

An Agent-Based Model of Strategic Adoption of Real-Time Payments

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ABSTRACT

Real-time payments (RTPs) allow consumers to receive funds before the completion of payment clearing and settlement. This early, irrevocable release of funds represents a credit risk to banks in the event there are issues with the payment, such as the consumer's deposit holdings being insufficient to cover the payment they are sending. We investigate the effects such risks may have on the strategic adoption of RTPs by banks. We define a network game in which consumer nodes with deposit holdings are assigned to bank nodes responsible for routing consumer payments within the network. Bank nodes make a strategic decision regarding which consumers may send RTPs in the network by selecting from a set of available strategies based on the initial deposits of the consumers. Using agent-based modeling and empirical game-theoretic analysis, we analyze this strategic decision in various game configurations. Our results show that bank nodes tend to choose strategies that allow many, but not all, consumer nodes to send RTPs. We find that this outcome in strategic equilibrium reduces successful payments and increases the incidence of insufficient funds availability, compared to a setting where RTPs are universally enabled. This manifests in our model because RTP enables receivers of payments to turn around those funds more quickly to make payments of their own. As a result, banks are better off when all payments are real-time, but a strategic bank node is inclined to avoid the liability of allowing its own depositors to use RTPs when the risk is considered high.

KEYWORDS

real time payments, financial network, game theory

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1 INTRODUCTION

The distinction between a standard payment and a *real-time payment* (RTP) lies in the speed and availability of the payment. Any payment mechanism defines a series of steps that must occur for

the payment to be executed. To initiate a payment, the *payer* (entity sending payment) issues a request to their payment service provider (PSP), say a bank. The request entails removal of funds from the payer's account and routing the payment to the bank account of the *payee* (entity receiving payment). These steps encompass the *clearing* and *settlement* functions, which for a standard payment must be accomplished for the payee's bank to credit the payee's account. Clearing and settlement can delay completion of the payment, for example due to grouping of payments into batches for processing, and communication required among banks to verify sufficiency of funds. These delays can be particularly significant for payments initiated outside of business hours.

A real-time payment allows the payee to receive the funds immediately. We focus on the *deferred settlement* case, in which an irrevocable credit of funds to the payee's account occurs before the clearing and settlement steps. Even if payment is initiated outside of regular business hours, the payee can still expect to receive the funds immediately, though the processing of the remainder of the payment steps is subject to business hours and batch processing as a standard payment [Committee on Payments and Market Infrastructures 2016].

Many RTP systems are in use today, including the Internet Banking System in China, the Real-Time Clearing system in South Africa, and the Faster Payments Service of the United Kingdom [Committee on Payments and Market Infrastructures 2016]. The US Federal Reserve is set to launch a real-time payment system, FedNow, in 2023 [Federal Reserve Board 2021]. The increasing provision of such services is driven by consumer demand. In cases where merchants insist on receiving funds before sending goods, RTPs enable the payer to receive their goods sooner. The merchant also benefits from more immediate opportunity to employ the funds in the business. However, deferring settlement necessitates that banks take on a credit risk. They face liability in the event problems arise, for instance due to fraud or other errors. The expediency of RTPs can also make it more difficult to catch potential problems before the payment is sent.

We seek to understand how such issues might impact bank adoption of RTP systems, particularly how they decide whom to offer real-time payment options. We develop an agent-based model that supports standard and real-time payments sent by consumer nodes and routed through bank nodes in a financial network. We model the risk of bank nodes using a scenario in which consumer nodes sending RTPs may initiate payments that exceed their deposit holdings. These *insufficient payments* are possible due to the deferred settlement feature of RTPs, delaying the verification of the payer's deposits until after the payment process has already begun. When such problematic payments occur, our model assigns liability to the payer's bank. We assume bank nodes in our model are willing to

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extend short-term credit to consumer nodes sending RTPs. When an insufficient payment occurs, the consumer node draws on this credit and transfers short-term liability of the remainder of the payment's value to its bank.

To study the problem of real-time payment adoption, we define a *game* played by strategic bank nodes. The decision facing bank nodes is which consumers, if any, should be allowed to send real-time payments in the network. The banks select from strategies that set varying thresholds on the amounts consumers must deposit in the bank in order to be allowed to send RTPs. Banks must strategically balance benefits of offering RTP, including the ability to attract consumers, with the cost of exposure to covering insufficient payments. We use a process known as *empirical game-theoretic analysis* (EGTA) [Tuyts et al. 2020; Wellman 2016] to identify Nash equilibria of our game under a variety of configurations.

Our contributions can be summarized as follows:

- (1) formulating the the real-time payments adoption question as a strategic decision made by banks;
- (2) defining an agent-based financial credit network model that supports standard and real-time payments with deferred settlement; and
- (3) analyzing the effects of real-time payment adoption for a particular payment scenario.

