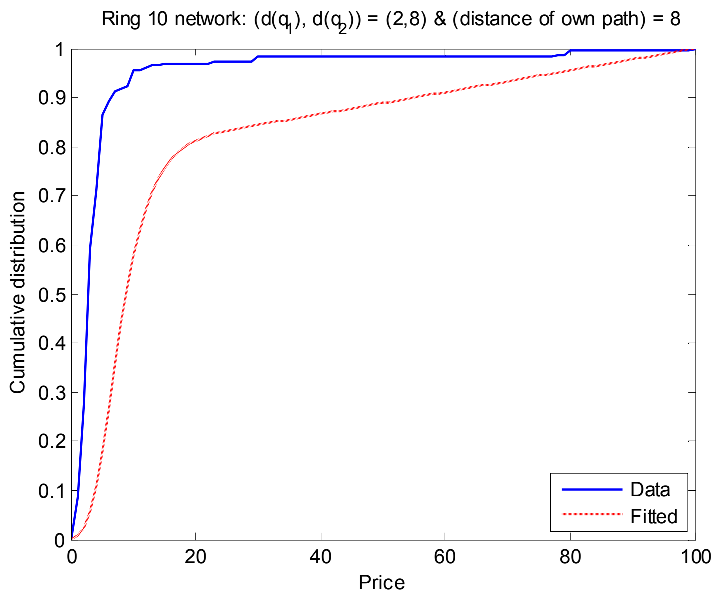
Ring 8 network: (d(q1), d(q2)) = (3,5) & (distance of own path) = 5
Cumulative distribution
Price
Data
Fitted

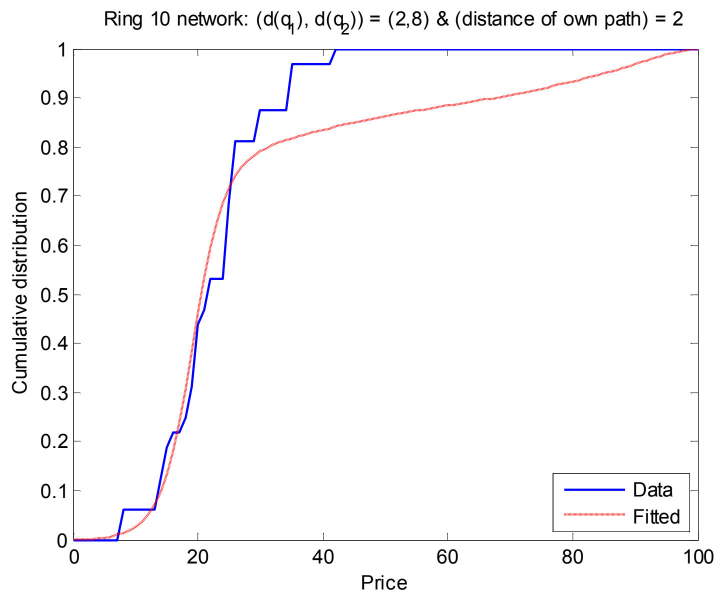


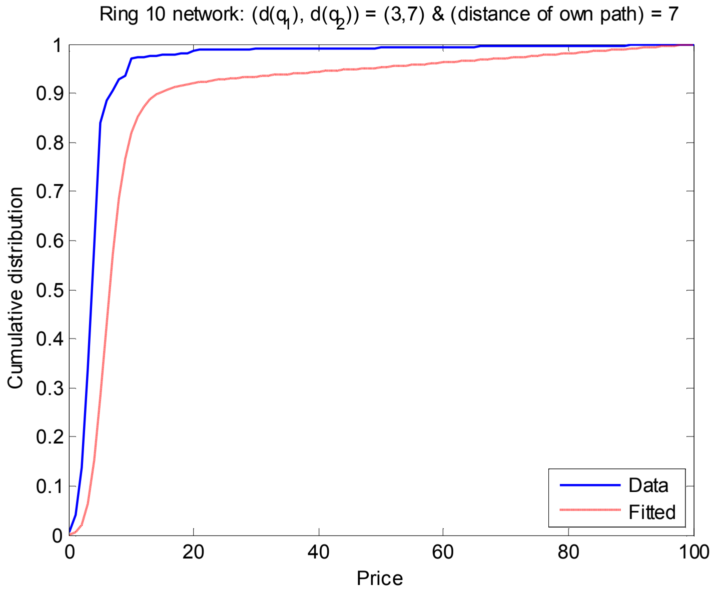
Ring 8 network: (d(q1), d(q2)) = (3,5) & (distance of own path) = 3
Cumulative distribution
Price
Data
Fitted

