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Abstract

This paper presents a three-period model to analyze why banks need bank reserves for interbank payments despite the availability of other liquid assets like Treasury securities. The model shows that banks need extra liquidity if they settle bank transfers without the central bank. In this case, each pair of banks sending and receiving bank transfers must determine the terms of settlement between them bilaterally in an over-the-counter transaction. As a result, a receiving bank can charge a sending bank a premium for the settlement of bank transfers, because depositors' demand for timely payments causes a hold-up problem for a sending bank. In light of this result, the large value payment system operated by the central bank can be regarded as an interbank settlement contract to save liquidity. A third party like the central bank must operate this system because a custodian of collateral is necessary to implement the contract. This result implies that bank reserves are not independent liquid assets, but the balances of collateral submitted by banks to participate into a liquidity-saving contract. The optimal contract is the floor system. Whether a private clearing house can replace the central bank depends on the range of collateral it can accept.

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1 Introduction

Base money consists of cash and bank reserves. Banks hold bank reserves not merely to satisfy a reserve requirement, but also to make interbank payments to settle bank transfers between their depositors. In fact, the daily transfer of bank reserves in a country tends to be as large as a sizable fraction of annual GDP.[1] Also, several countries have abandoned a reserve requirement.[2] Banks in these countries still use bank reserves to settle bank transfers.

But why do banks need payment instruments supplied by the central bank? Nowadays, there is an ample supply of Treasury securities in advanced countries, which are serving as liquid assets for institutional investors. It is not immediately clear why payment instruments for banks must exist separately from other liquid assets. Also, banks swap Treasury securities for bank reserves through open market operations. Why does the central bank need to replace liquid assets with liquid assets?

To address these questions, this paper constructs a hypothetical model to analyze how banks would settle bank transfers without the central bank. The model implies that banks would need extra liquidity in such a case, even if they can pay liquid assets that are transferable at no physical transaction cost.

The key reason for this result is a hold-up problem in the decentralized settlement of bank transfers. If there is no involvement by the central bank, each pair of banks must settle bank transfers between them bilaterally in an over-the-counter (OTC) transaction. In this transaction, depositors' demand for timely payments worsens the threat point for an originating bank, i.e., a bank sending bank transfers, because it creates a deadline for the completion of bank transfers. As a result, a bank receiving bank transfers can charge an originating bank a premium for the settlement of bank transfers. The presence of this premium increases the amount of liquidity necessary for interbank payments.

In light of this result, the interbank payment system operated by the central bank, a

[1]For example, the average daily transfer of bank reserves in the U.S. was 20.2% of annual GDP in 2014.
[2]They include Australia, Canada, Denmark, Mexico, New Zealand, Norway, Sweden, and the U.K.

so-called large value payment system, can be regarded as a contract to save liquidity. In this system, banks obtain bank reserves from the central bank in exchange for liquid assets through open market operations. Then, originating banks settle bank transfers unilaterally by remitting the equivalent nominal balances of bank reserves to receiving banks. The model replicates this feature of the large value payment system as a contract, because a contract specifies the terms of trade in advance. This effect of a contract prevents a hold-up problem due to ex-post bargaining, and hence a premium, in the settlement of bank transfers.

The model also explains why a third party like the central bank must provide this contract. Banks must collateralize the contract given limited commitment underlying banks' need for payment instruments. A mutual exchange of collateral, however, does not work due to ex-ante symmetry regarding the expected direction of bank transfers for each bank. Thus, banks need a third party acting as a custodian of collateral. Given this result, open market operations can be regarded as a channel through which banks submit collateral to the central bank. Bank reserves are the balances of collateral. The remittance of bank reserves is the reallocation of the balances of collateral among banks to settle bank transfers under the terms of the large value payment system as a contract.

The optimal contract corresponds to the floor system. This result is not only due to interest payments on bank reserves to implement the Friedman's rule, but also because of the elimination of the OTC interbank money market, in which a hold-up problem occurs due to ex-post bargaining. Also, this paper discusses whether a private clearing house can replace the central bank. The model indicates two issues. First, to operate the large value payment system, a clearing house must be able to be committed to returning collateral to banks after the settlement of bank transfers. Historical evidence suggests that this is not a significant challenge. Second, a private clearing house dominates the central bank if it can accept a wider range of collateral than the central bank. In this regard, the ability to monitor collateral and member banks' portfolios is key to determine whether a private clearing house can take over the role of the central bank in the interbank payment system.

Just to clarify, this paper does not aim to explain the entire historical evolution of the interbank payment system. For example, the central bank had existed long before Treasury securities became liquid assets. Also, the central bank's ability to lend cash to the government might help to make Treasury securities liquid by shielding the government from liquidity shocks. These issues are beyond the scope of this paper. Instead, taking as given the presence of liquid assets other than bank reserves, this paper analyzes why banks need payment instruments separately from other liquid assets in the current environment.

1.1 Related literature

The distinction between payment instruments and other liquid assets is related to the legal restriction theory of money. Wallace (1983) discusses why money is necessary despite the presence of interest-bearing Treasury securities, given the inconvenient institutional features of Treasury securities for retail payments. This paper brings this question to interbank payments, highlighting the fact that the interbank market is an OTC market. Also, Kocherlakota (2003) analyzes why long-term bonds should not be usable as payment instruments. This paper focuses on a different issue, investigating the distinction between payment instruments for banks and liquid assets in general, including short-term securities. Another related paper is the work by Piazzesi and Schneider (2015), which analyzes the effect of a large-scale asset purchase program by the central bank under a constraint that banks must use bank reserves to settle bank transfers.

There exists an extensive literature that investigates central-bank policies that replace illiquid assets with money. Freeman (1996) analyzes the effect of the discount window. Other papers on this issue include Green (1997), Fujiki (2003, 2006), Mills (2004), Gu, Guzman and Haslag (2011), and Chapman and Martin (2013).[3] Also, there is a search-theoretic literature

[3] Green (1997) discusses whether a private clearing house can take over the role of the central bank. Fujiki (2003, 2006) analyzes the effect of the central bank's liquidity provision policies on cross-border settlement. Mills (2004) proposes an alternative mechanism to the discount window based on collateralized lending.

on money and illiquid collateral, such as Shi (1996), Ferraris and Watanabe (2008), and Andolfatto, Berentsen and Waller (2013).[4] In the business-cycle literature, Kiyotaki and Moore (2012) investigate the effect of money supply that replaces illiquid private securities. In contrast to these papers, this paper analyzes why the central bank needs to replace liquid assets with bank reserves.

The analysis of OTC settlement of bank transfers is related to the paper by Martin and McAndrews (2010), which raises an open question on the need for the overnight interbank money market. Answering their question, this paper shows that the floor system is optimal given a hold-up problem in the OTC interbank money market. Another related paper is the work by Ennis and Weinberg (2013), which analyzes the effect of stigma in the OTC interbank money market. Also, Afonso and Lagos (2014) construct a dynamic search model to analyze the U.S. federal funds market.

This paper also adds to the literature on private interbank payment systems. Kahn (2013) analyzes how the competition between a public and a private interbank payment system limits the central bank's ability to manipulate monetary policy. Kahn (2009) brings this issue to cross-border settlement. Kahn and Roberds (2009) analyze the vertical integration of a public and a private interbank payment system through tiering.

From a broader perspective, this paper is related to the literature on electronic money, such as Skeie (2009). Also, Monnet and Nellen (2014) analyze the role of the clearing house in segregating collateral for a future contract between risk-averse investors. While this paper also characterizes the central bank as the custodian of collateral for an interbank settlement contract, this paper's main focus is on why banks need such a contract, given that banks make payments on behalf of depositors and also that the interbank market is an OTC market.

Gu, Guzman and Haslag (2011) analyze the optimal intraday interest rate. Chapman and Martin (2013) investigate the role of tiering to limit the central bank's exposure to credit risk.

[4]Shi (1996) shows useless assets except for the owner can serve as collateral to facilitate intertemporal exchange in a money-search model. Ferraris and Watanabe (2008) analyze the co-existence of money and credit by introducing money loans secured by illiquid capital. Andolfatto, Berentsen and Waller (2013) analyze optimal monetary policy with money backed by illiquid capital.

The remainder of the paper is organized as follows. The features of the interbank payment system in practice are briefly reviewed in section 2. The baseline model is presented in section 3. The central bank is introduced into the model in sections 4 and 5. Section 6 discusses whether a private clearing house can replace the central bank. Section 7 concludes.

2 Brief overview of the interbank payment system in practice

This section briefly summarizes the daily routine in the interbank payment system in practice to clarify the background of this paper's analysis. In each day, banks receive depositors' instructions to send bank transfers to other banks. For small-valued bank transfers, banks transmit the instructions to an electronic system called an automated clearing house (ACH). This system offsets incoming and outgoing bank transfers across banks to calculate the net amount of bank transfers to be sent by each bank. If a depositor requests a large-valued bank transfer, then it does not go through an ACH, but remains a gross bank transfer to be sent by a bank.