We find that banks in our model tend to select strategies that set positive but low thresholds on the deposits required for sending RTPs, resulting in outcomes where most but not all consumers have access to the service. In aggregate banks are generally better off when all consumers use RTP, as that increases the overall volume of successful payments. Nevertheless, individual banks are generally unwilling to assume a level of risk to grant all their own consumers the use of RTP.

2 RELATED WORKS

The credit network model is represented by a directed graph with weighted edges representing the capacity for agents in a network to transact with one another. It has been used to study trust networks for distributed payment in multi-unit auctions [Ghosh et al. 2007], informal borrowing [Karlan et al. 2009], and liquidity [Dandekar et al. 2011, 2015]. Cheng et al. [2016] extended the model to the financial credit model with the inclusion of interest rates on the directed edges.

Game theory has previously been applied to the payments space to study the real-time gross settlement (RTGS) system, which handles the settlement of payments between banks. Bech [2008] study the management of intraday liquidity by banks under different credit policies of the central bank. Banks can manage their liquidity by balancing the timing of settling payments. The authors find this payment scenario leads to two well-known games: the prisoner's dilemma and the stag hunt. Additional work on RTGS systems by Johnson et al. [2004] studies the effects of deferred settlement mechanisms on liquidity of banks. The authors use historical data from the US Federal Reserve's Fedwire Funds Service, a system used for commercial payments.

As real-time payment systems are relatively recent additions to the payment space, a number of works focus on a basic introduction. Topics in these works include how the payments differ from more

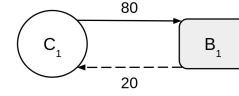


Figure 1: An example of a consumer node with 20 deposits currently in their bank account, but who is willing to hold an additional 80 units in the account.

traditional payment methods, potential benefits and drawbacks for both the consumer and PSPs, and discussions on existing RTP systems throughout the world [Committee on Payments and Market Infrastructures 2016; Hartmann et al. 2019; Santamaría 2019]. Prior literature in the RTP space also addresses RTP system design [Guo et al. 2015]. This includes proposals for additions to existing systems [Kulk 2021], as well as the implementation of new systems such as those incorporating the blockchain [Arshadi 2019; Zhong et al. 2019]. The design of RTP systems may be important when analyzing how banks and consumers may use them in the real world.

Galbiati and Soramaki [2008] use an agent-based model to study the liquidity demanded by banks with access to RTPs. Banks in their model are able to choose their demanded liquidity reserves for each day and payments are executed immediately as long as the bank has the available liquidity. When there is no available liquidity, payments suffer a delay, which can be costly. The authors focus their analysis on how liquidity demand relates to network efficiency, the number of banks in the system, and the volume of payments.

To our knowledge, none of the existing literature specifically addresses how banks might decide who can use RTP systems. Given the potential risk to banks, it is worth exploring how they may place a limitation on consumer use of RTPs and explore how such a limitation may be chosen.

3 FINANCIAL PAYMENT MODEL

We model a financial network similar to that described by Cheng et al. [2016]. The network consists of a set of nodes $B = \{1, \dots, b\}$ representing banks and a set of nodes $C = \{1, \dots, m\}$ representing consumers, with $b \ll m$. Nodes in the network are connected by a set of weighted, directed edges E . Edge $(i, j, type, v) \in E$ represents a value v owed by i to j if $type = debt$ or a value v of credit extended by i to j if $type = credit$. A debt edge from a bank node to a consumer node, $i \in B$ and $j \in C$, can be interpreted as representing deposits consumer j holds in its account at bank i . A credit edge from a consumer node to a bank node, $i \in C$ and $j \in B$, can be interpreted as consumer i 's willingness to hold additional deposits in its account at bank j . For example, a consumer's willingness to hold deposits may be bounded for reasons such as account use, interest rates, or FDIC insurance limits.

An example of the relationship between a consumer and a bank node in our model can be seen in Figure 1. The dashed debt edge $(B_1, C_1, debt, 20)$ represents consumer C_1 holding 20 units in its account at bank B_1 . The solid credit edge $(C_1, B_1, credit, 80)$ represents C_1 's willingness to hold up to 80 more units in its account at B_1 . Thus, at any given time, consumer C_1 is willing to hold at most 100 total units in its account.

There may exist multiple edges of each type between any pair of nodes i and j . We refer to the total debt between the pair of nodes as $d_{ij} = \sum_{(i,j,debt,v) \in E} v$. Similarly, the total credit extended from i to j is $c_{ij} = \sum_{(i,j,credit,v) \in E} v$. We constrict edges in our network to never be between two consumers such that if $i \in C$ and $j \in C$, $d_{ij} = 0$ and $c_{ij} = 0$.