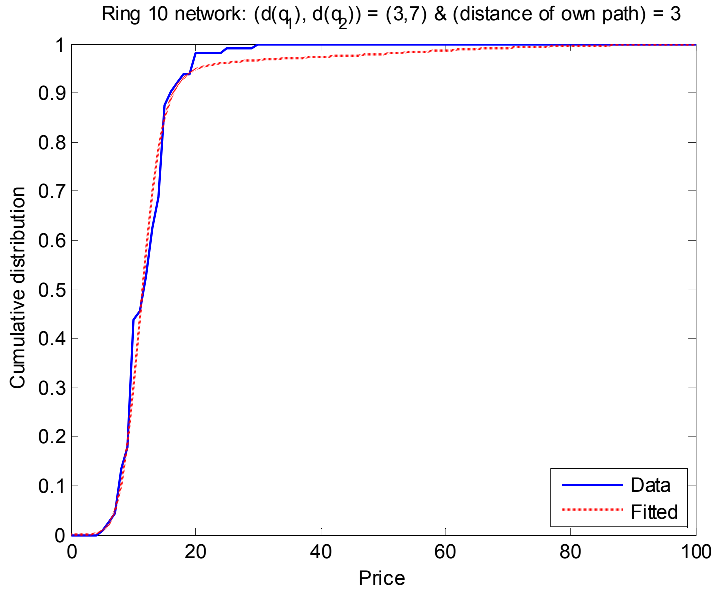
<u>Ring 10 network</u>

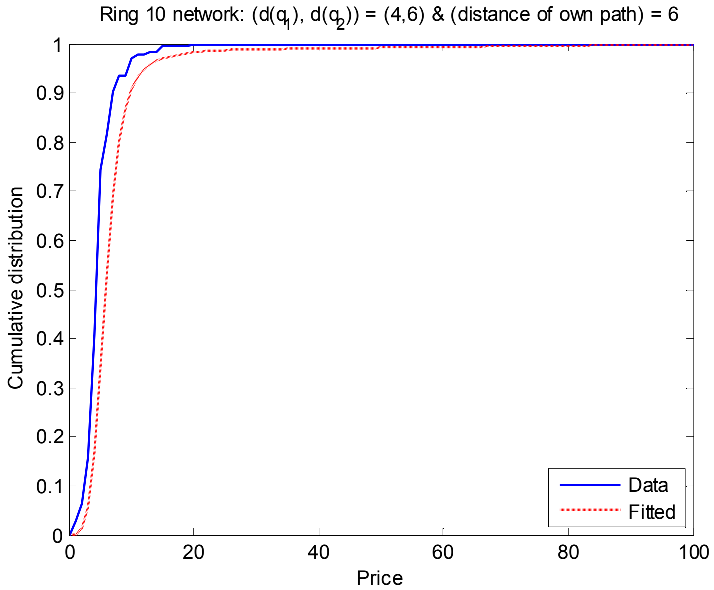


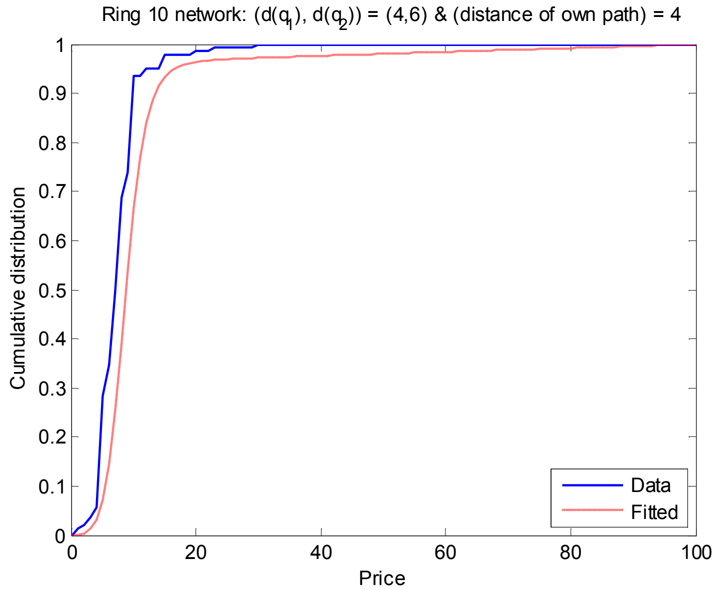





Ring 10 network: $(d(q_1), d(q_2)) = (3,7)$ & (distance of own path) = 7
Cumulative distribution
Price
Data
Fitted

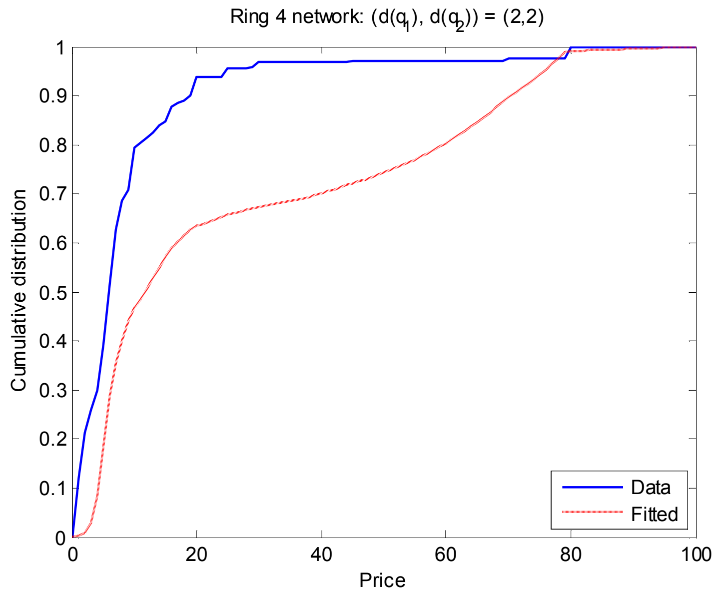

Ring 10 network: $(d(q_1), d(q_2)) = (3,7)$ & (distance of own path) = 3