Banks send net and gross bank transfers by remitting the corresponding nominal balances of bank reserves to receiving banks. Here, bank reserves are current-account balances at the central bank. The remittance of bank reserves settles bank transfers, which is processed by an electronic system called a large value payment system.[5]

Banks can obtain bank reserves in advance by selling liquid securities, such as Treasury securities and high-quality private securities, to the central bank through open market operations.[6] In each day, however, there can be some banks running short of bank reserves because of an imbalance between incoming and outgoing bank transfers for each bank. In such a case, those banks fulfill the shortfalls in bank reserves by borrowing bank reserves

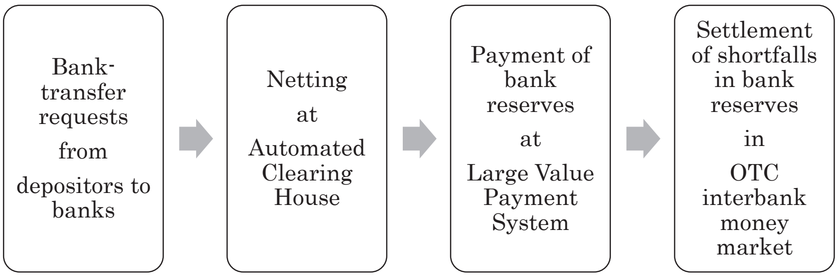
[5]For example, this system is called Fedwire in the U.S., TARGET2 in the Eurozone, CHAPS in the U.K., and BoJ-NET in Japan.

[6]The central bank supplies bank reserves through daylight overdrafts in the channel system. See section 5.2 for more details.

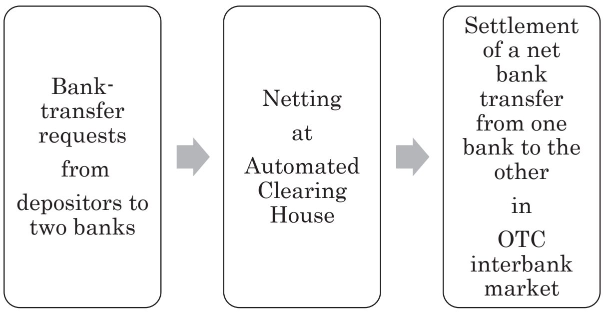
from other banks in an OTC interbank money market.[7]

In the following section, this paper presents a baseline model to analyze how banks would settle bank transfers if the large value payment system were removed from the current interbank payment system. Thus, banks directly go to the OTC interbank market to settle bank transfers after the realization of bank-transfer requests from depositors in the model (see Figure 1). To reflect an ample supply of Treasury securities and other liquid wholesale securities at present, the model also incorporates liquid bonds that are transferable at no physical transaction cost. The central bank will be introduced later into the model to clarify its role in the current interbank payment system.

Figure 1: Comparison between the interbank payment system in reality and the baseline model



(a) Interbank payment system in reality



(b) Baseline model

[7]The central bank normally allows banks to run negative balances of bank reserves during the daytime through daylight overdrafts. Banks can fulfill expected shortfalls in bank reserves in the interbank money market in each morning, and unexpected shortfalls in the market at the end of each day.

3 Baseline model of a decentralized interbank payment system

Time is discrete and indexed by $t = 0, 1, 2$. There are two banks indexed by $i = A, B$. Each bank receives a unit amount of goods from its depositors in period 0. For simplicity, assume that the deposit interest rate is set to zero.[8]

Banks can transform deposited goods into bank loans and bonds. Bank loans generate an amount R_L of goods in period 2 per invested good. Similarly, the gross rate of return on bonds in period 2 is R_B. Assume that

$$R_L > R_B > 1, \tag{1}$$

in which one equals the gross rate of return on deposits.

In period 1, bank i for $i = A, B$ receives depositors' orders to remit a fraction λ_i of its total deposits to the other bank.[9] The joint probability distribution of λ_A and λ_B is

$$(\lambda_A,\ \lambda_B) = \begin{cases} (\eta,\ 0) & \text{with probability } 0.5, \\ (0,\ \eta) & \text{with probability } 0.5, \end{cases} \tag{2}$$

where $\eta \in (0, 1)$. Thus, banks are symmetric ex-ante. Here, it is implicitly assumed that overlapping gross flows of bank transfers between banks are automatically canceled out at an ACH. Thus, only one of the banks must send net bank transfers to the other bank. For $i = A, B$, call bank i an "originating bank" if $\lambda_i = \eta$, and a "receiving bank" if $\lambda_i = 0$.

Assume limited commitment such that a bank can always walk away from a contract

[8]Here, it is implicitly assumed that depositors can store goods with no interest by themselves, and also that each bank can set the deposit interest rate for its depositors monopolistically. See Appendix A for the formal assumption about depositors.

[9]Assume that depositors cannot withdraw goods from banks in period 1, as banks cannot produce any good by terminating bank loans or bonds in period 1. Also, there is no consideration of a bank-transfer fee in the model. This assumption can be justified by implicitly assuming that depositors order bank transfers because they have a sufficiently high weight on utility from consumption in period 1 relative to that in period 2 due to idiosyncratic preference shocks. In this environment, a bank must promise a substantially high deposit interest rate to induce depositors to participate into a deposit contract ex-ante if it sets a bank-transfer fee. This arrangement is unprofitable for banks, as the loss from a high deposit interest rate dominates the gain from charging a bank-transfer fee. See Appendix A for more details.

with the other bank without punishment.[10] Thus, banks have to settle bank transfers by transferring bank loans and bonds between them after the realization of λ_A and λ_B in period 1.[11] Bonds are transferable at no physical transaction cost. In contrast, if a bank transfers its bank loans to the other bank in period 1, then the gross rate of return on the transfered bank loans becomes δ ($\in (0, R_L]$). The difference between R_L and δ can be interpreted as a loan monitoring cost incurred by the bank purchasing the bank loans.[12]

Assume that the interbank market is an OTC market; so banks determine the terms of settlement through bilateral bargaining. The outcome of bargaining is determined by Nash bargaining in which each bank has equal bargaining power. If banks do not reach any agreement, then no bank transfer is made. In this case, the originating bank must incur a cost $\gamma\eta$ ($\gamma > 0$) in period 2. This cost can be interpreted as a long-term cost due to loss of reputation with depositors, or a cost payable in period 2 due to a litigation filed by depositors for failed payments. For normalization, assume that the receiving bank does not face any penalty. The results shown below will go through as long as the penalty on the receiving bank is smaller than that on the originating bank. This assumption reflects the fact that a deposit contract includes the right to send a bank transfer on demand, for which an originating bank is liable, but a receiving bank is not.

In period 2, each bank receives returns on its bank loans and bonds, repays deposits given a zero deposit interest rate, and consumes the residual as its profit. Banks are risk-neutral; thus each bank chooses its portfolio of bank loans and bonds in period 0 to maximize the expected profit in period 2. An equilibrium is a Perfect Bayesian Nash equilibrium for the

[10] Assume that depositors can punish a defaulting bank so much that each bank can be committed to repaying deposits in period 2. Unlike depositors, banks cannot be committed to incurring a cost to punish each other.

[11] Banks cannot write a pledgeable contract in period 0 even if banks swap some assets as collateral between them. In this case, they take an equal amount of collateral from each other due to their ex-ante symmetry in period 0. Thus, a bank does not lose anything by reneging on a contract in period 1, because it can cancel out the collateral taken by, and from, the other bank.

[12] The gross loan interest rate, R_L, can be interpreted as the gross rate of return on bank loans net of the loan monitoring cost for an originating bank. Thus, this assumption does not imply that an originating bank does not have to monitor bank loans.

Table 1: Summary of events in the baseline model

Period 0	Period 1	Period 2
There are two banks; each bank receives a unit amount of goods from depositors, given a zero deposit interest rate.	One of the banks has an outflow of bank transfers, η, to the other bank. The probability to be the originating bank is 0.5 for each bank.	Banks receive returns on bank loans and bonds, repay deposits, and consume the residual.
Banks invest deposited goods into bank loans and bonds.	A bank must incur a penalty, $\gamma\eta$, if it fails to send bank transfers requested by its depositors within period 1.	The return of goods per loan equals R_L if bank loans are not transferred in period 1, and δ ($\leq R_L$) if bank loans are transferred in the period.
	Banks bargain over how much amounts of bank loans and bonds the originating bank must pay to the receiving bank to settle bank transfers.	The return of goods per bond always equals R_B ($< R_L$).

dynamic game between the two banks. See Table 1 for the summary of events in the model.

3.1 Parametric assumptions

Throughout the paper, assume that

Assumption 1. $R_B > (1+\gamma)\,\eta$.

This assumption ensures that it is possible to settle bank transfers if a bank invests into a sufficiently large amount of bonds. Also, assume that

Assumption 2. $\gamma > 4\left(\dfrac{R_L}{R_B} - 1\right)$,

so that banks choose to settle bank transfers in any equilibrium considered below.

3.2 Hold-up problem in a decentralized interbank payment system

Let us start from the case in which bank loans are transferable at no transaction cost:

Assumption 3. $\delta = R_L$.

Solve the model backward. Under Assumption 3, the bargaining problem between the originating and the receiving bank in period 1 takes the following form:

$$\max_{\{l \in [0,k],\, b \in [0,a]\}} [-(R_L l + R_B b - \eta) - (-\gamma\eta)]^{0.5} (R_L l + R_B b - \eta)^{0.5}, \tag{3}$$

where: k and a are the amounts of bank loans and bonds, respectively, held by the originating bank at the beginning of period 1; l and b denote the amounts of bank loans and bonds, respectively, that the originating bank pays to the receiving bank; and η is the face value of bank transfers in period 1.