We model a payment as a series of new edges added to the network. To initiate a standard payment, the payer must hold enough deposits in its account to cover the value of the payment. For consumer C_1 with an account at B_1 to send a payment of value v , it must be that $v \leq d_{B_1,C_1}$. We will later relax this constraint to allow for insufficient payments. By using v of its deposits for a payment, C_1 is now owed v fewer deposits by B_1 , which we represent with the creation of edge $(B_1, C_1, debt, -v)$. With v fewer deposits in its account, C_1 's willingness to hold more deposits must increase by v , since they were willing to hold that many deposits previously. We capture this by adding the edge $(C_1, B_1, credit, v)$ to the network.

Suppose the payee is consumer C_2 with an account at a different bank, B_2 . Consumer C_1 's bank will use the interbank network, which connects all banks in the network allowing payments to flow between them, to route the payment to C_2 's bank. We model the interbank network as a set of debt and credit edges, which connect any given bank node to every other bank node in the network. Our model assumes that banks have an infinite willingness to route payments on behalf of their consumers and thus models the credit edges between banks with infinite value. For simplification, we omit these credit edges from our figures. Routing the payment from B_1 to B_2 is reflected in the creation of the debt edge $(B_1, B_2, debt, v)$.

Upon receiving the funds from B_1 , B_2 is able to credit those funds to the payee's account. In doing so, B_2 now owes these additional deposits to C_2 , creating edge $(B_2, C_2, debt, v)$. The increase in deposits in C_2 's account decreases their willingness to hold more deposits by the value of the payment, adding edge $(C_2, B_2, credit, -v)$.

We model batch processing with a *queue* (Q). When the edges of a new payment are created, such as those above, they are stored in this queue. At regularly scheduled intervals, the *clearing period*, the queue is cleared by removing the edges and adding them to the network.

An example of a payment from consumer C_1 of 10 units to consumer C_2 is shown in Figure 2. At time $t = 0$ when the payment is initiated, the network remains unaffected. The queue however, now holds the edges created by the payment: $Q = \{(B_1, C_1, debt, -10), (C_1, B_1, credit, 10), (B_1, B_2, debt, 10), (B_2, C_2, debt, 10), (C_2, B_2, credit, -10)\}$. It is not until the next clearing period, $t = X$, that the edges are removed from the queue and added to the network. The edges in the figure display the total debt (d_{ij}) and total credit (c_{ij}) values instead of showing each individual edge.

3.1 Real-time Payments

We can implement real-time payments with deferred settlement in our network simply by changing which edges are added to the queue. Instead of placing all the edges in the queue, a RTP adds both the credit and debt edges between the payee and its bank to the network immediately. This models the irrevocable credit of funds to the payee's account. The deferred settlement is handled

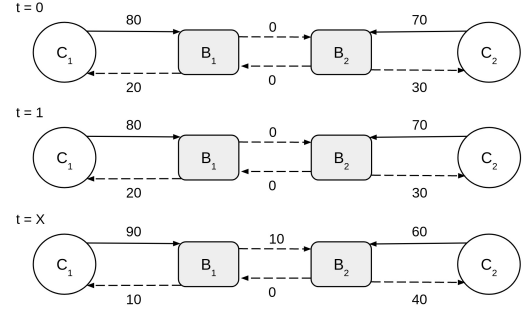


Figure 2: An example of processing a standard payment of 10 units from consumer C_1 to consumer C_2 in our model.

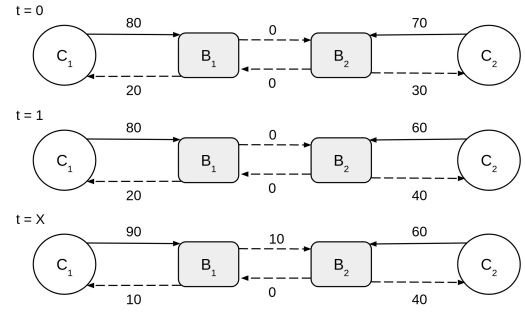


Figure 3: An example of processing a payment of 10 units from consumer C_1 to consumer C_2 as a real-time payment in our model.

by placing the remaining edges in the queue until the next clearing period, similar to a standard payment.

An example RTP is detailed in Figure 3. Similar to the previous example, consumer C_1 sends a payment of 10 units to consumer C_2 , however this time it is sent in real-time. Again, the edges depicted show the total debt (d_{ij}) and total credit (c_{ij}) values. The payment is initiated at time step $t = 0$ and the immediate change is demonstrated by the state of the network at the next time step, $t = 1$. The edges between consumer C_1 and bank B_1 and between banks B_1 and B_2 are not changed until the next clearing period, $t = X$. It can be seen that after clearing, the standard and real-time payments have the same effect on the network.

We also support the insufficient payment case, which we consider to be a byproduct of the expediency of the real-time payments system. Consumer C_1 's payment is considered insufficient if its value v exceeds C_1 's current deposits at bank B_1 : $v > d_{B_1,C_1}$. Insufficient payments can occur in our model only when the payment is sent in real-time.