Cumulative distribution
Price
Data
Fitted


Ring 10 network: $(d(q_1), d(q_2)) = (4,6)$ & (distance of own path) = 6
Cumulative distribution
Price
Data
Fitted

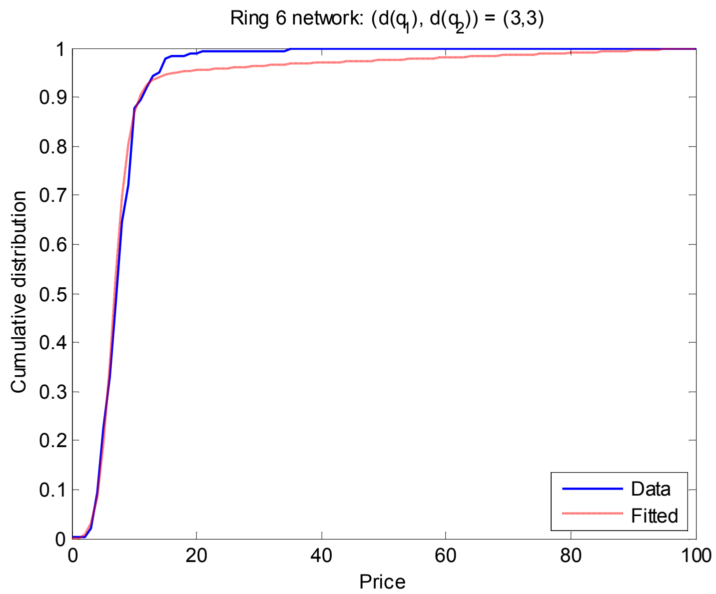

Ring 10 network: $(d(q_1), d(q_2)) = (4,6)$ & (distance of own path) = 4
Cumulative distribution
Price
Data
Fitted

