Joint Determination of Counterparty and Liquidity Risk in Payment Systems

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CEMLA 2023

Note: An early version of this paper was circulated with the title "Netting Relationships in Payment Systems". Some of the information in this presentation is preliminary and subject to revisions. Please do not distribute this material without the written consent of the authors. The views presented here are those of the authors and do not necessarily reflect those of the Bank of Canada, Payments Canada or the authors' institutional affiliations.

1. Introduction

Research Questions

1. **How do banks manage their funding liquidity and counterparty risk? Do banks manage these risks jointly?**

   → Develop a methodology that allows us to **jointly assess** how banks manage their **funding liquidity** and **counterparty risk** exposures.

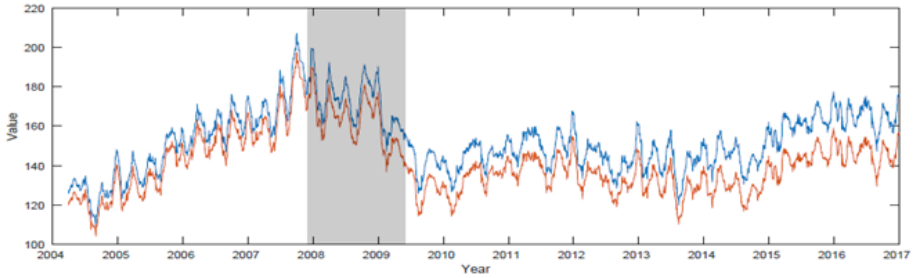
2. **Is there a difference in how banks issue and manage secured and unsecured credit obligations?**

   → Use the methodology to **gain insights** into how market participants issue **secured and unsecured** credit obligations and manage the resulting exposures.

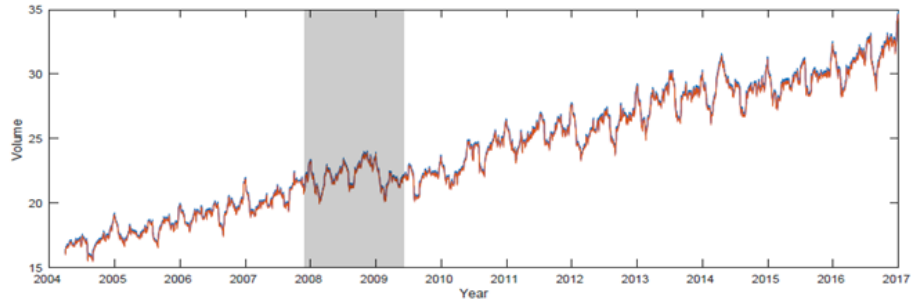
Payments data from the **Canadian LVTS**

Figure 2: System-wide gross value and gross volume of payment orders for the full sample period

Panel A: Gross value of payment orders (in billions of Canadian dollars)



Panel B: Gross volume of payment orders (in thousands)

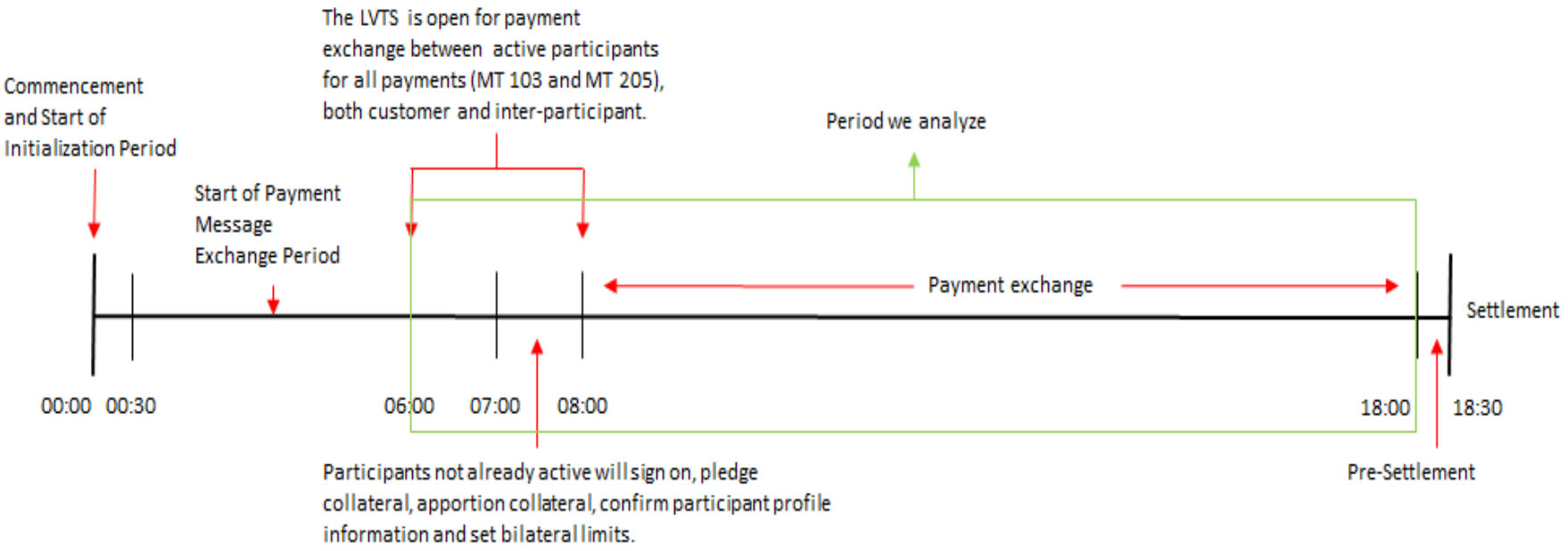


Payments from:

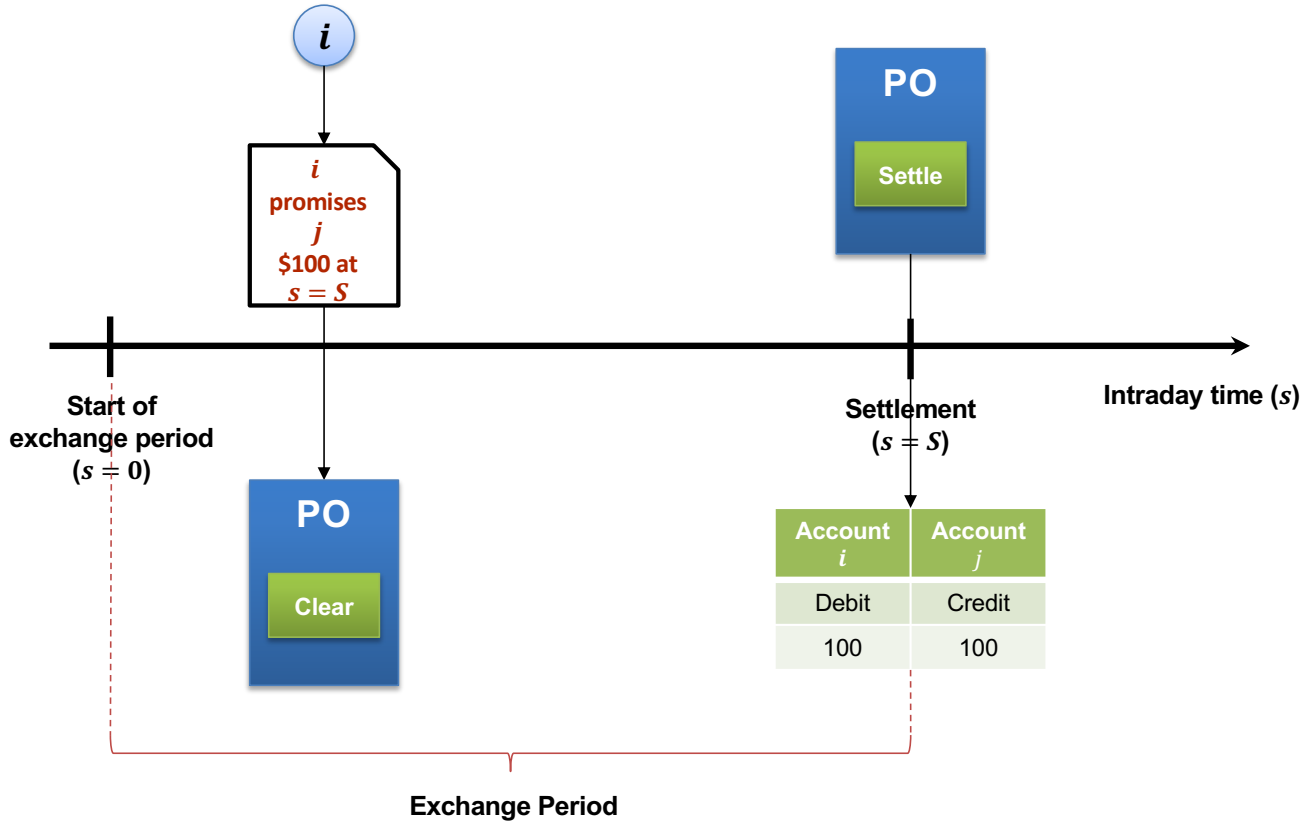
— All participants — All participants excluding the Bank of Canada

Panel A and B report the rolling moving average (21 trading days) of the aggregate gross value and the aggregate gross volume of payment orders processed in the LVTS, respectivelly, for the full sample period from March 1, 2004 to December 30, 2016. The shaded area corresponds to the Great Financial Crisis (from December 2, 2007 to June 1, 2009, NBER, 2010).