An example of an insufficient payment sent as a RTP is outlined in Figure 4. Consumer C_1 sends a payment of 25 units to consumer C_2 . Similar to the RTP case, the edges between the payee and its bank are updated immediately, while the remaining edges are added to the queue. The queue will look similar to in the previous two examples: $Q = \{(B_1, C_1, debt, -25), (C_1, B_1, credit, 25),$

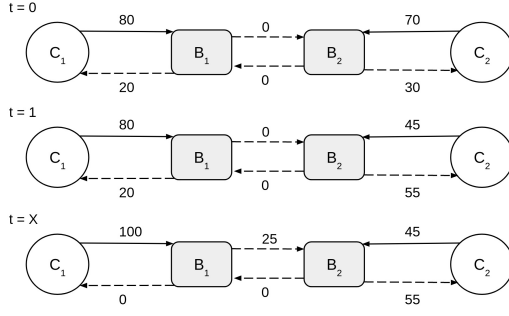


Figure 4: An example of processing an insufficient payment of 25 units from consumer C_1 to consumer C_2 in real-time.

$(B_1, B_2, \text{debt}, 25)$, $(B_2, C_2, \text{debt}, 25)$, $(C_2, B_2, \text{credit}, -25)$. The special case of an insufficient payment will be handled during the clearing of the queue. When the edges between the payer and the payer's bank are processed, the model will detect the insufficiency of the payment. The payer's bank will force the payer to cover as much of the payment as possible by supplying all of its current deposit holdings. This is reflected in a change in the edge $(B_1, C_1, \text{debt}, -25)$ to $(B_1, C_1, \text{debt}, -20)$, which is then added to the network. Note the consumer's total deposits are now equal to 0. As a result, the accompanying credit edge is also changed from $(C_1, B_1, \text{credit}, 25)$ to $(C_1, B_1, \text{credit}, 20)$, to reflect the amount that was actually taken from the account, and that the consumer is willing to replace. The payer's bank, must supply the remaining value of the payment $(v - d_{B_1, C_1})$ which enables the bank to pass on the full amount to the payee's bank, leaving the remaining edges of the payment unchanged.

4 PAYMENT GAME

We define a real-time payments game played by bank nodes in the financial payment network described. Banks in our network must decide which consumer nodes, if any, are allowed to send RTPs by selecting from one of 6 available strategies. Each strategy sets a different threshold on the amount consumer nodes must initially deposit in their accounts to be allowed to send RTPs. The thresholds range from allowing every consumer node to send RTPs to allowing no consumer nodes to send RTPs. In our model consumers may make insufficient payments, for which the payer's bank will be held liable in the short-term. As described in Section 3, the difference between the insufficient payment's value and the payer's deposit holdings, the *insufficient coverage*, must be covered by the payer's bank. Thus, the strategic real-time payments decision for bank nodes is to choose a strategy that balances the benefits of RTPs, including attracting consumer nodes, with a desire to avoid a large amount of insufficient coverage.

The game begins by initializing consumer nodes with a random amount of initial deposits drawn from an exponential distribution. This creates a set of consumers with realistic variation in levels of wealth, including a larger group with average deposit holdings and a small group of very wealthy individuals. Consumer nodes are also randomly assigned to one of two preferences for receiving payments with equal likelihood. Some consumer nodes are willing

to accept any kind of payment, while others accept only RTPs. We also initialize a set of bank nodes and the edges forming the interbank network. Bank nodes then select a strategy for adopting RTP use for their consumers.

All consumer nodes are assigned to a bank under the assumption that consumers prefer banks that allow them to send RTPs. Consumer nodes do not further differentiate between the banks in any way. The full assignment procedure is as follows:

- If no bank allows the consumer to send RTPs, the consumer is randomly assigned to any bank.
- If only one bank allows the consumer to send RTPs, the consumer is assigned to that bank.
- If multiple banks allow the consumer to send RTPs, the consumer is randomly assigned to one such bank.

When a consumer node is assigned to a bank, a credit edge is created from the consumer to the bank and a debt edge is created from the bank to the consumer. The value on the debt edge is set to the consumer node's initial deposits, representing the consumer placing all of its deposits into its account. We assume each consumer node is willing to hold an infinite amount of deposits in its bank account and set the value on the credit edges to infinity. A consumer node's bank assignment lasts for the duration of the game.

The game proceeds in discrete time steps, $t = \{0, \dots, T\}$. The game starts each time step by checking if it is in a designated clearing period. In every clearing period, the queue is cleared by removing the edges from Q and adding them to the network. When an insufficient payment is found, the edges between the payer and its bank node are handled as described in Section 3.1.