The left square bracket is the trade surplus for the originating bank, and the right parenthesis is that for the receiving bank. The first term in the left square bracket, $-(R_L l + R_B b - \eta)$, is a change in profit in period 2 for the originating bank in case of the successful settlement of bank transfers.[13] The second term in the left square bracket, $-\gamma\eta$, is the penalty for failed settlement of bank transfers. This penalty determines the threat point for the originating bank. In contrast, the trade surplus for the receiving bank equals the profit from receiving bank transfers, $R_L l + R_B b - \eta$, given no penalty on the receiving bank for failed settlement of bank transfers.

The solution to the bargaining problem is

$$R_L l + R_B b = \eta + \frac{\gamma\eta}{2}, \tag{4}$$

which is feasible under Assumption 1.[14] Thus, the originating bank must pay an extra value of assets, $\gamma\eta/2$, besides the face value of bank transfers, η.

[13] In this case, the originating bank pays assets worth $R_L l + R_B b$, while its deposit liabilities declines by η.

[14] Given Assumption 1 and the flow of funds constraint for each bank in period 0, $k + a = 1$, there exists a pair of l and b satisfying (4), $l \in [0, k]$, and $b \in [0, a]$ for every possible pair of k and a.

This result is due to lack of a centralized payment system provided by the central bank. Because of depositors' demand for timely payments, the originating bank must send bank transfers within period 1. In a bilateral transaction, this time constraint causes a hold-up problem, allowing the receiving bank to charge the originating bank a premium for the settlement of bank transfers. Hence, banks need extra liquidity for interbank payments if they settle bank transfers bilaterally by paying liquid assets.

3.3 Efficiency of a decentralized interbank payment system in case of liquid bank loans

Now move back to period 0. The profit maximization problem for each bank in the period is:

$$\begin{aligned} \max_{\{k\geq 0,\ a\geq 0\}} \ & R_L k + R_B a - 1 + \frac{1}{2}\frac{\gamma\eta}{2} + \frac{1}{2}\left(-\frac{\gamma\eta}{2}\right), \\ \text{s.t. } & k + a = 1, \end{aligned} \tag{5}$$

where the constraint is a flow of funds constraint that the sum of investments into bank loans, k, and bonds, a, must equal the total amount of deposits, 1, at each bank in period 0. The first two terms in the objective function are the returns on bank loans and bonds in period 2. The third term is the face value of deposit liabilities issued in period 0, given a zero deposit interest rate. The last two terms are the expected net gain and loss due to incoming and outgoing bank transfers, i.e., $\pm(R_L l + R_B b - \eta)$, as implied by (4).

Given $R_L > R_B > 1$ as assumed in (1), the solution to this problem is

$$(k,\ a) = (1,\ 0). \tag{6}$$

Thus, each bank invests only into the assets with the highest rate of return:

Proposition 1. Suppose Assumption 1 holds. Under Assumption 3, each bank chooses the efficient resource allocation, (6), in period 0.

3.4 Inefficiency of a decentralized interbank payment system in case of illiquid bank loans

The efficiency result described above is overturned if bank loans are illiquid. Now suppose that the cost of liquidating bank loans, $R_L - \delta$, is sufficiently high:

Assumption 4. $\delta < \dfrac{R_L}{1+\gamma}$.

This assumption implies $\delta < R_B$ given Assumption 2; thus, the rate of return on bank loans becomes smaller than that on bonds if transfered.

Under Assumption 4, the bargaining problem for the settlement of bank transfers in period 1 takes the following form:

$$\max_{\{l\in[0,k],\, b\in[0,a]\}} [-(R_L l + R_B b - \eta) - (-\gamma\eta)]^{0.5} (\delta l + R_B b - \eta)^{0.5}. \tag{7}$$

The left square bracket and the right parenthesis contain the trade surpluses for the originating and the receiving bank, respectively. Note that the gross rate of return on transferred bank loans, l, in the right parenthesis is changed from R_L to δ.

Denote the changes in profit for the originating and the receiving bank as a result of this bargaining by $\theta(a)$ and $\phi(a)$, respectively. Both $\theta(a)$ and $\phi(a)$ are the functions of the amount of bonds held by the originating bank, a, given that the bank invests the rest of deposits into bank loans in period 0, i.e., $k = 1 - a$. The solution to the bargaining problem implies that the following result holds for all $\delta \in (0, R_L)$ under Assumption 1:

$$\begin{aligned}&(\theta(a),\ \phi(a))\\ &= \begin{cases} (-\gamma\eta,\ 0), & \text{if } R_B a - \eta < -\frac{\delta\gamma\eta}{R_L-\delta}, \\ (-[R_L l(a) + R_B b(a) - \eta],\ \delta l(a) + R_B b(a) - \eta), & \text{otherwise,} \end{cases}\end{aligned} \tag{8}$$

where $l(a)$ and $b(a)$ denote the solutions for l and b, respectively, given a:

$$(l(a),\ b(a)) = \begin{cases} \left(\frac{\delta\gamma\eta - (R_L+\delta)(R_B a - \eta)}{2R_L\delta},\ a\right), & \text{if } R_B a - \eta \in \left[-\frac{\delta\gamma\eta}{R_L-\delta},\ \frac{\delta\gamma\eta}{R_L+\delta}\right], \\ (0,\ a), & \text{if } R_B a - \eta \in \left[\frac{\delta\gamma\eta}{R_L+\delta},\ \frac{\gamma\eta}{2}\right], \\ \left(0,\ \frac{1}{R_B}\left(\eta + \frac{\gamma\eta}{2}\right)\right), & \text{if } R_B a - \eta \geq \frac{\gamma\eta}{2}. \end{cases} \tag{9}$$

See Appendix B for the proof.

These equations imply that banks fail to agree on the settlement of bank transfers (i.e., $\theta(a) = -\gamma\eta$), if a is too small. In this case, the amount of bank loans that must be liquidated to settle bank transfers is too large, given a loan liquidation cost, $R_L - \delta$.

If banks agree to settle bank transfers, then the originating bank must pay assets worth more than the face value of bank transfers, i.e., $R_L l(a) + R_B b(a) > \eta$. This result holds because the receiving bank can charge the originating bank a premium, given the time constraint that the originating bank must complete bank-transfer requests within period 1. This hold-up problem is as same as the reason behind the second term on the right-hand side of (4).

In period 0, the profit maximization problem for each bank can be written as

$$\begin{aligned} \max_{\{k \geq 0,\ a \geq 0\}} \ & R_L k + R_B a - 1 + \frac{1}{2}\theta(a) + \frac{1}{2}\phi(a'), \\ \text{s.t. } & k + a = 1, \end{aligned} \tag{10}$$

where a' denotes the amount of bonds held by the other bank at the end of the period, which is taken as given by each bank. Under Assumptions 2 and 4, each bank invests into the just enough amount of bonds in period 0 to avoid liquidation of bank loans in period 1:

Proposition 2. Suppose Assumptions 1, 2 and 4 hold. Each bank chooses

$$(k,\ a) = \left(1 - a,\ \frac{1}{R_B}\left(\eta + \frac{\delta\gamma\eta}{R_L + \delta}\right)\right), \tag{11}$$

in period 0. Given this value of a, the originating bank pays only bonds for the settlement of bank transfers in period 1:

$$(l,\ b) = \left(0,\ \frac{1}{R_B}\left(\eta + \frac{\delta\gamma\eta}{R_L + \delta}\right)\right). \tag{12}$$

Proof. See Appendix C. □

Thus, banks must invest into an extra value of bonds besides the face value of bank transfers, η, ex-ante if they settle bank transfers bilaterally by paying liquid assets.

3.5 Interpreting the bilateral settlement of bank transfers as an overnight interbank loan

It is possible to interpret the bilateral settlement of bank transfers in period 1 as an interbank repo. In this interpretation, the originating bank pledges to repay the debit position of bank transfers, η, with an extra amount of liquidity as interest in period 2. The asset transfer in period 1 corresponds to the submission of collateral. For this transaction, assume that the receiving bank must incur a monitoring cost, $(R_L - \delta)$, per bank loan submitted as collateral, so that it cannot change the monitoring cost by simply switching from a spot transaction to a repo. Under this assumption, it makes no difference whether the originating bank pays its assets in period 1, or commits to repaying the return on those assets in period 2, as the assets mature in period 2.

Alternatively, banks would be able to arrange an unsecured loan if they could form a long-term relationship. In such a case, they would be able to eliminate a premium, or the interest, for the settlement of bank transfers, as there would be no hold-up problem between them.[15] Thus, the bilateral settlement of bank transfers in period 1 corresponds to either a direct payment of assets or an interbank repo under limited commitment. Note that repos take up a large share of overnight interbank loan transactions in reality, which indicates that limited commitment is an important feature of the overnight interbank loan market.[16]

4 Liquidity-saving effect of legal tender

Now introduce the central bank into the baseline model with illiquid bank loans. For simplicity, assume the classical dichotomy holds, so that it is sufficient to describe the model in

[15]Without limited commitment, it is the first-best if each bank pledges to increase its deposit liabilities by η without any compensation if it becomes the receiving bank. In this case, each bank can invest all the deposits into bank loans in period 0 without worrying about the resale of its assets in period 1. If the three periods in the model repeat, then a sequential change in deposit liabilities for each bank without corresponding asset transfers can be seen as a result of unsecured loans.

[16]See Demiralp, Preslopsky, and Whitesell (2004) for more details on the importance of a repo in the overnight interbank loan market.

real terms. This section covers two cases. In the first case, the central bank issues interest-bearing liabilities backed by bonds, which corresponds to the Friedman's rule. In the second case, the central bank designates its liabilities as legal tender. It will be shown that the efficiency of the interbank payment system improves only in the second case, as a hold-up problem in the settlement of bank transfers is prevented only in that case.

