Payment Networks: A Review of Recent Research

James Chapman, Lana Embree, and Tom Roberts, Financial Stability Department; Nellie Zhang, Funds Management and Banking

- *Network analysis offers a new approach to understanding the complex relationships among participants in Canada's Large Value Transfer System (LVTS), the main system used for clearing and settling transactions between financial institutions.*
- *Network analysis can help payments-system supervisors to better understand the importance of individual participants in the system and the connections between them.*
- *Research using network analysis that takes account of the intensity of transactions between groups of LVTS participants suggests that there are two communities of participants in the LVTS: one consisting of the five major banks and another consisting of some smaller, more regionally focused participants that interact closely with one another.*

A stable and efficient financial system is a critical component of a well-functioning economy. It intermediates the flow of funds between savers and borrowers, and it helps to allocate risk to those best able to manage it. In assessing the risks and vulnerabilities of the financial system as a whole, it is important to understand the relationships among financial institutions, markets, and infrastructure (e.g., trading links, risk exposures, and payment relationships).

One of the central pieces of infrastructure in a well-developed financial system is its large-value or wholesale payments system used to process payments between financial institutions. Financial Institutions (FIs) transfer significant dollar amounts through these systems, as they process payments among themselves on behalf of their clients. Canada's wholesale payments system—the Large Value Transfer System (LVTS)—is a systemically important payments system. The rules and risk controls of this system insure that as payments pass the system's risk controls throughout the day, they are final and irrevocable.[1] The LVTS is a key infrastructure in the financial system because LVTS payments are used to complete important business transactions and to settle Canadian-dollar obligations arising from securities and foreign exchange transactions. Every business day, the LVTS successfully completes thousands of transactions worth billions of dollars. In 2008, the wholesale payments systems of the G-10 countries processed a total value of payments that was 62.2 times their GDP, on average; for Canada, this ratio was 28.7 times (BIS 2009).[2] Given the central role

1 Arjani and McVanel (2006) provide an overview of the structure of the LVTS and its relationship to the Canadian financial system.

2 A possible explanation for Canada's lower ratio of payments to GDP is that some large participants in the LVTS settle a significant amount of payments between clients across their own books, rather than with another participant through the LVTS.

of wholesale systems and the large volume of transactions settled through them, financial-stability policy making and oversight of systemically important infrastructure, in particular, can benefit from understanding the relationships that exist between participants in these systems.

A wholesale payments system, such as the LVTS, can be thought of as a complex network in which the relationships between its member FIs can be modelled using the tools of network analysis. Network analysis is an interdisciplinary field that has developed in the past decade (Vega-Redondo 2007). It examines the bilateral relationships in a given system of participants and then considers the overall effect that a given pattern of bilateral relationships can have on the system as a whole. The application of network analysis is relatively new to financial economics.

In this article, we review work done at the Bank of Canada and at other central banks that applies network analysis to data on payments systems.[3] These techniques give us a new approach to analyzing the systemic risks inherent in payments systems. Known as payment networks, this branch of network analysis focuses on payments systems and draws on techniques from monetary economics.

Modelling Payments Systems as Networks

Given its oversight responsibilities for designated payment, clearing, and settlement systems under the Payment, Clearing and Settlement Act (PCSA), the Bank of Canada has a strong interest in better understanding the behaviour of the LVTS and ensuring that it is well risk-proofed. A network approach provides a framework for understanding the complex interrelationships between participants in a payments system in a way that complements conventional economic modelling.

The payment-network approach to modelling is typically implemented as follows: a payments system is simplified into a set of nodes, where each node represents a participant in the system (e.g., a bank). The nodes form a network by being linked to each other according to key financial relationships. For example, the network approach could be used to model payments, securities trades, loans, or credit limits. The links that are modelled will depend on both the data available and the questions being addressed. Two possible areas of interest involve understanding how financial shocks or problems can spread from one institution to others (financial contagion) and measuring the systemic importance of different participants.

By identifying and studying the links between participating institutions, researchers can better understand whether the interconnected nature of payments-system participants increases or reduces the resiliency of the system to shocks.