After performing any necessary clearing, the game attempts to create L new payments in the network. For each payment a payer, payee, and value are randomly selected. The value of the payment is drawn uniformly from a fixed interval. Consumer nodes are limited to at most one payment per time step. Each payment is processed in the following manner:

- If the receiver accepts only RTPs and the sender cannot send RTPs, they are deemed incompatible and the payment fails.
- If the sender can send RTPs, the payment is processed as a RTP.
- If the sender cannot send RTPs and the receiver is willing to accept all payment types, the payment is processed as a regular payment.

Drawing each payment from a fixed interval may result in an insufficient payment. The first chance to catch a possibly insufficient payment is when it is initiated. We define a consumer C_1 's *available funds*, A_{C_1} as its current total deposits minus the value of any pending payments in the queue for which C_1 is the payer, or $A_{C_1} = d_{B_1, C_1} + \sum_{(B_1, C_1, \text{debt}, v) | v < 0} v$. A payment of value v initiated by C_1 is marked as potentially insufficient if $v > A_{C_1}$. Note that we use the term potentially insufficient here, as it is possible for the consumer node to receive funds between the payment's initiation and the next clearing period, such that at clearing, $v \leq d_{B_1, C_1}$. A standard payment deemed potentially insufficient will terminate the payment process immediately. While the expediency of a real-time payment does not allow the bank nodes to catch an insufficient payment before it is sent, our game provides an opportunity for the payer to potentially do so. Consumer nodes check the validity of their

payments before sending them with probability $p \in [0, 1]$, the *consumer check probability*. We define this probability as a game configuration variable that applies to all consumer nodes in the network. If a consumer node checks their payment and finds it may be insufficient, they adjust the payment's value to be valid so that $v = \max(0, A)$. A payment with a value equal to 0 triggers the termination of the payment process. Anytime the payment process is terminated early, the payment attempt is still counted and subsequently decrements the total number of payments left to attempt in the time step. If the payment process does not terminate for any reason, the appropriate processing steps continue.

The final time step, $t = T$, only clears the queue and no new payments are created. At the end of the game, bank nodes are awarded a payoff for selecting their chosen strategy that relies on three values: the total value of initial deposits attracted (D), the total value of RTPs routed (R), and the amount of insufficient payments coverage (I). The deposits a bank holds for its consumers may be viewed as representing a consumer's level of business with the bank, however the deposits themselves are a liability that must be paid upon demand. Therefore, we model the utility a bank node receives from deposits as a fraction of their value. Similarly, the utility a bank derives from routing payments in real-time for its consumers is a fraction of its value representing consumer satisfaction and continued business. We model our payoff assuming a consumer derives slightly more satisfaction from being able to send a 100 unit payment in real-time than from being able to send a 5 unit payment in real-time. Conversely, the loss to bank nodes in our game is equal to the value of insufficient coverage required. Banks hold the short-term liability for insufficient payments, even if they are able to push the liability onto consumers in the long-run.

The equation for the payoff to bank B is:

$$\text{payoff}_B = 0.5 * D + 0.02 * R - I$$

We model games with $m = 225$ consumer nodes, $b = 3$ bank nodes and $T = 720$ time steps, with $L = 45$ payments attempted per time step with values $v \sim U\{1, \dots, 100\}$. We test clearing period lengths $X \in \{4, 6, 12, 24\}$ and consumer check probability $p \in \{0, 0.25, 0.5, 0.75\}$, for a total of 16 different game configurations for analysis.

5 EMPIRICAL GAME-THEORETIC ANALYSIS

To analyze the real-time payments game we use extensive simulation of strategy combinations in a process referred to as EGTA. The process selects a *strategy profile*, a list of strategies and the number of players employing each strategy, and uses the profile in repeated simulations of the payment game. In each game, consumer and bank nodes are randomly initialized, banks are randomly assigned to a strategy in the profile such that the specified number of banks employ each strategy, and random payments are generated and cleared over 720 time steps. Profiles are selected for simulation in an iterative procedure with the aim of finding symmetric mixed-strategy Nash equilibria similar to the manner used in previous EGTA studies [Cassell and Wellman 2013; Wellman et al. 2013]. The calculated payoff to a bank node for employing a strategy is the sample average of payoffs observed over the many simulation runs.

The equilibria identified by EGTA for the different game configurations classified by clear period and consumer check probability can be seen in Table 1. We sort the 6 strategy thresholds into three categories low, medium, and high based on the minimum amount of initial consumer deposits each requires for real-time payments use. Most of the Nash equilibria identified were mixed-strategy equilibria, except for the case where the consumer check probability is equal to 0.75 which has a pure-strategy Nash equilibria for all clear periods. We report the total probability a bank node will adopt a strategy with a threshold belonging to each category, calculated from the probability assigned to playing the strategies in equilibrium.