4.1 Introduction of central-bank liabilities just as interest-bearing assets

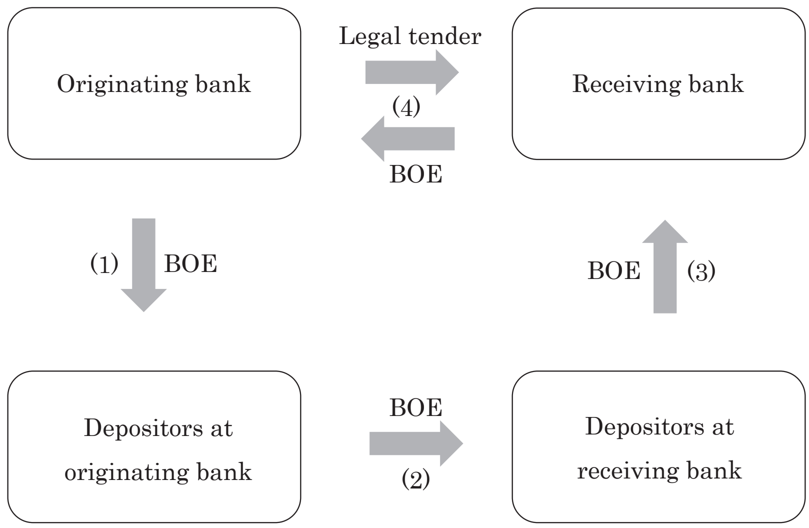
Suppose that the central bank allows banks to swap bonds with its liabilities in period 0. The central bank repays the liabilities by the whole return on its bonds in period 2; thus the central bank issues interest-bearing liabilities. Assume that these liabilities are transferable between banks at no physical transaction cost, just like bonds. Also assume that the central bank cannot accept bank loans due to lack of monitoring ability, so that the role of the central bank does not simply arise from the replacement of illiquid assets with liquid central-bank liabilities.

In this case, bank reserves and bonds are identical assets. Thus, no change occurs to the baseline model. Hence, Propositions 1 and 2 remain to hold. This result illustrates that the Friedman's rule is not enough to improve the efficiency of the interbank payment system, because, unlike retail payers, banks can use interest-bearing bonds for payment instruments. Thus, just supplying central-bank liabilities as interest-bearing assets does not have any effect on the interbank payment system.

4.2 Introduction of central-bank liabilities as legal tender

Next, suppose that the central bank does not only issue interest-bearing liabilities backed by bonds, but also designates its liabilities as legal tender. Consider the following arrangement in period 1. After the realization of bank-transfer requests to each bank (i.e., λ_i for $i = A, B$), the originating bank issues bills of exchange (BOE) to its depositors requesting bank

Figure 2: Settlement of bank transfers by bills of exchange (BOE) and legal tender



Note: The numbers in parentheses indicate the order of transactions in period 1.

transfers. These depositors, in turn, send BOE to their payees, so that the payees can present BOE to their bank, i.e., the receiving bank. The receiving bank, then, presents BOE to the originating bank (see Figure 2).

If each bank exchanges its bonds for central-bank liabilities of face value η in period 0, then the originating bank in period 1 can settle its outgoing bank transfers by simply paying the central-bank liabilities to the receiving bank in period 1. The receiving bank cannot bargain over the terms of settlement in this case, because a creditor is obliged by law to accept legal tender at face value for the fulfillment of the payer's financial obligation to the creditor.[17] Thus:

Proposition 3. If the central bank issues legal tender in exchange for bonds at par value in period 0, then each bank only invests into an amount η/R_B of bonds in period 0.

[17]The definition of legal tender is such that a creditor cannot sue a debtor for non-repayment if a debtor pays his debt in legal tender.

Hence, the use of legal tender saves the amount of liquidity necessary to settle bank transfers. The reason for this result is the elimination of ex-post bargaining over the terms of settlement. This result coincides with the historical use of BOE and cash, such as gold and legal tender notes, in the interbank settlement of bank transfers.[18]

5 Large value payment system as a collateralized interbank settlement contract

Currently, banks settle bank transfers by remitting bank reserves in the large value payment system. Bank reserves, however, are usually not designated as legal tender.[19] Yet, an originating bank can settle bank transfers unilaterally by remitting the equivalent nominal balance of bank reserves to a receiving bank under a rule set by the central bank.[20]

This feature of the large value payment system can be replicated by introducing an interbank settlement contract into the baseline model. In general, an interbank settlement contract takes a form such that the originating bank transfers amounts $\hat{l}$ and $\hat{b}$ of bank loans and bonds, respectively, to the receiving bank, according to the realization of bank-transfer requests, $(\lambda_A,\ \lambda_B)$, in period 1. In return, the receiving bank increases its deposit liabilities by η to complete bank transfers. Given limited commitment between banks, however, each bank can bail out of a contract any time without punishment from the other bank. Assume that if either bank bails out, banks can bargain over the settlement of bank transfers bilaterally as in the baseline model.

Without the central bank, each bank's payoff in an interbank settlement contract must be as same as that in bilateral bargaining in period 1, because Nash bargaining does not leave any room for Pareto improvement. Thus, if ex-post payoffs for banks in a contract differ from those in bilateral bargaining, then one of the banks necessarily bails out of the

[18] See Cannon (1900, Ch. 6) for the U.S. example.

[19] Usually, legal tender status is limited to minted coins and central-bank notes. See 31 U.S.C. §5103 for example.

[20] For example, see Regulation J of the Federal Reserve System.

contract. Also, even if banks exchange collateral between them in period 0, they take an equal amount of collateral from each other given their ex-ante symmetry in period 0. Thus, a bank does not lose anything by reneging on a contract, as it can cancel out the collateral taken by, and from, the other bank.

Given this result, introduce the central bank as a custodian of collateral for an interbank settlement contract. Assume that the central bank can offer a custodian service such that it receives amounts $\hat{l}$ and $\hat{b}$ of bank loans and bonds, respectively, as collateral from each bank in period 0, transfers the originating bank's collateral to the receiving bank in period 1, and then returns the resulting balance of collateral for each bank in period 2.

Guess and verify that in this case, banks can be committed to not starting bilateral bargaining in period 1. Under this conjecture, the receiving bank would just leave bank transfers unsettled if it bailed out a contract in period 1. Thus, the condition for the receiving bank to remain in a contract becomes

$$\delta\hat{l} + R_B\hat{b} \geq \eta, \tag{13}$$

where the left-hand side is the value of asset transfer to the receiving bank in a contract, and the right-hand side is an increase in its deposit liabilities under a contract.[21]

Under this participation constraint, the optimal contract problem in period 0 is:

$$\begin{aligned} \max_{\{k\geq 0,\, a\geq 0,\, \hat{l}\geq 0,\, \hat{b}\geq 0\}} \quad & R_L k + R_B a - 1 - \frac{1}{2}(R_L\hat{l} + R_B\hat{b} - \eta) + \frac{1}{2}(\delta\hat{l} + R_B\hat{b} - \eta), \\ \text{s.t.} \quad & k + a = 1, \\ & \delta\hat{l} + R_B\hat{b} \geq \eta, \\ & k \geq \hat{l},\ a \geq \hat{b}, \end{aligned} \tag{14}$$

where the first constraint is the flow of funds constraint for each bank in period 0, the second one is the participation constraint for the receiving bank in period 1, and the third line contains the feasibility constraints such that each bank invests into sufficient amounts

[21] If the receiving bank receives a penalty for failed bank transfers, then the penalty is added to the right-hand side of (13) as a negative value.

of assets to submit amounts $\hat{l}$ and $\hat{b}$ of bank loans and bonds, respectively, as collateral in period 0.

Under Assumptions 2 and 4, the solution to this problem is

$$(\hat{l},\ \hat{b},\ k,\ a) = \left(0,\ \frac{\eta}{R_B},\ 1-a,\ \hat{b}\right). \tag{15}$$

This contract reduces the amount of bonds that each bank must invest into in period 0, as implied by (11) and (15). This result obtains because the use of a contract eliminates ex-post bargaining by specifying the terms of settlement of bank transfers in advance.

Now verify the pledgeability of this contract. If banks enter into this contract in period 0 and then either bank bails out of the contract in period 1, banks can transfer only bank loans between them because the central bank keeps their entire bond holdings until period 2, given $a = \hat{b}$. Thus, the bilateral bargaining problem in this case is

$$\max_{\tilde{l}\in[0,k]} [-(R_L\tilde{l} - \eta) - (-\gamma\eta)]^{0.5}(\delta\tilde{l} - \eta)^{0.5}, \tag{16}$$

where the left square bracket and the right parenthesis are the trade surpluses for the originating and the receiving bank, respectively, and $\tilde{l}$ is the amount of bank loans transfered from the originating bank to the receiving bank.

Under Assumption 4, the total trade surplus, $(1+\gamma)\eta/R_L - \eta/\delta$, is negative due to a high loan liquidation cost. Thus, banks do not settle bank transfers outside the contract. Also, each bank in period 1 has a weakly higher payoff from the contract than no settlement of bank transfers, because the contract characterized by (15) leaves each bank break-even, while the originating and the receiving bank's payoff are $-\gamma\eta$ and 0, respectively, in case of no settlement of bank transfers. Therefore, no bank has incentive to bail out of the contract in period 1. Hence:

Proposition 4. Under Assumptions 1, 2, and 4, banks participate into the interbank settlement contract characterized by (15) in period 0.