The Canadian LVTS Daily Operating Schedule

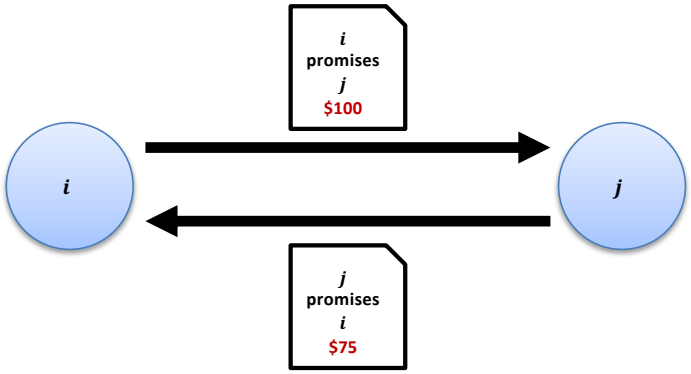


A Deferred Net Settlement (DNS) System

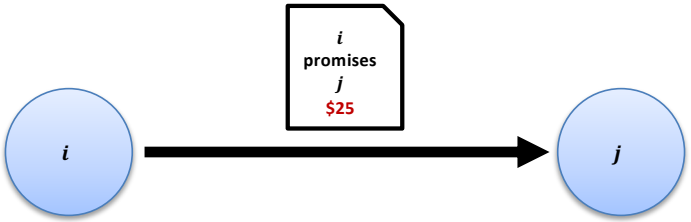


Bilateral Netting

Gross credit obligations



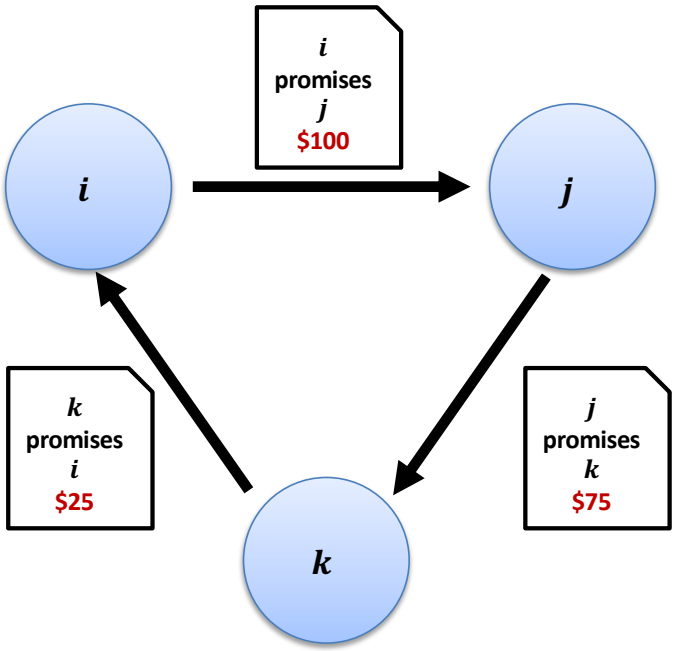
Net credit obligations



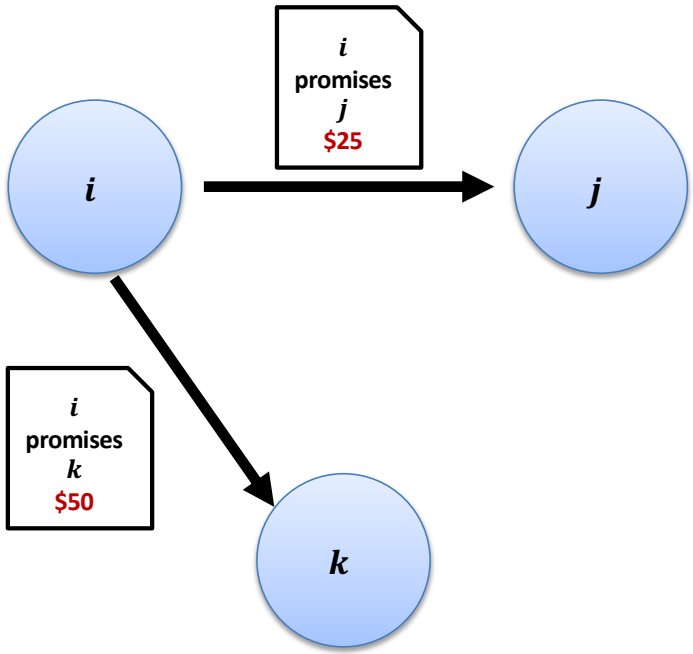
Netting is "the **offsetting of obligations** between or among participants … thereby reducing the number and value of payments or deliveries needed to settle a set of transactions" (BIS, 2012).

Multilateral Netting

Gross credit obligations



Possible Arrangement of Net credit obligations



Main Features of the Canadian LVTS

- **Wholesale payments system**
  - Open to a limited number of direct participants (DPs)

- **Payments Canada** is the **payments operator (PO)**
  - Processes all payment orders and acts as the central counterparty (CCP)
  - Collects collateral from either the issuer or the receiver of a payment order to remain risk neutral.