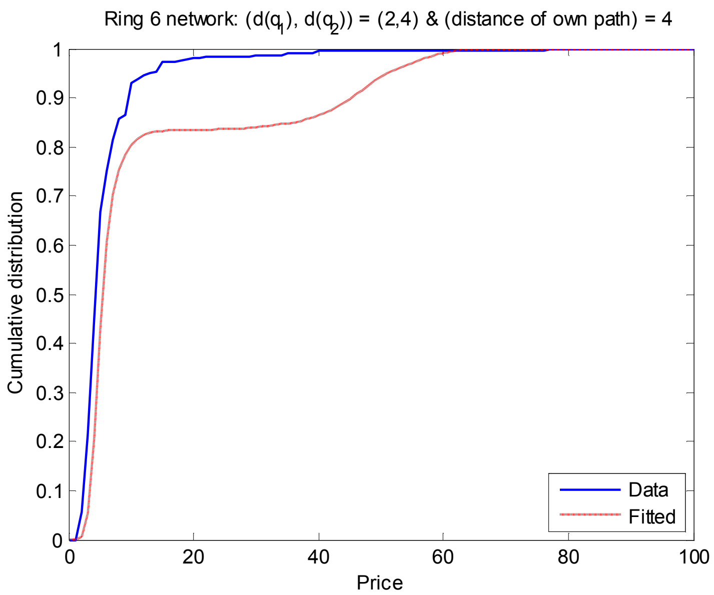
2. Sample data: 31 ~ 60 rounds

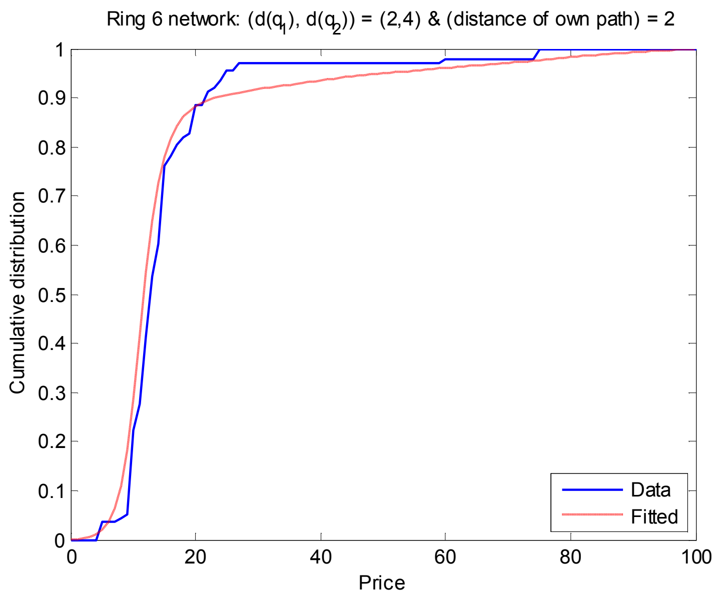
Ring 4 network



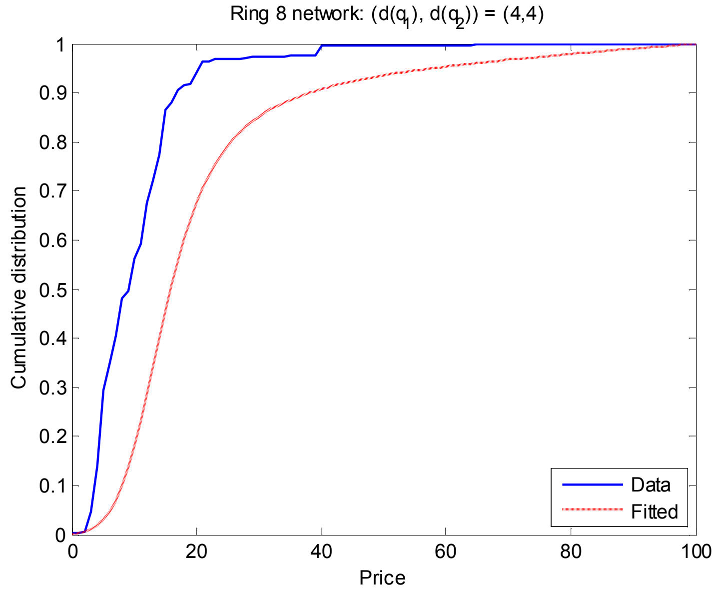
Ring 6 network

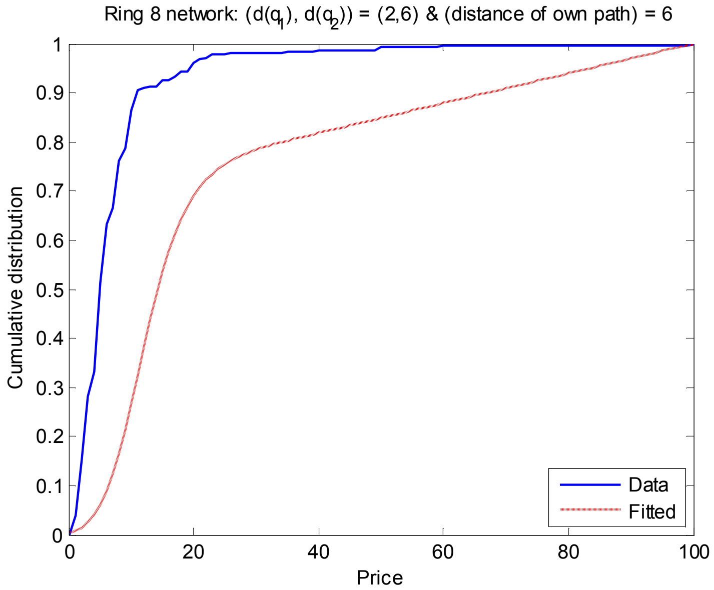