The results show an increase in the clear period and consumer check probability leads to an increase in the probability a bank node adopts strategy with a low threshold on deposits. Intuitively, as consumer nodes are more likely to check the validity of their payments and correct errors, the number of insufficient payments decreases. Thus, bank nodes may be more willing to allow broader use of RTPs. A lower clearing period, on the other hand, allows payee's of standard payments to receive funds in a more timely manner than when the clearing period is very high. The difference between a RTP and a standard payment becomes smaller. In this case, it may not be as worthwhile for bank nodes to provide as many consumer nodes the use of RTPs.

6 EFFECTS OF EQUILIBRIA

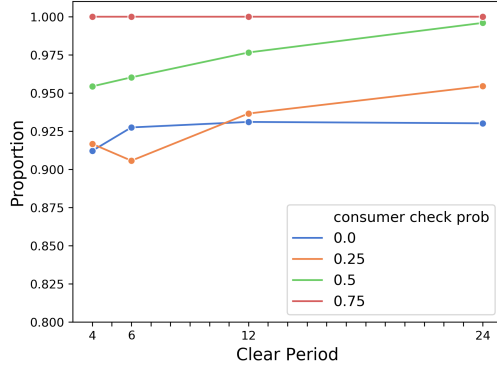
We analyze the effect bank nodes adopting the Nash equilibrium strategies has on the network, in particular on consumer nodes' access to RTPs, the success of payments attempted, and insufficient payments made. Bank nodes play the payment game 1,000 times as described: randomly initialize bank and consumer nodes, bank nodes adopt a strategy, consumer nodes are assigned to banks, and random payments are created and cleared in the network over 720 time steps. However for this analysis, bank nodes are required to adopt the equilibrium strategy identified by EGTA for the game configuration being analyzed. When the equilibrium is mixed, the bank nodes will be assigned to one of the pure strategies that make up the equilibrium (the support) according to a weighted draw with weights equal to the probability assigned to playing each strategy in equilibrium.

We also compare the success of payments and insufficient payments under the equilibria to the all-RTPs and no-RTPs cases. For the first case, bank nodes allow all consumer nodes the use of RTPs. This represents a situation in which banks might be required, for instance by federal regulation, to allow everyone access to RTPs. In the second case, bank nodes do not allow any consumer nodes to send RTPs, representing the status quo before RTP systems were introduced. A consumer's preference to accept only RTPs in this case can be viewed as unwillingness to accept payments through the banking system without a RTP system in place.

The proportion of a bank node's consumers that are allowed to send RTPs when the bank adopts the equilibrium strategies is shown in Figure 5. In all game configurations, the majority of consumer nodes are allowed to send RTPs, although in many cases not all. The proportion tends to decrease as the clearing period length decreases and increase as the consumer check probability increases.

Table 1: The probability of a bank node selecting a strategy that sets a low threshold in equilibrium increases as the consumer check probability and clear period increase.

Clear Period X	Consumer Check p	0			0.25			0.5			0.75		
	Strategy Threshold	low	med	high	low	med	high	low	med	high	low	med	high
24		0.58	0.42	0	0.61	0.39	0	1	0	0	1	0	0
12		0.54	0.46	0	0.46	0.54	0	1	0	0	1	0	0
6		0.51	0.49	0	0.37	0.63	0	0.92	0.08	0	1	0	0
4		0.48	0.52	0	0.39	0.61	0	0.75	0.25	0	1	0	0

**Figure 5: The proportion of consumer nodes allowed to send real-time payments under the equilibria increases as the clear period and consumer check probability increases.**

This aligns with the trends seen in the equilibria in Table 1. As the clear period decreases, the probability of selecting a strategy with a lower threshold decreases. As a result, the proportion of consumer nodes allowed to send RTPs also decreases. On the other hand, when the consumer check probability increases, the probability of choosing a strategy with a lower threshold increases and the proportion of consumer nodes allowed to send RTPs increases as well. The exception occurs when the consumer check probability is 0.75 and the pure strategy Nash equilibrium is to allow everyone to send RTPs. This results in a proportion of 1 for all clearing periods.

As described in Section 4, issues with consumer compatibility and deposit values may lead to early termination of payments. We examine the frequency of such instances by studying the proportion of a bank node's payments that are deemed successful because they did not terminate early. To calculate, we use the expected number of payments attempted per bank node. We also compare the equilibria case to the case where all consumer nodes may send RTPs. The results are in Figure 6.

Most payments attempted in the network are successful, regardless of game configuration and in both the equilibria and all-RTPs cases. Under the equilibria, the success tends to slightly decrease as the clear period decreases. At lower clear periods the bank nodes tend to allow fewer consumer nodes to send RTPs. With fewer consumers sending RTPs, there may exist more cases where the payer's allowed payment type and payee's desired payment type are incompatible and therefore, increases the number of unsuccessful payments. When compared to the equilibria, we see that allowing

everyone to send RTPs leads to a higher proportion of successful payments in all game configurations. The only exception is when consumer check probability is 0.75, where allowing everyone to send RTPs is the equilibrium. Instead of a decrease in the proportion of successful payments, the all-RTPs case shows a slight increase in the proportion of successful payments as the clear period decreases. This may be attributed to the larger number of payments made between clearing as a result of longer clearing periods. Thus, there are more cases of consumer nodes validating payments and finding they have no available funds.