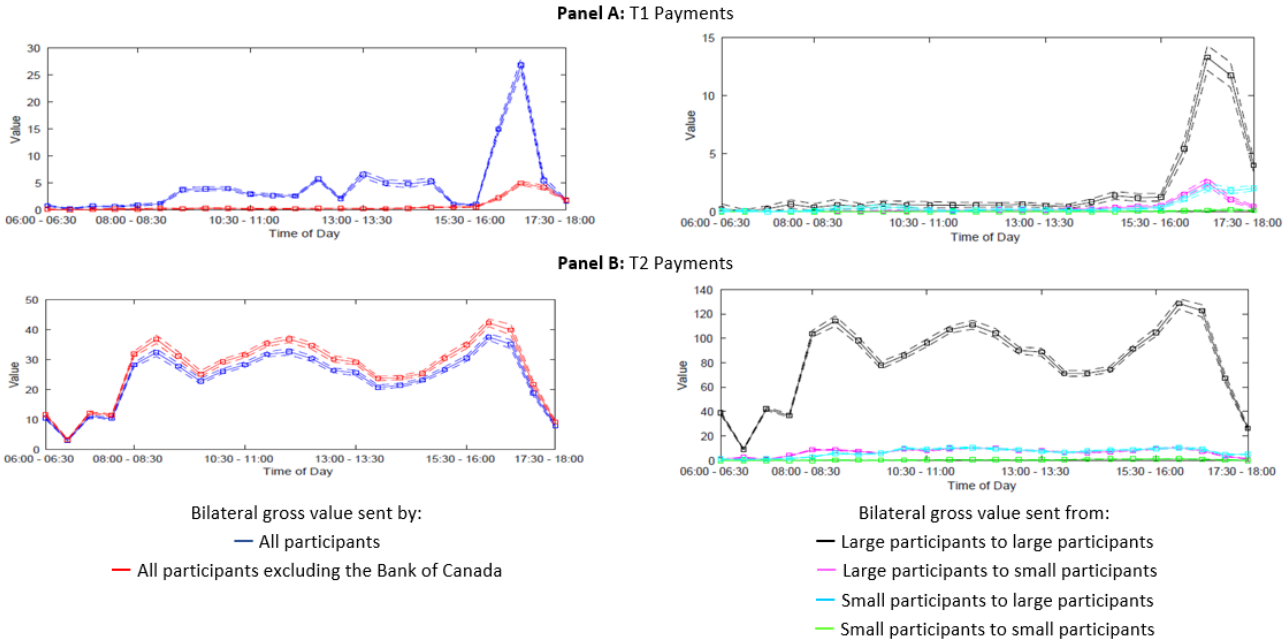
- **RTGS-equivalent system** (collateralized DNS)
  - Equivalency in terms of finality on a gross basis after clearing
  - Bilateral and multilateral netting prior to settlement
  - Throughout the day, DPs issue payment orders that represent claims on central bank balances. These claims (credit obligations) must be settled at the end of the day.

- **From the point of view of the recipient (i.e., the creditor):**
  - **Secured payments (T1):** Collateralized with the assets of the issuer (i.e., the debtor) using a *defaulter-pay arrangement*.
  - **Unsecured payments (T2):** Supported with the assets of the recipient (i.e., the creditor) using a *survivor-pay arrangement*.

- **These arrangements closely resemble collateral and capital requirements in the wider banking system**

Gross Payment Order Value

Figure 4: Bilateral gross value sent by direct participants for the full sample period



All values are in millions of Canadian dollars. Estimates are for the full sample period from March 1, 2004 to December 30, 2016.
Dotted lines represent confidence intervals at the 95% level.

- **Banks prefer to issue unsecured rather than secured payments**
  - However, as we get closer to settlement banks tend to rely more on secured payments.
- **As a portion of gross value issuance, small banks tend to issue more secured payments and receive more unsecured payments than large banks.**

Why is this work important?

1. Limited literature on joint management of risks and their interactions

- We usually assess risks in silos
- However, risks interact with each other and different banks might choose different risk profiles

2. Secured vs. unsecured exposures and capital vs. collateral requirements

- Limited empirical evidence on the use and degree of substitutability between secured (i.e., defaulter-pay) and unsecured (i.e., survivor-pay) credit obligations.
- Limited evidence on the use and degree of substitutability between collateral and capital requirements.

3. Coordination as a risk management tool

- **McAndrews and Potter (2002)** is closest to our research.
  - They study how exogenous shocks, such as the events of 9/11, affect systemwide netting, bilateral netting, and coordination in payment systems.
  - In contrast, we emphasize how **marginal and total netting** relate to **secured and unsecured credit exposures.**
- Previous literature shows that **timing of payment orders** can increase **collateral efficiency** and make **funding relatively less costly**.
  - For example, Bech and Garratt (2002); Bech (2003); Ashcraft and Duffie (2007); Kambhu, Weidman and Krishnan (2007).
  - We show that **timing and coordination is related to marginal netting.**
  - We also show that there are different marginal netting effects for **secured and unsecured credit exposures.**

2. Methodology and Empirical Results

Summary of Methodology

1. **Calculate the total amount of counterparty risk in the system throughout the day:**
   - *Total bilateral netting*
   - *Total multilateral netting*
   - *Net credit risk in the system (before collateral)*

2. **Assess how individual banks manage liquidity and counterparty risk *at the margin* throughout the day:**
   - *Marginal bilateral netting*
   - *Marginal multilateral netting*
   - *Marginal credit risk contributions* to the system

Clearing Capacity

- **Let $Val_{t,s}^{ij}$ be the sum of the value of all payments sent from DP i to j up to time s on calendar date t.**

$$Val_{t,s}^{ij} = \sum_{d=0}^{s} P_{t,d}^{ij}$$

- **T1 Clearing Capacity:**

$$\boldsymbol{T1MCC_{t,s}^{i} = \sum_{d=0}^{s} T1C_{t,d}^{i} \times \psi_{t,d}^{i} + \sum_{j \neq i}^{N} \left(T1Val_{t,s}^{ji} - T1Val_{t,s}^{ij} \right)}$$

- **T2 Clearing Capacity:**

$$\boldsymbol{T2BCC_{t,s}^{i} = BCL_{t,s}^{ji} + \left(T2Val_{t,s}^{ji} - T2Val_{t,s}^{ij} \right)}$$

$$\boldsymbol{T2MCC_{t,s}^{i} = \sum_{j \neq i}^{N} BCL_{t,s}^{ji}(\theta) + \sum_{j \neq i}^{N} \left(T2Val_{t,s}^{ji} - T2Val_{t,s}^{ij} \right)}$$