Note that the central bank cannot offer a better contract than (15), because this contract is the second-best contract under (13). The central bank cannot remove this constraint, as the receiving bank can always choose to leave bank transfers unsettled under limited commitment.

5.1 Characterizing the large value payment system as a contract

The interbank settlement contract described above replicates the key features of the large value payment system. Open market operations can be interpreted as a channel through which banks submit collateral to the central bank. Bank reserves correspond to the balances of collateral under the custody of the central bank. The remittance of bank reserves is equivalent to the reallocation of the balances of collateral to settle bank transfers under the terms of the contract. This result implies that the large value payment system can be characterized as a contract, and improves the efficiency of the interbank payment system by specifying the terms of settlement of bank transfers in advance.

In addition, the central bank in the model can implement the contract only by retaining pledged collateral until the end of the settlement of bank transfers. This result is consistent with the fact that the central bank usually does not have a rule to confiscate bank reserves when a bank opts out of the large value payment system. It is also consistent with the fact that the central bank in practice does not guarantee to release its assets by absorbing bank reserves on demand from banks.

In this regard, it is true that banks in reality hold an inventory of liquid securities besides bank reserves. This inventory, however, is likely for dealing with banks' customers, as it is inefficient if banks maintain an enough amount of liquidity to settle bank transfers outside the large value payment system after adjusting their bank-reserve holdings. Thus, the observation that banks hold an inventory of liquid securities does not contradict the feature of the optimal contract that banks do not keep liquidity to settle bank transfers outside the contract.

5.2 Optimality of the floor system

The optimal contract in the model can be implemented by the floor system. In the floor system, the central bank supplies a sufficiently large amount of bank reserves for interbank payments in advance, so that banks do not need to borrow bank reserves in the interbank money market. To give banks incentive to hold the supplied amount of bank reserves, the central bank pays interest on bank reserves. Consequently, this interest rate determines the short-term nominal interest rate in the financial market. This system has been adopted by New Zealand since July 2006.

In the optimal contract, banks pledge to the central bank the enough amount of bonds to settle possible bank transfers in the future, so that they do not have to settle any bank transfer bilaterally in period 1. This feature of the contract is equivalent to the elimination of the OTC interbank money market, because the bilateral transaction in period 1 can be interpreted as an overnight interbank loan, as described in section 3.5.[22] Also, the central bank in the model passes on to banks the whole return on bonds pledged as collateral. This policy is equivalent to interest payments on bank reserves. Furthermore, the interest paid by the central bank equals that on bonds, i.e., the short-term interest rate in the financial market.

Given this result, it is possible to compare the floor system and the conventional reserve-supply policy within the model, in the latter of which the central bank supplies a partial amount of bank reserves and leaves active transactions in the OTC interbank money market. To feature the conventional policy, suppose that the central bank in the model accepts bonds from each bank as collateral only up to a smaller amount than η/R_B in period 0. In this case, banks can settle only a fraction of bank transfers through the interbank settlement contract, and must leave the rest of bank transfers to be settled through bilateral bargaining

[22]The floor system obviates the need for both secured and unsecured interbank overnight loan transactions. In light of the model, it is sufficient for efficiency if secured transactions due to limited commitment are eliminated.

in period 1. This policy requires banks to prepare a larger amount of bonds in period 0 than the floor system, because of a premium for the bilateral settlement of bank transfers in period 1.[23,24]

It is also possible to extend the model to incorporate another contract featuring the channel system. In the channel system, the central bank supplies bank reserves to banks through daylight overdrafts. If a bank runs an overnight credit position in bank reserves, then it receives interest. But a bank must pay a higher interest rate if it runs a debit position. Given the threat point created by the two central-bank interest rates, banks cancel out debit and credit positions in bank reserves by arranging interbank loans in the OTC interbank money market. It can be shown that a contract featuring the channel system requires banks to prepare a larger amount of bonds in period 0 than the optimal contract, because it utilizes the bilateral settlement of bank transfers in period 1. See appendix D for more details.

These results clarify that the optimality of the floor system is not solely due to the Friedman's rule. While interest payments on bank reserves are necessary to minimize the cost for banks to hold bank reserves, the optimality of the floor system also rests on the presence of the large value payment system, which makes it possible to eliminate the bilateral settlement of bank transfers, or the OTC interbank money market, by an ample supply of bank reserves.

5.3 Robustness of the model to the convertibility between cash and bank reserves

The model abstracts from the fact that banks can convert bank reserves into cash at par any time. Given the status of cash as legal tender, depositors in reality can withdraw cash

[23]Splitting bank transfers into multiple lots does not affect the baseline model, because the bargaining problem in period 1, (7), is linear to the size of bank transfers to be settled, η. Thus, the result of the model remains the same even if banks bargain over multiple lots of bank transfers simultaneously.

[24]Here the conventional policy still incorporates interest payments on bank reserves, as the central bank earns zero profit in this policy. To replicate no interest on bank reserves in the conventional policy, simply assume that the central bank returns only a fraction of bonds submitted as collateral to banks in period 2. This policy further increases the amount of liquidity necessary to settle bank transfers.

from banks to pay it to their sellers even if bank transfers are unavailable. Cash payments, however, are imperfect substitutes to bank transfers because of a higher physical transaction cost. Thus, the convertibility between cash and bank reserves does not eliminate a penalty that depositors impose on banks for failed bank transfers. The transaction cost would be also high if banks withdrew cash from the central bank and settled bank transfers between them with cash outside the large value payment system. It is implicitly assumed that banks do not have incentive to pay such a high transaction cost.

6 Can a private clearing house replace the central bank?

So far, the custodian of collateral in the interbank settlement contract has been assumed to be the central bank. Can a private clearing house take over the role of the central bank? This question is motivated by recent developments of private electronic interbank payment systems, such as the Clearing House Interbank Payment System (CHIPS).[25] While CHIPS is currently only a netting mechanism in which the net balance of bank transfers for each bank is settled through a transfer of bank reserves at the central bank in each day, its existence implies that it is technologically possible to replace the central bank's electronic large value payment system.

The model indicates two issues. First, the custodian of collateral must be able to be committed to returning collateral to banks after the settlement of bank transfers. Indeed, the central bank in practice occasionally releases its assets by absorbing bank reserves through open market operations. This action can be interpreted as the return of collateral to banks. In history, the New York Clearing House, the first private clearing house in the U.S. preceding the Federal Reserve, issued specie certificates in exchange for gold, so that member banks

[25]These private interbank payment systems are also called large value payment systems. CHIPS mainly clears large-valued bank transfers on the dollar side in foreign exchange trades. The net balances of bank transfers in CHIPS are settled by the transfers of bank reserves at the Fedwire at the end of each day. Another private interbank payment system is CLS, which allows a payment versus payment settlement between multiple currencies. See Kahn and Roberts (2001) for more details on CLS.

could settle checks with specie certificates rather than a physical transfer of gold (Gorton 1984.)[26] Thus, historical evidence suggests that a private clearing house can install a proper governance structure, such as mutual ownership by member banks, to be committed to returning collateral to its member banks.

The other issue is the range of eligible collateral. In practice, collateral policies differ among clearing houses. For example, while the Federal Reserve limits eligible collateral to government-guaranteed securities in normal time, the European Central Bank accepts private securities for a large portion of collateral on a regular basis.[27] As to private clearing houses, CHIPS accepts only bank reserves for collateral.[28] In history, the New York Clearing House issued loan certificates against member banks' portfolios during banking panics between 1857 and 1914. Banks could use the loan certificates to settle checks among them, so as to save gold for the repayment of deposits during the banking panics.

The model implies that the large value payment system saves more liquidity if the custodian of collateral can accept a wider range of collateral.[29] It is an open question what determines the range of eligible collateral for a clearing house. For this question, an interesting fact is that when the New York Clearing House issued loan certificates, it had power to supervise member banks regularly to expel unsound banks from its membership. As described by Gorton (1984), it needed to monitor the financial health of its member banks to prevent troubled banks from covertly submitting non-performing assets as collateral. Thus, a clearing house's ability to supervise its member banks may determine the range of collateral it can accept. A further investigation into this question is left for future research.[30]

[26]The New York Clearing House is currently running CHIPS.

[27]See Cheun, von Köppen-Mertes, and Weller (2009) for more details.

[28]In this system, participating banks must prepay bank reserves through the Fedwire to run negative net positions of bank transfers in the system in the course of each day.

[29]For example, see section 5.2.

[30]A related issue is tiering. In this arrangement, the central bank limits the membership of its large value payment system to a small number of large banks. As a result, small banks settle bank transfers through deposit balances at these large banks. As analyzed by Kahn and Roberds (2009) and Chapman and Martin (2013), this arrangement can be seen as delegated monitoring for the central bank. Alternatively, this paper's model suggests that tiering occurs if some banks are too small to handle wholesale securities

7 Conclusions

This paper shows that a hold-up problem in the bilateral settlement of bank transfers results in an endogenous need for the large value payment system operated by the central bank. In light of this result, the large value payment system is a collateralized interbank settlement contract, in which bank reserves are the balances of collateral under the custody of the central bank. The optimal contract corresponds to the floor system.

To clarify these results in a simple set-up, this paper abstracts from the fiscal cost of interest payments on bank reserves for the consolidated government. In the literature, Berentsen, Marchesiani and Waller (2014) compare the channel and the floor system with a financial constraint on the central bank. It is left for future research to analyze the optimal interbank payment system with such a constraint.