Financial contagion can be better understood by examining how participants are connected as a network, because the links studied in network analysis can present avenues through which financial shocks could spread to other institutions. However, when applying network analysis, consideration must be given to the nature of the links being studied. For example, although some links can provide channels through which financial disruptions could spread among LVTS participants, other links can promote resiliency by dispersing risk among participants. By identifying and studying the links between participating institutions, researchers can better understand whether the interconnected nature of payments-system participants increases or reduces the resiliency of the system to shocks. This framework allows the overseer of the system to appropriately monitor or mitigate any potential risks.

Network analysis allows us to examine how participants are linked to one another. A network may be quite simple, where each institution transacts with only a few others and knows the risk exposures of its counterparties. It could, however, be quite complex, where the number and size of each institution's counterparties varies greatly. The complexity of the network itself can contribute to increased uncertainty (Haldane 2009; Caballero and Simsek 2010). For example, complexity can be a factor in market disruption because participants are uncertain regarding their counterparties' exposures to a troubled institution. A better understanding of the network of relationships (links) can help to reduce uncertainty in stress scenarios.

3 A related body of research takes a network approach to analyze the balance-sheet exposures of banks. See for example (Gauthier, Lehar, and Souissi 2010) or (Gauthier, He, and Souissi 2010).

Network analysis can also provide an alternative approach to assessing the systemic importance of particular participants in a payments system by identifying participants that might have a large impact on a system if they default or have some type of liquidity problem. This approach is useful, given that the effects on the payments system of operational, credit, or liquidity events at one participant would be a function of both the participant's size and its interconnectedness. Interconnectedness depends on the breadth and intensity of a participant's financial relations with other members of the payments system. A participant could be considered highly connected, and therefore important to the system, if it transacts with many participants or if its transactions represent large values (possibly with few participants). Network analysis can help to provide a more complete picture—beyond simple measures of value and volume of transactions—of a participant's role and importance in a system.

In summary, the network approach to payments systems provides a new conceptual framework to assess their vulnerabilities and risks. Research in this area, as well as the resulting tools, can complement existing approaches of conventional economic modelling or statistics.

Recent Research

Research into payments-system networks can be divided into two broad categories. The first category, network topology, seeks to describe the key features of a typical payment network. The second category, network characteristics, seeks to use these features, along with economic theory, to help uncover previously unknown and potentially important insights about the payment network.

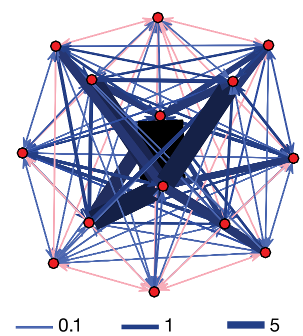
Network topology of the LVTS

The way in which a payment network is measured and understood is through its topology, which is the pattern (or layout) of the links between nodes. The topology of the network characterizes the structure and functions of complex networks and can assist in understanding how the structure of a network influences its stability, resiliency, and efficiency in the face of a disruption.

The seminal study of payment-network topologies is by Soramäki et al. (2007). In their paper, the authors describe the payment network composed of nodes that represent members of the Fedwire Funds Service, the wholesale system at the centre of the U.S. financial system, operated by the Federal Reserve, and links that represent the existence of a payment between two members. They show that this network displays the classical features of a complex network; that is, the number of links that originate with a given node follows a power-law distribution, where the network has a few nodes with many links and a large number of nodes with few links.[4] This hub-and-spoke-like structure of the network implies that the Fedwire system is resilient to a random outage but may be vulnerable to a shock that affects a strongly connected node.

Embree and Roberts (2009) provide a characterization of Canada's LVTS using a network-topology approach similar to that of Soramäki et al. They find that the LVTS is, in general, a highly connected network, with a small number of large participants at the centre. The finding that a small group of participants form the hub of a payments system is common to the network analyses of wholesale systems in many other countries. This structure can be seen in **Chart 1**, where nodes represent the 14 LVTS members, and links represent average daily payment flows during 2008. A discernibly small number of these banks are more strongly connected than other participants.