Clearing Function

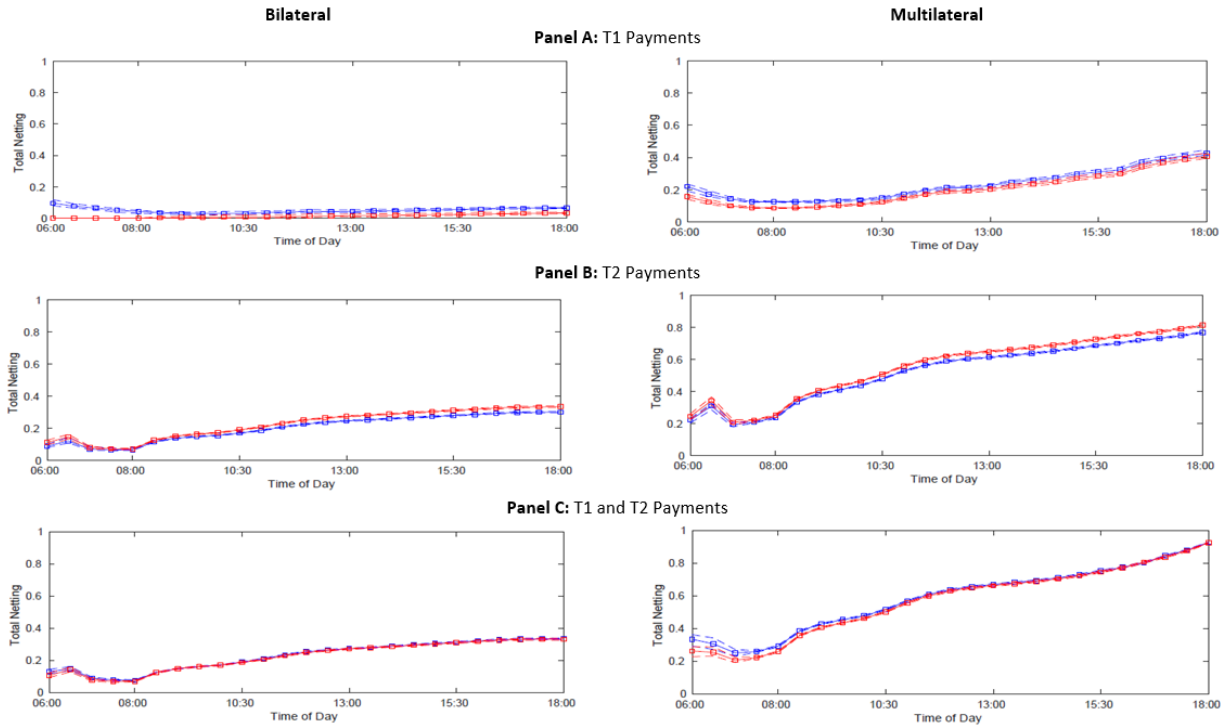
- **PO's Clearing Decision:**

$$\mathbf{T1Clearing} = \begin{cases} \mathbf{1} & \textbf{if } T1P_{t,s}^{ij} \leq T1MCC_{t,s}^{i} \\ \mathbf{0} & \textbf{otherwise} \end{cases}$$

$$\mathbf{T2Clearing} = \begin{cases} \mathbf{1} & \textbf{if } T2P_{t,s}^{ij} \leq T2BCC_{t,s}^{i} \textbf{ AND } T2P_{t,s}^{ij} \leq T2MCC_{t,s}^{i} \\ \mathbf{0} & \textbf{otherwise} \end{cases}$$

Total Netting (Full Sample Period)