It still remains an open question if a private clearing house can replace the central bank in the interbank payment system. The model implies that it depends on whether a private clearing house can accept a wider range of collateral than the central bank. In this regard, historical experience suggests a possible linkage between a clearing house's ability to supervise member banks and the range of eligible collateral it can accept. In addition, the model abstracts from a financial crisis, focusing on the regular function of the interbank payment system. A further investigation into these issues is left for future research.

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used as collateral in the large value payment system.

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Appendices

A Baseline model with a formal assumption about depositors

A.1 Preference and technology

Time is discrete and indexed by $t = 0, 1, 2$. There are two banks indexed by $i = A, B$. Each bank has a fixed customer base consisting of a unit continuum of risk-neutral depositors. Each depositor is endowed with a unit of goods in period 0. A depositor can save its good in two ways. One is storage technology, in which a depositor can store its good without depreciation or appreciation between consecutive periods. The other is a bank deposit. If a depositor deposits its good in period 0, then the depositor's bank can transform the good into a bank loan or a bond in that period. A bank loan generates an amount R_L of goods in period 2 per invested good. Similarly, the gross rate of return on a bond in period 2 is R_B. Assume that

$$R_L > R_B > 1, \tag{17}$$

in which the last term is the gross rate of return on storage.

Each depositor becomes a buyer or a seller due to an idiosyncratic preference shock in period 1. A buyer can consume goods produced by sellers at the other bank in period 1, but cannot consume goods in period 2. A seller can produce goods at a unit utility cost per good in period 1, and consume goods in period 2. Each depositor maximizes the following expected utility:

$$U = p_1 \rho c_{b,1} + (1 - p_1)(-h_{s,1} + c_{s,2}). \tag{18}$$

where: p_1 is the unconditional probability to be a buyer in period 1 for each depositor in period 0; $c_{b,1}$ is the consumption in period 1 in case of becoming a buyer; $h_{s,1}$ and $c_{s,2}$ are the production in period 1 and the consumption in period 2, respectively, in case of becoming a seller; and ρ (> 0) is the weight on utility in case of becoming a buyer. Assume that ρ is arbitrarily large.

A.2 Deposit contracts

There exists a competitive goods market so that buyers can buy goods from sellers in period 1. Depositors, however, are anonymous to each other; thus, buyers cannot buy goods on credit. Banks can offer a deposit contract in which buyers can order their bank to remit deposit balances from their accounts to the sellers' bank accounts in period 1. Hence, buyers can pay the price of goods in period 1 by bank transfers.

For simplicity, assume that depositors can punish a defaulting bank so much that each bank can be committed to repaying the outstanding balance of deposits in period 2 without enforcement by the court. Each bank can set the deposit interest rate for its depositors monopolistically in period 0, given the assumption that the customer base for each bank is fixed. To satisfy the participation constraint for depositors, a bank cannot set a deposit rate lower than zero, because in such a case, depositors would be better off by storing goods by themselves. Furthermore, a bank does not gain from setting a positive bank-transfer fee for buyers, because in such a case, a bank must offer an arbitrarily high deposit interest rate to keep depositors indifferent between a deposit contract and storage in period 0, given the assumption that ρ is arbitrarily large. Thus, banks offer a deposit contract with a zero deposit interest rate and a zero bank-transfer fee in period 0.

Neither depositor or bank can generate goods by terminating bank loans or bonds in period 1. Hence, the maturity of deposits comes in period 2.

A.3 Probability distribution of bank-transfer requests

The buyer fraction of depositors at each bank is stochastic. For $i = A, B$, λ_i denotes the buyer fraction of depositors at bank i. The joint probability distribution of λ_A and λ_B is

$$(\lambda_A,\ \lambda_B) = \begin{cases} (\eta,\ 0) & \text{with probability } 0.5, \\ (0,\ \eta) & \text{with probability } 0.5, \end{cases} \tag{19}$$

where $\eta \in (0, 1)$. Given (2), the unconditional probability for each depositor to be a buyer, i.e., p_1, is

$$p_1 = 0.5\eta. \tag{20}$$

The depositor's utility function, (18), implies that the relative price of goods in period 1 in terms of goods in period 2 equals one. It also implies that buyers spend all of their deposits to buy goods from sellers in period 1. Thus, η equals the fraction of deposits to be sent to the other bank.

A.4 Settlement of bank transfers

Assume that banks cannot be committed to any future behavior between them. Thus, they need to settle bank transfers by transferring bank loans and bonds between them after the realization of λ_A and λ_B in period 1. Bonds are transferable at no physical transaction cost. In contrast, if a bank sells its bank loans to the other bank in period 1, then the gross rate of return on the transfered bank loans becomes δ ($\in (0, R_L]$). The difference between R_L and δ can be interpreted as a loan monitoring cost incurred by the bank purchasing the bank loans.

Also assume that the interbank market is an OTC market; so banks bargain over the terms of settlement bilaterally. The outcome of bargaining is determined by Nash bargaining in which each bank has equal bargaining power. If banks do not reach any agreement, then no bank transfer is made. In this case, the originating bank must incur a cost γ (> 0) per failed bank transfer in period 2. This cost can be interpreted as representing a long-term cost due to loss of reputation, or a cost payable in period 2 due to a litigation filed by depositors for failed payments. In contrast, the cost of failed settlement of bank transfers for the receiving bank, i.e., the bank with $\lambda_i = 0$, is normalized to zero. Thus, the originating bank must pay a higher penalty for failed settlement of bank transfers than the receiving bank. The underlying assumption is that a deposit contract includes the right to send a bank transfer on demand, for which the originating bank is liable, but the receiving bank is not.

A.5 Each bank's objective and the definition of equilibrium

In period 2, each bank receives returns on its bank loans and bonds, repays deposits given a zero deposit interest rate, and consumes the residual as its profit. Each bank is risk-neutral, and chooses its portfolio of bank loans and bonds in period 0 to maximize the expected profit in period 2. An equilibrium is a Perfect Bayesian Nash equilibrium for the two banks.

B Proof for (8) and (9)

Given $\delta < R_L$, the first-order conditions for the bargaining problem, (7), with respect to l and b are:

$$-\frac{R_L}{-[R_L l + R_B b - \eta] + \gamma\eta} + \frac{\delta}{\delta l + R_B b - \eta} + \underline{\theta}_l - \overline{\theta}_l = 0, \tag{21}$$

$$-\frac{R_B}{-[R_L l + R_B b - \eta] + \gamma\eta} + \frac{R_B}{\delta l + R_B b - \eta} - \overline{\theta}_b = 0, \tag{22}$$

where $\underline{\theta}_l$, $\overline{\theta}_l$, and $\overline{\theta}_b$ are proportional to the non-negative Lagrange multipliers for $0 \leq l$, $l \leq k$, and $b \leq a$. The Lagrange multiplier for the other constraint, $0 \leq b$, is always zero, because it is positive only if $\underline{\theta}_l > \overline{\theta}_l$. Note that if $\underline{\theta}_l > \overline{\theta}_l$, then $b = l = 0$, under which $\delta l + R_B b - \eta$ is negative.

Given that the denominator in each side is the same across the two conditions and the assumption that $R_L \geq \delta$, $\underline{\theta}_l = \overline{\theta}_l = \overline{\theta}_b = 0$ cannot hold. Thus, there are four cases to consider: $\{l = 1-a,\ b = a\}$; $\{l \in (0,\ 1-a),\ b = a\}$; $\{l = 0,\ b = a\}$; and $\{l = 0,\ b \in (0, a)\}$.

In the first case, $\underline{\theta}_l = 0$ and $\overline{\theta}_l \geq 0$. For this case to happen, it must hold that

$$\frac{R_L}{-[R_L(1-a) + R_B a - \eta] + \gamma\eta} \leq \frac{\delta}{\delta(1-a) + R_B a - \eta}. \tag{23}$$

Given (22) and the assumption $R_L \geq \delta$, $\overline{\theta}_b > 0$.

In the second case, $\underline{\theta}_l = \overline{\theta}_l = 0$. In this case, (21) implies that

$$\exists l \in (0,\ 1-a),\ \text{s.t.}\ \frac{R_L}{-[R_L l + R_B a - \eta] + \gamma\eta} = \frac{\delta}{\delta l + R_B a - \eta}. \tag{24}$$

Given (22) and the assumption $R_L \geq \delta$, $\overline{\theta}_b > 0$.

In the third case, $\underline{\theta}_l \geq 0$, $\overline{\theta}_l = 0$, and $\underline{\theta}_b \geq 0$. Thus, (22) implies

$$\frac{R_B}{-[R_B a - \eta] + \gamma\eta} \leq \frac{R_B}{R_B a - \eta}. \tag{25}$$

Also, (21) implies

$$\frac{R_L}{-[R_B a - \eta] + \gamma\eta} \geq \frac{\delta}{R_B a - \eta}. \tag{26}$$

In the fourth case, $\underline{\theta}_l \geq 0$, $\overline{\theta}_l = 0$, and $\underline{\theta}_b = 0$. Hence:

$$\exists b \in (0,\ a),\ \text{s.t.}\ \frac{R_B}{-[R_B b - \eta] + \gamma\eta} = \frac{R_B}{R_B b - \eta}. \tag{27}$$

This condition is sufficient for (21) under $l = 0$ and $\underline{\theta}_l \geq \overline{\theta}_l = 0$, given the assumption $R_L \geq \delta$.