Chart 1: Average daily gross payment flows in the LVTS, 2008
Can$ billions



Source: Bank of Canada

Examination of how this tendency towards centralization in a hub evolves within an average day reveals that it is typically higher at the beginning and the end of the day than during the rest of the day. This suggests that during these two periods, certain participants may play a more significant role in the payment network than at other times of day.

4 A power-law distribution is a probability distribution that exhibits scale invariance: for a given ratio of two values in the distribution, the relative frequency of encountering the two values does not change. For example, with a power-law exponent of 2, a node of degree 6 is four times less frequent than a node of degree 3; a node of degree 10 is four times less frequent than a node of degree 5. Many man-made and natural phenomena exhibit this property (e.g., the ranking of cities by population).

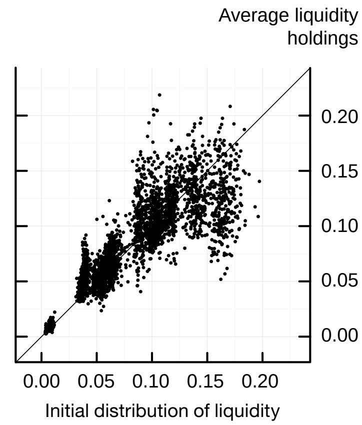
Characteristics revealed by the network structure of the LVTS

In addition to the work that characterizes the network topology of payments systems, a second fruitful avenue of research involves exploring the structure of the payment network to uncover characteristics that would not be apparent from simply focusing on the behaviour of an individual member of the payments system. Such characteristics may include identifying key participants for circulating liquidity in the system, as well as participants that are important for subgroups of system participants. This type of study depends on intimate knowledge of the institutional features of the payments system. Because of these information requirements and the recent development of this field, there are only a handful of published studies that fit into this category. These include two empirical Bank of Canada studies that use certain readily observable transaction linkages among the direct participants in the LVTS to uncover important payment behaviours and relationships that are hard to see by examining the behaviour of each participating FI in isolation.

In the first study, Bech, Chapman, and Garratt (2010) examine the implicit network structure defined by the bilateral credit limits (BCLs) among participants. They then develop a method of determining which participant is likely to hold the most liquidity at any point in time during the payment cycle.[5] The authors characterize this participant as being "central" to the system. A central participant plays an important role in ensuring that liquidity flows through the system and therefore that payment activity continues to function smoothly. This has important policy implications, since a well-functioning payments system requires that liquidity flow between participants in a timely manner to ensure prompt execution of payments across the system's participants, as well as their customers.

Chart 2 shows the relation between the initial and the average distribution of liquidity for all participants on all dates. Each point on the chart represents the initial and average share of an individual's liquidity on a given day in the sample. Points above the 45-degree line represent participants that held more liquidity throughout the day than at the beginning of the day; points below the 45-degree line are participants that held less liquidity during the day than at the beginning of the day. Since the majority of points do not lie on the 45-degree line, we can see that the distribution of liquidity throughout the day does not match the initial allocation. This is an important point, since a participant outage during the

Chart 2: Initial versus average liquidity holdings



Source: Bank of Canada

day can lead to difficulties for the system if that participant holds a large amount of system liquidity (McPhail and Senger 2002).

Bech, Chapman, and Garratt go on to investigate the intraday dynamics of liquidity in the LVTS. Using empirical methods based on Markov chain theory, they estimate the unobservable payment speeds of LVTS participants by calculating an expected average distribution of liquidity (known as a "stationary distribution"). Their estimated payment speeds are obtained as follows. Given the model, Markov chain theory implies that for a given a set of payment speeds there is a unique stationary distribution. The authors then estimate the payment speeds by matching the stationary distribution to the observed average distribution of liquidity in the model.

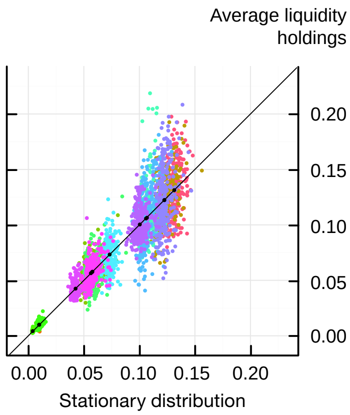
Their results show that there is a large degree of heterogeneity in payment speeds. In the most extreme case, one participant can be six times quicker in processing outgoing payments than another.