We also compare these results to the no-RTPs case, where the average proportion of successful payments across all game configurations is only 0.32. This highlights the importance of real-time payments for promoting consumer liquidity. Allowing RTPs for at least some participants in the network promotes increased consumer participation in the banking system. Furthermore without a delay in receiving funds for which a consumer is the payee, the funds are available for the consumer's immediate use as a payer.

The disincentive for bank nodes to offer real-time payments services to consumers is the risk of insufficient payments. We measure the effect insufficient payments have on bank nodes by the percentage of a bank's payments that are insufficient, as well as the average total insufficient coverage required by a bank. The results when bank nodes adopt the equilibrium strategies are shown in Table 2 and when bank nodes allow all consumers to send RTPs in Table 3. If banks do not allow anyone to send real-time payments, insufficient payments in our model are caught and terminated before processing.

Few payments made by consumer nodes in our network turn out to be insufficient, however when they occur the bank nodes tend to cover the majority of the payment. This trend is evident regardless of whether bank nodes adopt the equilibrium strategies or allow all consumer nodes to send RTPs. As the consumer check probability increases, both the number of insufficient payments and the insufficient coverage required tend to decrease. With consumer nodes more likely to check their payments when the consumer check probability is high, the likelihood they catch and correct potentially insufficient payments is also high. Conversely, as the clear period decreases, the number of insufficient payments tends to increase and the insufficient coverage required tends to decrease. The exception occurs when the consumer check probability is 0.75. In this case both the number of insufficient payments and insufficient coverage required increase as the clear period decreases.

To explain this phenomenon, we must consider consumer nodes as both payers and payees. When the clear period decreases, the

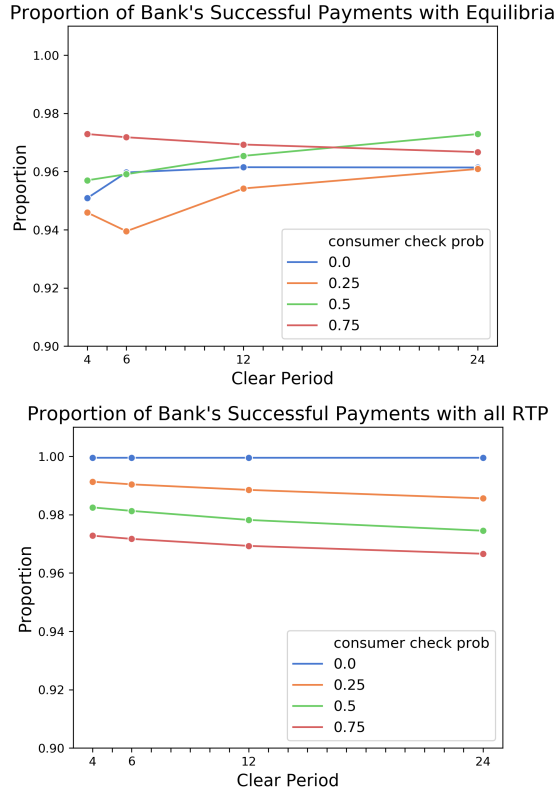


Figure 6: When bank nodes adopt the equilibrium strategies, the proportion of successful payments decreases as the clear period decreases. Furthermore, its value is always smaller than when all consumers send real-time payments.

number of time steps between clearing becomes smaller. At a smaller clear period, there are fewer opportunities for a given consumer to receive funds as a payee. Now when a clear period occurs, this consumer has accumulated fewer deposits to use when settling payments for which they are the payer than they might have if the clear period were longer. Thus, we see an increase in the number of instances in which a payment's value is strictly larger than the payer's deposit holdings at the time of settlement. On the other hand, a smaller clearing period also limits the number of payments for which a given consumer node may be the payer. Note that this limitation has a stronger impact on a consumer node's ability as a payer than as a payee, as consumers make at most one payment, but may receive any number of payments per time step. With fewer opportunities to make payments between clearing, the *total* amount owed in payments for any given consumer node at clearing time will be smaller with a clearing period of 4 than 24. So while we may see an increase in the number of payments for which consumer nodes do not have enough deposits, the amount of deposits a consumer node has tends to be closer to the total value of the payments made.