Figure 6: Total netting for the full sample period



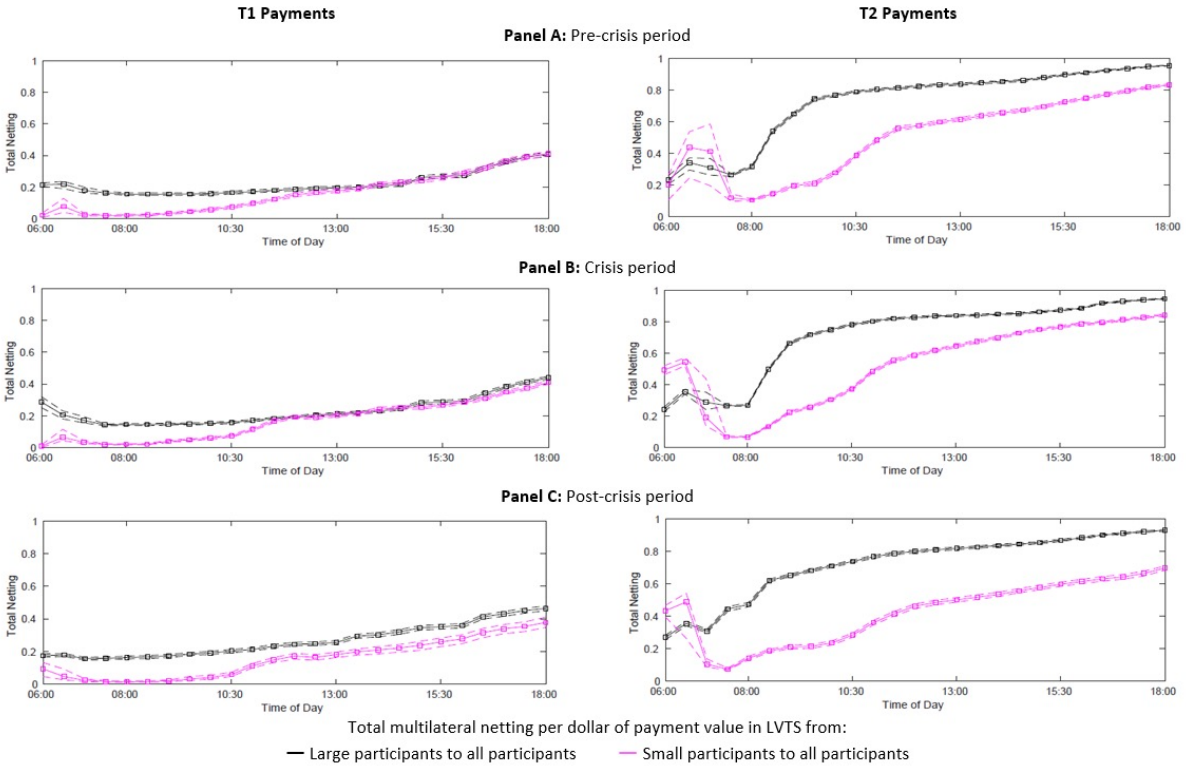
$$\eta_{t,s}^{ij} = \eta_{t,s}^{ji} = min\left(\frac{Val_{t,s}^{ji}}{Val_{t,s}^{ij}}, \frac{Val_{t,s}^{ij}}{Val_{t,s}^{ji}}\right)$$

$$\eta_{t,s}^{i} = min\left(\frac{\sum_{j\neq i}^{N} Val_{t,s}^{ji}}{\sum_{j\neq i}^{N} Val_{t,s}^{ij}}, \frac{\sum_{j\neq i}^{N} Val_{t,s}^{ij}}{\sum_{j\neq i}^{N} Val_{t,s}^{ji}}\right)$$

- **T1 (secured credit exposures)**
  - Mostly multilateral netting
- **T2 (unsecured credit exposures)**
  - Bilateral and multilateral netting
- **Most exposures are netted**
  - Between 95%-98% of combined T1 and T2 exposures are netted

Total Multilateral Netting by Participant Size

Figure 7: Total multilateral netting by size of direct participant for the pre-crisis, crisis and post-crisis periods



Panel A, B and C show estmates for the pre-crisis period (March 1, 2004 to December 1, 2007), crisis period (December 2, 2007 to June 1, 2009) and post-crisis period (June 2, 2009 to December 30, 2016), respectively. Dotted lines represent confidence intervals at the 95% level.

- **Large banks net more exposures than small banks**
  - The gap has widened after the GFC
- **Small banks add more counterparty risk to the system per dollar of payment order**

Marginal Trade-offs for a $1 Payment

		Liquidity Risk	Counterparty Risk
T1 (Secured)	**Issuer**	**LR↑** Collateral falls by $1	**CR↓** Counterparty exposure falls by $1
	Receiver	**LR↓** Collateral increases by $1	**CR↑** Counterparty exposure increases by $1
T2 (Unsecured)	**Issuer**	**LR↑** Bilateral credit line falls by $1 Potential funding from **counterparty *j*** decreases	**CR↓** Bilateral exposure falls by $1 Counterparty risk from **counterparty *j*** decreases
	Receiver	**LR↓** Bilateral credit line increases by $1 Potential funding from **counterparty *j*** increases	**CR↑** Bilateral exposure increases by $1 Counterparty risk from **counterparty *j*** increases

Coordination leads to netting of credit exposures and unencumbering of collateral assets, which increases liquidity.

Marginal Netting Specification

- **Bilateral:**

$$\Delta T1Val^{ij}_{t,s+h} = \alpha + \beta^{ij}_{1,t,s+h}\left(\Delta T1Val^{ji}_{t,s+h}\right) + \beta^{ij}_{2,t,s+h}\left(\Delta T2Val^{ji}_{t,s+h}\right) + \varepsilon^{ij}_{t,s+h}$$

$$H_0: No\ Marginal\ Bilateral\ Netting\ (\beta^{ij}_{1,t,s+h} = \beta^{ij}_{2,t,s+h} = 0)$$

- **Multilateral:**

$$\Delta T1Val^{i}_{t,s+h} = \alpha + \beta^{i}_{1,t,s+h}\left(\Delta \sum_{j\neq i}^{N-1} T1Val^{ji}_{t,s+h}\right) + \beta^{i}_{2,t,s+h}\left(\Delta \sum_{j\neq i}^{N-1} T2Val^{ji}_{t,s+h}\right) + \varepsilon^{i}_{t,s+h}$$

$$H_0: No\ Marginal\ Multilateral\ Netting\ (\beta^{i}_{1,t,s+h} = \beta^{i}_{2,t,s+h} = 0)$$