As illustrated by **Chart 3**, when the speed of payment processing is taken into account, the stationary distribution of liquidity holdings in the LVTS shows a closer match with the participants' average liquidity holdings. **Chart 3** is similar to **Chart 2**, with the exception that the horizontal axis now contains the expected stationary distribution instead of the historical initial distribution, and the liquidity holdings of individual participants (both average and stationary) are segregated by colour to show that there is a clear ranking of the amount of average liquidity held among participants.[6]

5 A measure of liquidity in the LVTS is defined in the **Box** on page 16.

6 Each colour represents all the daily observations of average and stationary liquidity for a given bank in the LVTS.

Chart 3: Stationary versus average liquidity holdings



Source: Bank of Canada

In the second Bank of Canada study, Chapman and Zhang (2010) use the network aspects of LVTS transactions data to examine various degrees of interconnectedness among the system's direct participants.[7] The researchers examine whether LVTS participants send payments to all other LVTS participants equally, or whether they form clusters of transaction relationships and then send relatively more payments to members of the same cluster. Knowledge of this partition can help to identify groups or clusters of closely connected participants. Identifying these clusters or partitions is important to understanding the impact of a participant outage on the entire system.

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Chapman and Zhang use the model derived by Čopič, Jackson, and Kirman (2009) to estimate the most probable partitions of participants. This model uses the concept of "community" and assumes that participants that are members of the same community transact with each other relatively more intensely than with participants outside the community.

To measure this relative intensity, the model requires a measure of transaction intensity among LVTS participants, as well as a pair-wise maximum level of intensity (or capacity). These maximums are constructed for every combination of participants to serve as a benchmark for comparison with the actual observed payment flow. Chapman and Zhang use two measures of transaction intensity: (i) a "liquidity" measure that compares the average daily total value of payments sent from one participant to another against an estimate of the cyclical maximum liquidity available to the payment sender,[8] and (ii) an "averages" measure that compares a payment sender's outflow of bilateral transactions with its multilateral average.[9] This last measure effectively takes into account the fact that LVTS participants differ by orders of magnitude in the amount of payments they make.

Using these two measures, the authors find that the most likely partition of the LVTS network includes two larger communities that seem to be based on both transactions amount and geographic location. One community consists of the five major Canadian banks; the other is a smaller community of financial institutions that are more regionally focused and based in Montréal. These two communities are not easily discernible if one looks only at simpler metrics, such as bilateral payment flows. Uncovering such a network structure can have useful policy implications. For example, identifying clusters can contribute to a better understanding of the potential impact of problems experienced by a key member of a community, even if they are not one of the largest participants in the system.

Benefits and Limitations

Work on network centrality and clustering could be useful in helping to assess a participant's systemic importance in payments systems and in the financial system more generally. The simulated system-wide effect of removing a bank or combination of banks further illustrates this potential network aspect of a disruption. Even though the exact consequences of any particular bank failure are unknown in advance, the presence of significant network linkages between banks could exacerbate the problem. In these cases, a relative ranking of banks' centrality in the payments system could help prioritize the policy responses of financial regulators in the event of any future financial crisis.

Empirical research on the structure of financial systems suffers from a scarcity of data. Whereas

7 Direct participants are the financial institutions that are members of the LVTS.

8 It is estimated as the sum of the maximum amount of daily gross payment receipts and the maximum bilateral credit limit granted to the payment sender.

9 Under the "averages" measure, the observed interaction among pairs of participants is defined to be the number of days on which one participant's payment flow to the other exceeds the average payment flow to all system members.

Defining Liquidity in the LVTS

Bech, Chapman, and Garratt (2010) focus on the Tranche 2 payment stream in the LVTS.[1] They study Tranche 2 for two reasons. First, the majority of payments are executed in this Tranche of the LVTS.[2] Second, in Tranche 2, the amount and size of payments between any two pairs of participants are restricted by mutually agreed upon Bilateral Credit Limits (BCLs), as well as a multilateral Net Debit Cap for all Tranche 2 payments, known as T2NDC. A participant's T2NDC is a function of the BCLs granted to that participant.[3] These BCLs are backed by collateral posted by the system participants.