The insufficient payment coverage trend at consumer check probability 0.75 may be understood by analyzing the effect of consumer check probability on payment value. When the probability a

consumer node checks their payments is high, it is likely that an insufficient payment will be caught and corrected. By definition, a corrected insufficient payment's value will be smaller than the original value. Thus, the value of payments on average is less when consumer nodes correct insufficient payments more often. Smaller payment values means fewer deposits. The increase in the number of insufficient payments along with the decrease in deposits causes the insufficient coverage requirement for bank nodes to slightly increase.

Our analysis also illustrates an important relationship between banks and consumer use of RTPs. From our analysis, it can be seen that all parties involved tend to be better off when all consumer nodes send their payments in real-time. This is evident in the proportion of successful payments being larger and insufficient payments, both the number and resulting required coverage, being smaller when all consumer nodes send RTPs compared to the other cases for all game configurations. An individual bank node playing our payment game, however, is more likely to play a strategy that limits the number of its consumers who send RTPs in the event insufficient payments are likely. We can conclude that, while bank nodes might be better off when all consumers in the network are allowed to send RTPs, a strategic bank node would prefer not to assume the risk required to allow all of its consumers the use of RTP.

7 CONCLUSION

In this study, we analyze how the adoption of real-time payments by banks may be affected by potential payments risk, specifically the possibility of insufficient payments. We introduce a payment model that supports consumer nodes sending both standard and real-time payments with deferred settlement through the interbank network. Within this framework, we model insufficient payments as the case where the value of a RTP is greater than the current deposit holdings of the payer and for which the payer's bank becomes liable. Such a scenario captures both the risks of the expediency of RTP and the credit risk borne by banks in the deferred settlement case. We ask which consumers banks should allow to send RTPs in this scenario by modeling the decision as a strategic game played by bank nodes. Bank nodes select a strategy based on the initial deposits of consumer nodes. The strategic decision for bank nodes requires balancing the benefits of real-time payments and a desire to attract consumers, with a desire to limit their liability.

Our results show that while bank nodes never choose strategies with high thresholds, the likelihood of allowing all consumers to send RTPs is dependent on different game configuration variables. When consumer nodes are less likely to send insufficient payments, bank nodes are willing to allow all, or nearly all consumers to send real-time payments. However, if consumer nodes may send many insufficient payments, bank nodes become more likely to select a strategy with a medium level threshold. Bank nodes also tend to prefer strategies with medium level thresholds to strategies with lower thresholds when the clearing period is lower. This is likely because a shorter clearing period makes real-time payments more similar to standard payments. In this case, it becomes less worthwhile for bank nodes to allow as many consumers the use of RTPs.

Table 2: When bank nodes adopt the equilibrium strategies, few insufficient payments are made, but the insufficient coverage required by banks is large.

Consumer Check p	0		0.25		0.5		0.75	
Clear Period X	% insufficient	% coverage	% insufficient	% coverage	% insufficient	% coverage	% insufficient	% coverage
24	4.6	79	3.3	75	1.8	70	0.75	65
12	4.9	74	3.9	72	2.3	68	1.1	65
6	5.1	72	4.4	72	2.8	69	1.3	67
4	5.3	72	4.5	71	3.0	69	1.4	68

Table 3: If all payments are sent as real-time payments, the number of insufficient payments made is small, but bank nodes cover the majority of the payment.

Consumer Check p	0		0.25		0.5		0.75	
Clear Period X	% insufficient	% coverage	% insufficient	% coverage	% insufficient	% coverage	% insufficient	% coverage
24	4.2	78	2.9	74	1.7	70	0.76	65
12	4.6	73	3.4	70	2.2	68	1.1	65
6	4.8	70	3.7	69	2.6	68	1.3	67
4	4.9	70	3.8	69	2.7	68	1.4	68

We compare the effects of bank nodes adopting the equilibrium strategies to the cases where bank nodes allow everyone or allow no one to send RTPs. The results of this analysis demonstrate that bank nodes are better off when all consumer nodes are sending payments in real-time than when bank nodes adopt the equilibria or don't allow RTPs. This is evident in the proportion of payments that are successfully made in the network, the number of insufficient payments made in the network, and the insufficient coverage required by bank nodes as a result of insufficient payments. However, the Nash equilibrium in many situations for banks in our game is to select a strategy that places a limitation on the number of consumers who are allowed to send RTPs. From these results, we can infer that although outcomes for the banks are more favorable when all consumers send RTPs, strategic banks are unwilling to assume the liability risk required to provide all their own consumers the use of RTPs.

While our work offers some insight into the strategic decision faced by banks in the real-time payments space and the effects the decision may have on the network, it is important to note this model is rather simplistic. Future work may explore how other factors may affect the real-time payments decision. For example, consumers may be endowed with additional features that would impact their payments, the network may be made of more node types than just consumers and banks, and issues with payments could stem from other scenarios such as fraud. Addressing these, as well as other potential additions, may help paint a more complete picture of the real-time payments question.

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