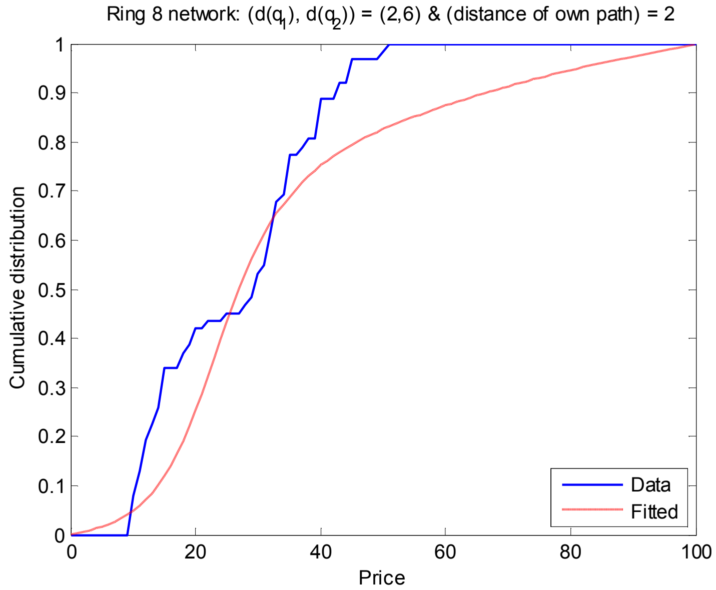


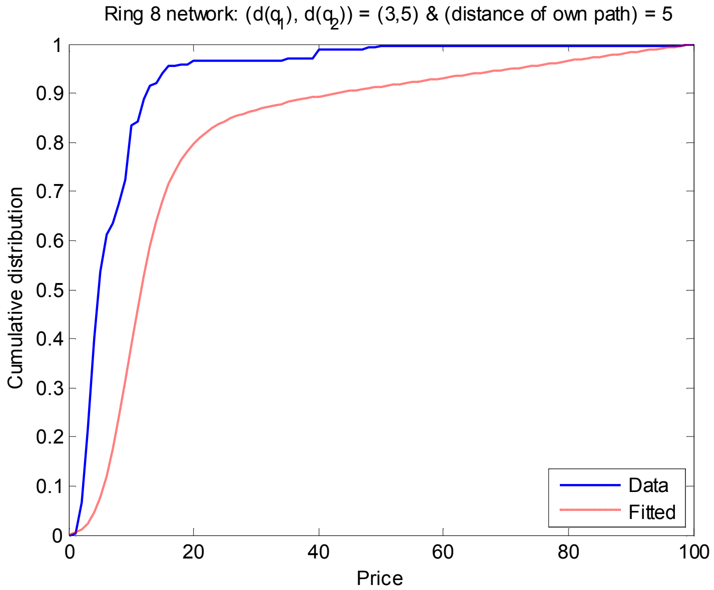


Ring8 network

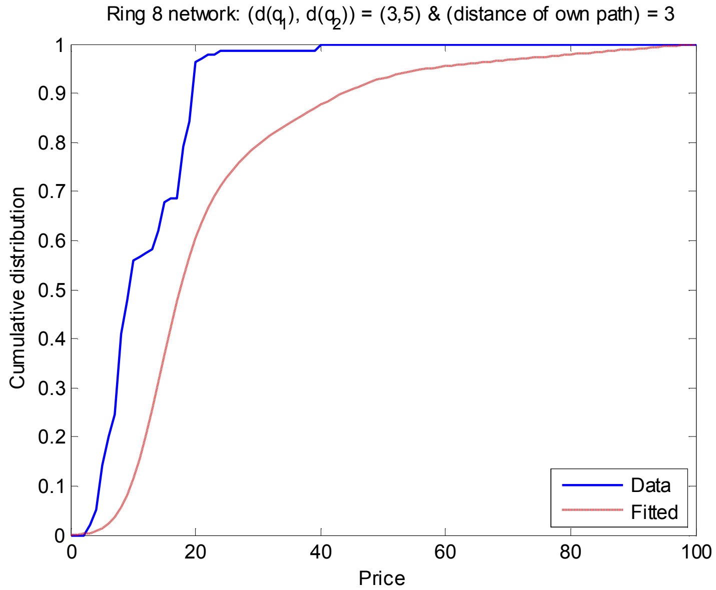






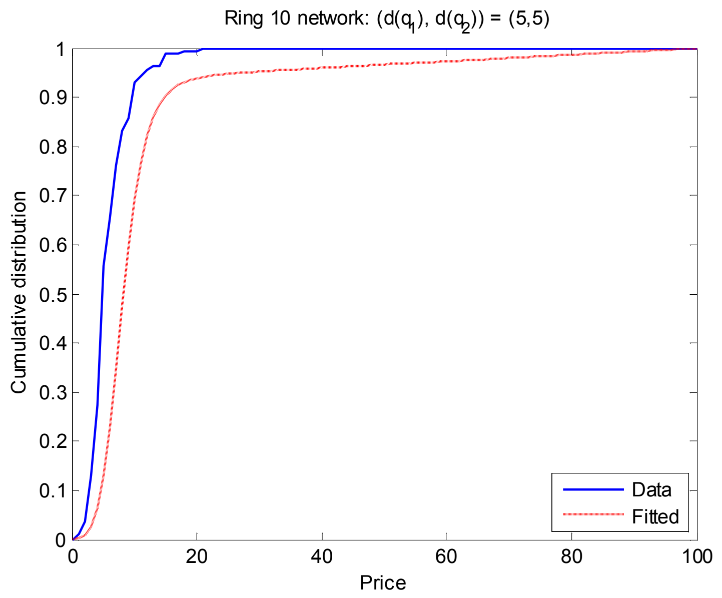