  - Where $\Delta T1Val^{ij}_{t,s+h} = T1Val^{ij}_{t,s+h} - T1Val^{ij}_{t,s}$

Marginal Netting Estimation

- **We estimate the following regression:**

$$\Delta T1Val^{ij}_{t,s+h} = a + b^{ij}_{1,t}\left(\Delta T1Val^{ji}_{t,s+h}\right) + b^{ij}_{2,t}\left(\Delta T2Val^{ji}_{t,s+h}\right)$$
$$+c^{ij}_{1,t}\left(Controls^{i}_{t,s}\right) + c^{ij}_{2,t}\left(Controls^{j}_{t,s}\right) + c^{ij}_{3,t}\left(Others'\ Controls_{t,s}\right)$$
$$+c^{ij}_{4,t}\left(Controls^{i}_{t,s+h}\right) + c^{ij}_{5,t}\left(Controls^{j}_{t,s+h}\right) + c^{ij}_{6,t}\left(Others'\ Controls_{t,s+h}\right) + e^{ij}_{t,s+h}$$

- **for each interval $[s, s+h)$ over the time series $t = 1, \ldots, T$.**
  - Econometric issues: This approach mitigates the problem of (very) large serial correlation intraday (in s)
  - Big data issues: It also helps a lot with computational problems (running out of RAM)

- We let $h = 5, 10, 15, \mathbf{30\ minutes}$.

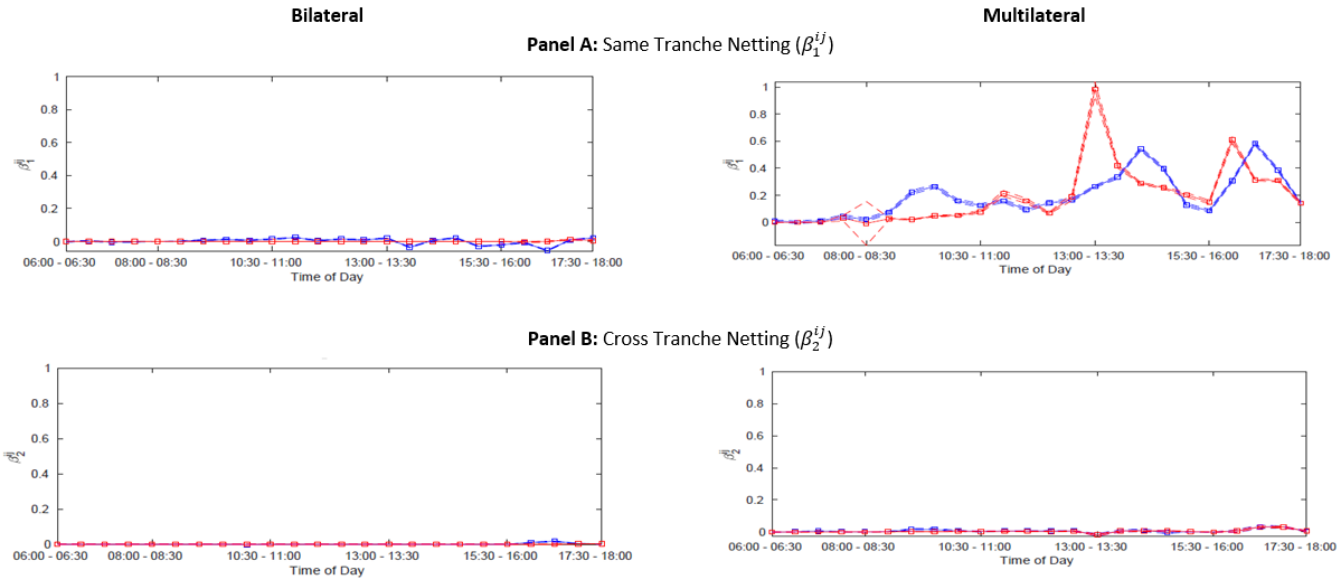
- **Challenges:**
  - Large database (almost 3TB) cannot be easily loaded all at once to estimate a panel
  - Run a regression for each ij pair, get cross-sectional average $\boldsymbol{b}$ and bootstrap CIs
  - Run a panel without time-varying $\boldsymbol{b}$ (including separate periods and random selection of days)
  - Run the specification above for smaller $\boldsymbol{T}$