The usual definition of liquidity is the ability to make a trade or payment promptly. The authors therefore define the liquidity available to a participant in the system at any moment as the net payments that have been made to the participant, as well as their initial T2NDC. The latter can be thought of as liquidity since it is the maximum amount of payments that a participant can make unilaterally. Since the summation of all net payments in the system must equal zero at any moment, the sum of the T2NDCs may be thought of as the total amount of available liquidity in the system.

The authors calculate the initial share of this total available liquidity to which each participant has access at the start of a payment cycle as the ratio of each participant's T2NDC to the sum of T2NDCs. The authors then propose a measure for the observed average amount of liquidity that one participant holds during a payment cycle. This is defined as the total of two quantities: the time-weighted sum of the liquidity balance in Tranche 2, and the participant's T2NDC on that day. The first part of the quantity is the average net payments to an individual participant during the day, and the second is the initial amount of liquidity held by the individual participant. The distribution of such average liquidity holdings across all participants represents the average allocation of liquidity between participants in the LVTS.

1 The LVTS is composed of two payment streams: Tranche 1 and Tranche 2. The two streams differ primarily in terms of collateralization. Tranche 1 payments are fully collateralized by the sender and settle in real time on a gross basis like an RTGS system in many other countries, while Tranche 2 payments are partially collateralized by the sender and are also backed by a survivors-pay collateral pool and are settled at the end of the day on a net basis.

2 Tranche 1 payments are primarily payments between participants and the Bank of Canada. These are for transactions such as foreign exchange settlement.

3 This is a necessarily brief explanation of the institutional details of the LVTS system. Arjani and McVanel (2006) provide further information.

information regarding an institution's bilateral on- and off- balance-sheet exposures is not usually readily available, payments systems offer an opportunity to observe actual financial activity. But even with this payment information, such as LVTS data, a direct connection to a participant's underlying financial activity might be difficult to detect because of lack of information about payment rationale, or the amount of time between a payment request and the corresponding payment settlement. Nonetheless, innovative econometric techniques can complement network analysis by helping to interpret the economic significance of observed payments data.

Payments data typically reveal little about the financial linkages that involve indirect participants, and this is arguably an obstacle to our understanding of the financial system, as well as a challenge to determining the systemic importance of individual banks.[10] There have been some recent attempts to capture these indirect linkages. For example, Becher, Millard, and Soramäki (2008) use the 2003 CHAPS Traffic Survey by the Bank of England, which consists of a sample of CHAPS payments for five days in February 2003, including those of indirect participants.[11] The Banking Act 2009 in the United Kingdom has since legislated that the Bank of England can require the operators of interbank payments systems to provide it with information, including data on indirect clearers, as it deems necessary (Bank of England 2009). For its part, the Bank of Canada does not regularly collect data from Canadian payments systems apart from the LVTS. Further surveys or data access on financial

10 Indirect participants are smaller banks and deposit-taking institutions that are not direct members of the payments system and that, instead, rely on direct participants to execute payments on their behalf.

11 The Clearing House Automated Payments System (CHAPS) is the United Kingdom's wholesale system.

exposures or payments in Canada would be beneficial for understanding the structure of the Canadian financial system.

Conclusion

Network analysis is a relatively new method of analyzing financial systems. This approach allows researchers to study the operation of the payments system as a whole, rather than at the participant level. For example, recent work on the LVTS has uncovered a couple of communities within the payments system and has provided new ways to evaluate the systemic importance of participants. This type of information significantly enhances the ability of financial-stability policy-makers and payments-system overseers to analyze issues that might affect the payments system as a whole. While not the focus of this article, network analysis can also be used in the context of the financial system more broadly, to understand liquidity and contagion (Cifuentes, Ferrucci, and Shin 2005; Gauthier, He, and Souissi 2010; Gauthier, Lehar, and Souissi 2010).

The main limitation to this work is the lack of available data from which to make high-quality inferences about network structures. One consequence of the ongoing reforms to the international financial system is an increasing interest in and collection of the types of data needed for the effective modelling of payments systems and financial networks.

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