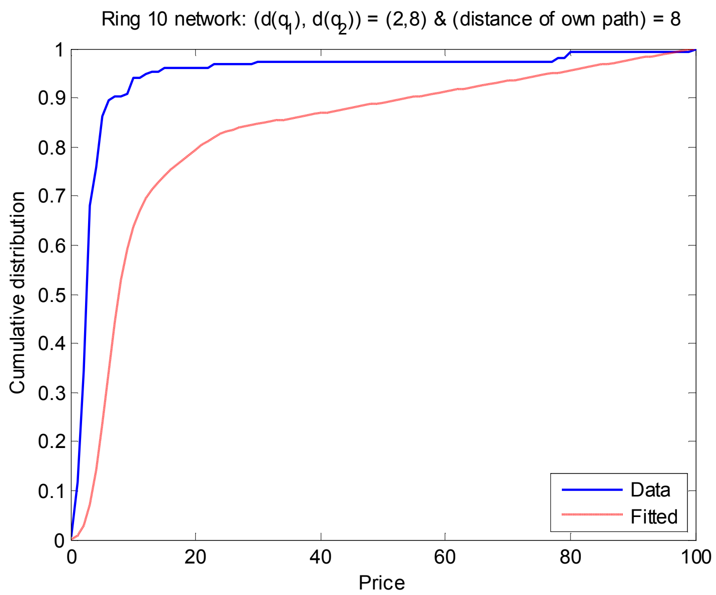
Ring 8 network: (d(q1), d(q2)) = (3,5) & (distance of own path) = 5
Cumulative distribution
Price
Data
Fitted
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100