Summarizing the four cases, the solutions for l and b under $\delta < R_L$ take the following form:

$$(l(a),\ b(a)) = \begin{cases} (1-a,\ a), & \text{if } R_B a - \eta \leq \frac{\delta\gamma\eta - 2R_L\delta(1-a)}{R_L+\delta}, \\ \left(\frac{\delta\gamma\eta - (R_L+\delta)[R_B a - \eta]}{2R_L\delta},\ a\right), & \text{if } R_B a - \eta \in \left(\frac{\delta\gamma\eta - 2R_L\delta(1-a)}{R_L+\delta},\ \frac{\delta\gamma\eta}{R_L+\delta}\right), \\ (0,\ a), & \text{if } R_B a - \eta \in \left[\frac{\delta\gamma\eta}{R_L+\delta},\ \frac{\gamma\eta}{2}\right], \\ \left(0,\ \frac{1}{R_B}\left[\eta + \frac{\gamma\eta}{2}\right]\right), & \text{if } R_B a - \eta > \frac{\gamma\eta}{2}, \end{cases} \tag{28}$$

if both banks have non-negative trade surpluses in each case.

In the third and the fourth case, it is immediate that both banks have non-negative trade surpluses. In the second case, the necessary and sufficient condition for non-negative trade surpluses for both banks is

$$\delta\gamma\eta + (R_L - \delta)[R_B a - \eta] \geq 0. \tag{29}$$

In the first case, the necessary and sufficient conditions for non-negative trade surpluses are:

$$\gamma\eta \geq R_L(1-a) + R_B a - \eta, \tag{30}$$

$$\delta(1-a) + R_B a - \eta \geq 0. \tag{31}$$

If (29) and (30)-(31) are not satisfied in the second and the first case, respectively, then banks do not settle bank transfers in period 1 in that case.

Now show the following lemma:

Lemma 1. Under Assumption 1, $(l(a),\ b(a)) = (1-a, a)$ never occurs in equilibrium.

Proof. This lemma is equivalent to say that the first case of (28) does not exist for any $a \in [0,1]$, or violates (30) or (31). First, a necessary condition for the existence of the first case is that there exists $a \in [0,1]$ such that

$$R_B a - \eta \leq \frac{\delta\gamma\eta - 2R_L\delta(1-a)}{R_L + \delta}, \tag{32}$$

as implied by (28). Note that both sides of this condition are increasing linear functions of a and also that the left-hand side is higher than the right-hand side at $a = 1$ under Assumption 1. Thus, there exists $a \in [0,1]$ satisfying (32) if and only if the intercept of the left-hand side is lower than that of the right-hand side:

$$-\eta < \frac{\delta\gamma\eta - 2R_L\delta}{R_L + \delta}. \tag{33}$$

If this condition is violated, then the first case does not exist for any $a \in [0,1]$.

Suppose that (33) holds. This condition is equivalent to

$$(\eta - \delta)R_L > \delta[R_L - (1+\gamma)\eta]. \tag{34}$$

Thus, $\eta > \delta$, and hence $R_B > \delta$, follows given Assumption 1. For the first case to exist in this case, both (30) and (31) must be satisfied. Given $R_B > \delta$, these two conditions can be written as

$$a \geq \max\left\{\frac{R_L - (1+\gamma)\eta}{R_L - R_B}, \frac{\eta - \delta}{R_B - \delta}\right\}, \tag{35}$$

where the first and the second term in the max operator are derived from (30) and (31), respectively. Under (33) and Assumption 1, it can be shown that:

$$\begin{aligned}
&\frac{R_L - (1+\gamma)\eta}{R_L - R_B} - \frac{\eta - \delta}{R_B - \delta} \\
&\qquad \propto R_L(R_B - \delta) - (1+\gamma)\eta(R_B - \delta) - \eta(R_L - R_B) + \delta(R_L - R_B) \\
&\qquad = R_L(R_B - \eta) + (\eta - \delta)R_B - (1+\gamma)\eta(R_B - \delta) \\
&\qquad = R_L(R_B - \eta) + (\eta - \delta)R_B - (1+\gamma)\eta(R_B - \eta + \eta - \delta) \\
&\qquad = [R_L - (1+\gamma)\eta](R_B - \eta) + (\eta - \delta)[R_B - (1+\gamma)\eta] > 0.
\end{aligned} \tag{36}$$

The inequality holds due to $\eta > \delta$ under (33). Thus, (30) is sufficient for (31) under (33) and Assumption 1.

Finally, show that (30) is violated in the first case of (28), if (33) and Assumption 1 hold. In this case, the first case of (28) can exist only for $a \in [0, a^*]$ such that

$$R_B a^* - \eta = \frac{\delta\gamma\eta - 2R_L\delta(1 - a^*)}{R_L + \delta}. \tag{37}$$

The root for this equation can be explicitly solved as

$$a^* = \frac{R_L(\eta - \delta) - \delta[R_L - (1+\gamma)\eta]}{R_L(R_B - \delta) - \delta(R_L - R_B)}. \tag{38}$$

It can be shown that

$$
\begin{aligned}
a^* - \frac{R_L-(1+\gamma)\eta}{R_L-R_B} & \\
&\propto R_L(\eta-\delta)(R_L-R_B)-\delta[R_L-(1+\gamma)\eta](R_L-R_B) \\
&- R_L(R_B-\delta)[R_L-(1+\gamma)\eta]+\delta(R_L-R_B)[R_L-(1+\gamma)\eta] \\
&= R_L(\eta-\delta)(R_L-R_B)-R_L(R_B-\delta)[R_L-(1+\gamma)\eta] \\
&\propto \frac{\eta-\delta}{R_B-\delta}-\frac{R_L-(1+\gamma)\eta}{R_L-R_B}<0, \quad (39)
\end{aligned}
$$

where the last inequality is implied by (36). Thus, a^* is below the lower bound for a that satisfies (30). Hence, banks cannot have non-negative trade surpluses in the first case of (28), if (33) holds. □

It remains to pin down the range of a for the second case of (28). The necessary and sufficient condition for non-negative trade surpluses in the second case of (28), i.e., (29), implies

$$
a \geq \frac{1}{R_B}\left(\eta-\frac{\delta\gamma\eta}{R_L-\delta}\right). \tag{40}
$$

Now show that the right-hand side of this condition is higher than the lower bound for a satisfying the range of $R_B a-\eta$ in the second case of (28).

If (33) is violated, then (32) never holds for $a \in [0,1]$ as shown in the proof for Lemma 1. In this case, the range of $R_B a-\eta$ in the second case of (28) does not have a non-negative lower bound for a, so (40) becomes the lower bound for a in the second case of (28).

If (33) is satisfied, it can be shown that the right-hand side of (40) is greater than a^* in

(38), that is, the root for (37):

$$
\begin{aligned}
&\frac{1}{R_B}\left(\eta - \frac{\delta\gamma\eta}{R_L-\delta}\right) - a^* \\
&\quad \propto \eta[R_L-(1+\gamma)\delta][(R_L+\delta)R_B - 2\delta R_L] - \{\eta[R_L+(1+\gamma)\delta] - 2\delta R_L\}(R_L-\delta)R_B \\
&\qquad = \eta R_L(2\delta R_B - 2\delta R_L) - \eta(1+\gamma)\delta(2R_L R_B - 2\delta R_L) + 2\delta R_L(R_L-\delta)R_B \\
&\qquad = 2\delta R_L\left[-\eta(R_L-R_B) - \eta(1+\gamma)(R_B-\delta) + R_B(R_L-\delta)\right] \\
&\qquad \propto -\eta(R_L-R_B) - \eta(1+\gamma)(R_B-\delta) + R_B(R_L-R_B+R_B-\delta) \\
&\qquad = (R_L-R_B)(R_B-\eta) + (R_B-\delta)[R_B-(1+\gamma)\eta] > 0. \qquad (41)
\end{aligned}
$$

The last inequality follows from $R_B > \delta$ under Assumption 1 and (33), as implied by (34).

Thus, (40) is the lower bound for a in the second case of (28) regardless of whether (33) is satisfied. Banks do not make any deal in period 1 if the value of a is lower than the right-hand side of (40).

C Proof for Proposition 2

If $l(a) = 0$ at the optimum of the bargaining problem (10), then each bank chooses the lower bound for a such that $l(a) = 0$, because an increase in the bond holdings only results in a transfer of more bonds in case of an outflow of bank transfers as long as $l(a) = 0$, as implied by (8). Hereafter, denote the lower bound for a such that $l(a) = 0$ by $\hat{a}$.