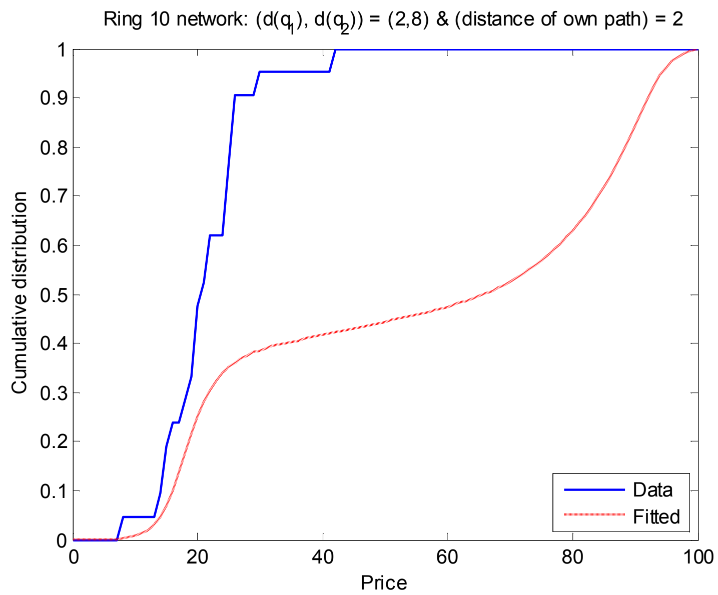


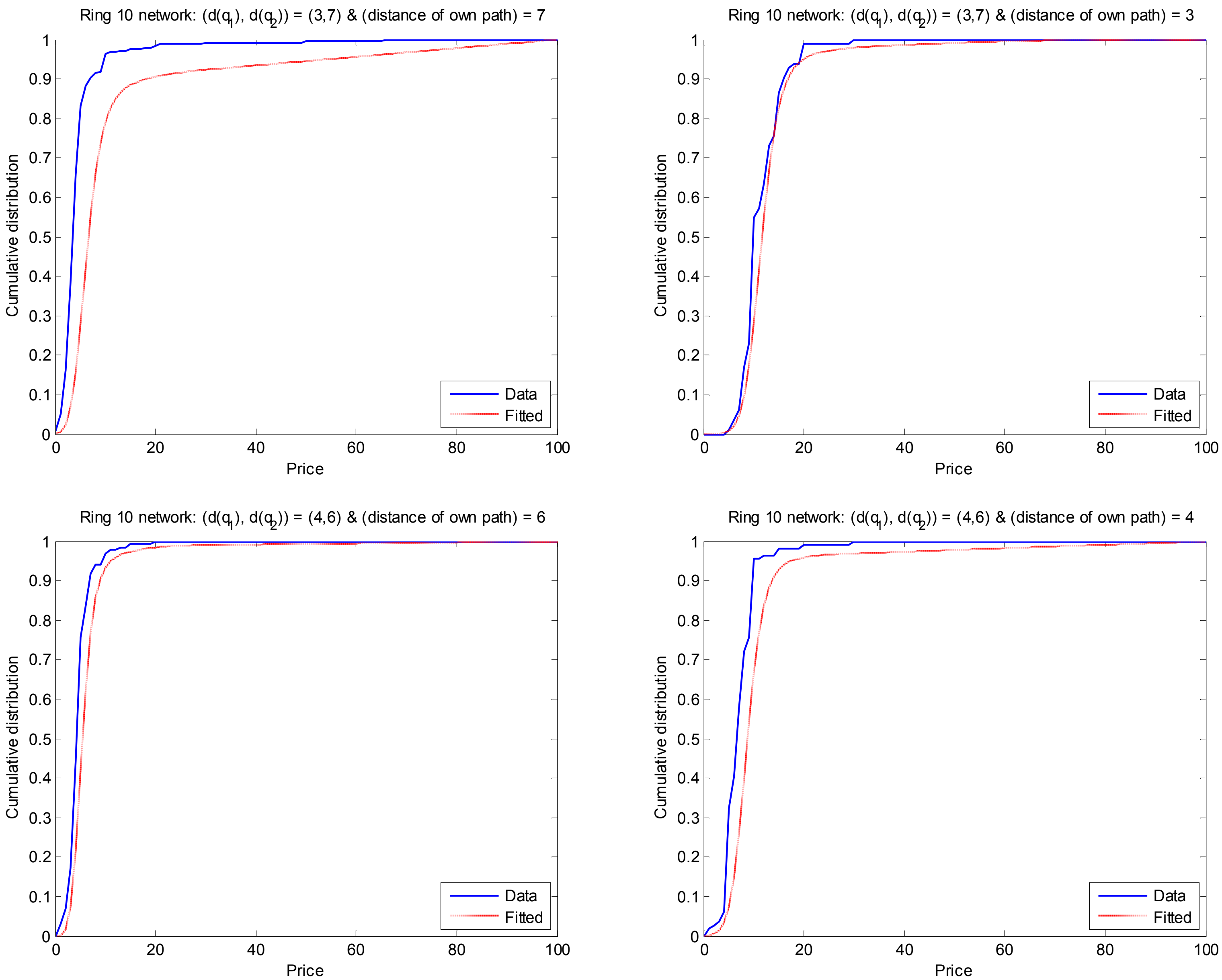
Ring 8 network: (d(q1), d(q2)) = (3,5) & (distance of own path) = 3
Cumulative distribution
Price
Data
Fitted
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100

Ring 10 network








Ring 10 network: (d(q1), d(q2)) = (3,7) & (distance of own path) = 7
Cumulative distribution
Price
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
Data
Fitted
Ring 10 network: (d(q1), d(q2)) = (3,7) & (distance of own path) = 3
Cumulative distribution
Price
Data
Fitted
Ring 10 network: (d(q1), d(q2)) = (4,6) & (distance of own path) = 6
Cumulative distribution
Price
Data
Fitted
Ring 10 network: (d(q1), d(q2)) = (4,6) & (distance of own path) = 4
Cumulative distribution
Price
Data
Fitted