Next, compare $\hat{a}$ and the value of a such that $l(a) > 0$. For the range of a such that $l(a) > 0$, the objective function in the profit maximization problem for a bank in period 0, (10), can be written as

$$
\begin{aligned}
\Pi(a,\ a') \equiv\ & R_L(1-a) + R_B a - 1 \\
&+ \frac{1}{2}\left\{-R_L\frac{\delta\gamma\eta - (R_L+\delta)(R_B a - \eta)}{2R_L\delta} - R_B a + \eta\right\} + \frac{1}{2}\phi(a'). \qquad (42)
\end{aligned}
$$

The derivative of this function with respect to a is

$$\frac{\partial \Pi(a,\ a')}{\partial a} = -R_L + R_B + \frac{1}{2}\left[\frac{R_L(R_L+\delta)R_B}{2R_L\delta} - R_B\right] \tag{43}$$

$$= -R_L + R_B + \frac{1}{2}\frac{R_L-\delta}{2\delta}R_B \tag{44}$$

$$\propto R_L R_B - \delta(4R_L - 3R_B). \tag{45}$$

Because the objective function in the profit maximization problem for a bank in period 0, (10), is continuous at both $\hat{a}$ and the upper bound for a such that $l(a) > 0$, choosing a value of a such that $l(a) > 0$ is dominated by choosing $a = \hat{a}$ in period 0 if

$$\delta < \frac{R_L R_B}{4R_L - 3R_B}. \tag{46}$$

Finally, find the condition under which choosing $a = \hat{a}$ in period 0 dominates no settlement of outgoing bank transfers. If no settlement of outgoing bank transfers is optimal for a bank, then each bank sets $a = 0$ in period 0 because it does not need any liquidity for interbank settlement in period 1. Thus, choosing $a = \hat{a}$ in period 0 dominates no settlement of outgoing bank transfers if and only if

$$\begin{aligned} R_L\left[1 - \frac{1}{R_B}\left(\eta + \frac{\delta\gamma\eta}{R_L+\delta}\right)\right] + R_B\left[\frac{1}{R_B}\left(\eta + \frac{\delta\gamma\eta}{R_L+\delta}\right)\right] - 1 \\ + \frac{1}{2}\left[-R_B\frac{1}{R_B}\left(\eta + \frac{\delta\gamma\eta}{R_L+\delta}\right) + \eta\right] + \frac{1}{2}\phi(a') \\ > R_L - 1 + \frac{1}{2}(-\gamma\eta) + \frac{1}{2}\phi(a'), \end{aligned} \tag{47}$$

where the left- and the right-hand side are the expected payoff for a bank with $a = \hat{a}$ and $a = 0$, respectively. This condition is equivalent to

$$\delta < \frac{R_L[(2+\gamma)R_B - 2R_L]}{2(R_L - R_B)(1+\gamma)}, \tag{48}$$

because

$$-\left(\frac{R_L}{R_B}-1\right)\left(\eta+\frac{\delta\gamma\eta}{R_L+\delta}\right)+\frac{1}{2}\left(-\frac{\delta\gamma\eta}{R_L+\delta}\right)-\frac{1}{2}(-\gamma\eta)$$
$$\propto -2\left(\frac{R_L}{R_B}-1\right)\eta[R_L+(1+\gamma)\delta]+\gamma\eta R_L$$
$$= -2\left(\frac{R_L}{R_B}-1\right)\eta(1+\gamma)\delta+\eta R_L\left[\gamma-2\left(\frac{R_L}{R_B}-1\right)\right]. \quad (49)$$

If both (46) and (48) hold, then it is optimal for a bank to choose $a=\hat{a}$ in period 0. Under Assumption 2, (46) is sufficient for (48) as

$$\frac{R_L[(2+\gamma)R_B-2R_L]}{2(R_L-R_B)(1+\gamma)}-\frac{R_LR_B}{4R_L-3R_B}$$
$$\propto [(2+\gamma)R_B-2R_L](4R_L-3R_B)-2(R_L-R_B)(1+\gamma)R_B$$
$$=\gamma R_B(4R_L-3R_B)-2(R_L-R_B)(4R_L-3R_B)$$
$$-2(R_L-R_B)(1+\gamma)R_B$$
$$=(2R_L-R_B)[\gamma R_B-4(R_L-R_B)]. \quad (50)$$

Assumption 4, in turn, is sufficient for (46) under Assumption 2, because

$$\frac{R_LR_B}{4R_L-3R_B}-\frac{R_L}{1+\gamma} \propto R_B(1+\gamma)-(4R_L-3R_B) \quad (51)$$
$$=-4(R_L-R_B)+R_B\gamma. \quad (52)$$

Thus, Assumptions 2 and 4 are sufficient for $a=\hat{a}$ in period 0.

D Comparison between the channel system and the floor system

This section confirms the optimality of the floor system in comparison to an alternative modern reserve-supply policy, the so-called channel system. This system has been adopted by Australia, Canada, the Euro area, Norway, and the U.K. In this system, the central bank supplies only a tiny, or even no, amount of bank reserves to banks overnight. For example, the targeted overnight balance of bank reserves in Canada was zero for March 2006 to May 2007. The central bank, however, allows a large volume of collateralized overdrafts of bank reserves during each day, so that banks can smoothly send bank reserves to each other to settle bank transfers among them. The settlement of bank transfers is final immediately after bank reserves are transferred to the receiving bank, because the central bank guarantees the transfer of bank reserves in any event.

At the end of each day, an imbalance between outgoing and incoming bank transfers for each bank results in a distribution of debit and credit positions of bank reserves across banks. If these positions are left overnight, then the central bank charges a higher interest rate on a debit position than the interest rate that it pays on a credit position. Typically, banks arrange overnight loans of bank reserves in the interbank money market, so that no bank has a debit position of bank reserves overnight. The interbank interest rate tends to fall between the two central-bank interest rates on bank reserves.

D.1 Extension of the model to nest the channel system

To nest the channel system in the model, consider the following contract. In period 0, the central bank requires each bank to pledge an amount $(1 + f)\eta/R_B$ of bonds as collateral, where f is the central-bank interest rate on overnight credit positions of bank reserves, which will be defined below. This collateral corresponds to the collateral for an intraday overdraft of bank reserves at the central bank in reality. In period 1, the central bank guarantees the settlement of bank-transfer requests to each bank, $(\lambda_A,\ \lambda_B)$, immediately after they are realized. This assumption reflects the fact that the central bank provides intraday overdrafts of bank reserves and the finalty of bank-reserve transfers in the channel system. If no action is taken afterwards, then the central bank charges the originating bank an interest rate, f, on the face value of bank transfers, η. This interest charge is subtracted from collateral pledged by the originating bank in period 0; thus, no collateral is returned to the originating bank in this case. Also, the central bank adds an amount $(1 + d)\eta/R_B$ of bonds to the receiving bank's collateral, where d is the overnight interest rate on a credit position of bank reserves. Assume $f \geq d \geq 0$, so that the central bank has enough bonds to pass to the receiving bank. The central bank returns the remaining balance of collateral to each bank in period 2.

If the receiving bank sends a reverse transfer of bank reserves, η, to the originating bank, then the net transfer of bank reserves becomes zero for each bank. In this case, the central bank neither charges or adds interest on any bank's collateral in period 1. Assume that after the realization of bank-transfer requests from depositors in period 1, banks can negotiate the terms of a reverse transfer of bank reserves through Nash bargaining with equal bargaining power for each bank. This transaction corresponds to an overnight repo in the OTC interbank money market, as a direct payment of assets in period 1 and an interbank repo due in period 2 are equivalent in the model (see section 3.5 for this property of the model.)

D.2 Equilibrium with the channel system

Now solve the bargaining problem for a reverse transfer of bank reserves in period 1. This problem can be written as:

$$\max_{b' \geq 0} \{-(R_B b' - \eta) - (-f\eta)\}^{0.5} [R_B b' - \eta - d\eta]^{0.5}, \tag{53}$$

where b' is the amount of bonds that the originating bank pays to the receiving bank for a reverse transfer of bank reserves. The left curly and the right square bracket in (53) are the trade surpluses for the originating and the receiving bank, respectively. Note that the threat point is determined by interest rates on overnight debit and credit positions of bank reserves, f and d, because bank transfers requested by depositors have been settled before the bargaining.

The solution to this problem is

$$b' = \left(1 + \frac{f+d}{2}\right) \frac{\eta}{R_B}. \tag{54}$$

Thus, the interbank interest rate, $(f+d)/2$, falls between the two central-bank interest rates, f and d.

To minimize the friction associated with the contract, assume that the originating bank can receive a reverse transfer of bank reserves to pay off an overdraft at the central bank at the same time as it takes back collateral from the central bank and pays it to the receiving bank. Hence, paying b' is feasible as it is less than the amount of bonds pledged as collateral to the central bank, $(1+f)\eta/R_B$.

In reality, an originating bank in the channel system cannot make these transactions simultaneously. Thus, it cannot take back collateral from the central bank before having a reverse transfer of bank reserves from a receiving bank. See Neville and McVanel (2006) for an example in Canada. The result described below shows that even without such a friction, the channel system is dominated by the floor system.

D.3 Liquidity costs associated with the channel system

Overall, each bank in this contract must invest into an amount $(1+f)\eta/R_B$ of bonds in period 0. To minimize the amount of bonds necessary, the central bank must set $f = d = 0$. Note that this policy eliminates incentive for banks to trade in period 1, and makes the contract equivalent to the optimal contract shown in section 5, which corresponds to the floor system. Thus, the floor system dominates the channel system, as long as the channel system involves the active use of the OTC interbank money market.

This result illustrates two liquidity costs associated with the channel system. First, allowing banks to have an intraday debit position of bank reserves raises a collateral requirement for banks, because the central bank must make sure that an overnight debit position of bank reserves is secured even if a bank does not repay an intraday debit position of bank reserves by the end of the day.

Second, even if the central bank can induce banks to pay off an intraday debit position of bank reserves without collateral, banks still need to hold the amount of bonds necessary to settle bank transfers in the OTC interbank money market in period 1, i.e., b'. If f and d are set positive as is usual in the channel system, then the value of b' exceeds the amount of bonds necessary for the floor system, i.e., η/R_B. This result holds because raising f and d strengthens the bargaining position of the receiving bank against the originating bank. Thus, the active use of the OTC interbank money market makes the liquidity-saving effect of the channel system smaller than that of the floor system.