Table 6: Control variables used in marginal netting regressions

Type	Control	Description	Bilateral Regression	Multilateral Regression
Clearing Capacity	$T1MCC^{i}_{t,s}$	T1 multilateral clearing capacity for DP i	✓	✓
	$\Delta T1MCC^{i}_{t,s+h}$	Change in $T1MCC$ for DP i over period h	✓	✓
	$T2MCC^{i}_{t,s}$	T2 multilateral clearing capacity for DP i	✓	✓
	$\Delta T2MCC^{i}_{t,s+h}$	Change in $T2MCC$ for DP i over period h	✓	✓
	$T2BCC^{ij}_{t,s}$	T2 bilateral clearing capacity of DP i w.r.t. DP j	✓	
	$\Delta T2BCC^{ij}_{t,s+h}$	Change in $T2BCC$ of DP i w.r.t. DP j over period h	✓	
	$T1MCC^{j}_{t,s}$	T1 multilateral clearing capacity for DP j	✓	
	$\Delta T1MCC^{j}_{t,s+h}$	Change in $T1MCC$ for DP j over period h	✓	
	$T2MCC^{j}_{t,s}$	T2 multilateral clearing capacity for DP j	✓	
	$\Delta T2MCC^{j}_{t,s+h}$	Change in $T2MCC$ of DP j over period h	✓	
	$T2BCC^{ji}_{t,s}$	T2 bilateral clearing capacity of DP j w.r.t. DP i	✓	
	$\Delta T2BCC^{ji}_{t,s+h}$	Change in $T2BCC$ of DP j w.r.t. DP i over period h	✓	
	$\overline{T2BCC}^{i,j}_{t,s}$	Avg. T2 bilateral clearing capacity of DP i		✓
	$\overline{\Delta T2BCC}^{i,j}_{t,s}$	Avg. change in $T2BCC$ of DP i over period h		✓
	$\overline{T1MCC}^{j}_{t,s}$	Avg. T1 multilateral clearing capacity for DP j		✓
	$\overline{\Delta T1MCC}^{j}_{t,s}$	Avg. change in $T1MCC$ for DP j over period h		✓
	$\overline{T2MCC}^{j}_{t,s}$	Avg. T2 multilateral clearing capacity for DP j		✓
	$\overline{\Delta T2MCC}^{j}_{t,s}$	Avg. change in $T2MCC$ for DP j over period h		✓
	$\overline{T2BCC}^{j,i}_{t,s}$	Avg. T2 bilateral clearing capacity of DP j w.r.t. DP i.		✓
	$\overline{\Delta T2BCC}^{j,i}_{t,s}$	Avg. change in $T2BCC$ of DP j w.r.t. DP i over period h		✓
Others	$D^{SysWP}_{t,d}$	Indicator variable for change in system-wide percentage from $\theta = 0.24$ to $\theta = 0.3$ on May 1, 2008.	✓	✓
	$Time_{t,d}$	Time trend variable	✓	✓
	$\tau^{ij}_{t,d+h}$	Expected arrival time of a payment from DP i to DP j from s to $s+h$	✓	
	$\tau^{ji}_{t,d+h}$	Expected arrival time of a payment from DP j to DP i from s to $s+h$	✓	
	$\tau^{i,N-1}_{t,d+h}$	Expected arrival time of a payment from DP i to any other DP from s to $s+h$		✓
	$\tau^{N-1,i}_{t,d+h}$	Expected arrival time of a payment from any other DP to DP i from s to $s+h$		✓

Marginal Netting in T1 (Secured Exposures)

Figure 14: Marginal Netting in T1 Payment Orders During the Full Sample Period



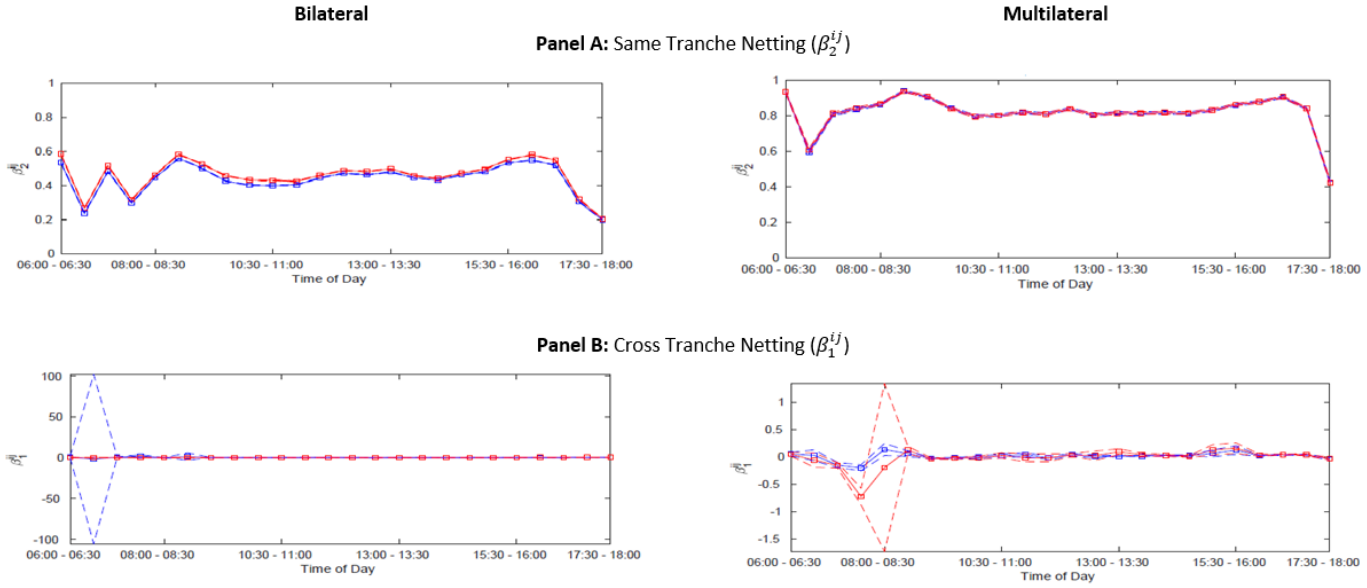
Marginal netting per dollar of payment value in LVTS from:
— All participants — All participants excluding the Bank of Canada

Dotted lines represent confidence intervals at the 95% level.

- **For T1 (secured exposures) banks rely almost exclusively on multilateral coordination.**
- **Banks do not see T1 (secured exposures) and T2 (unsecured exposures) as substitutes.**

Marginal Netting in T2 (Unsecured Exposures)

Figure 15: Marginal Netting in T2 Payment Orders During the Full Sample Period



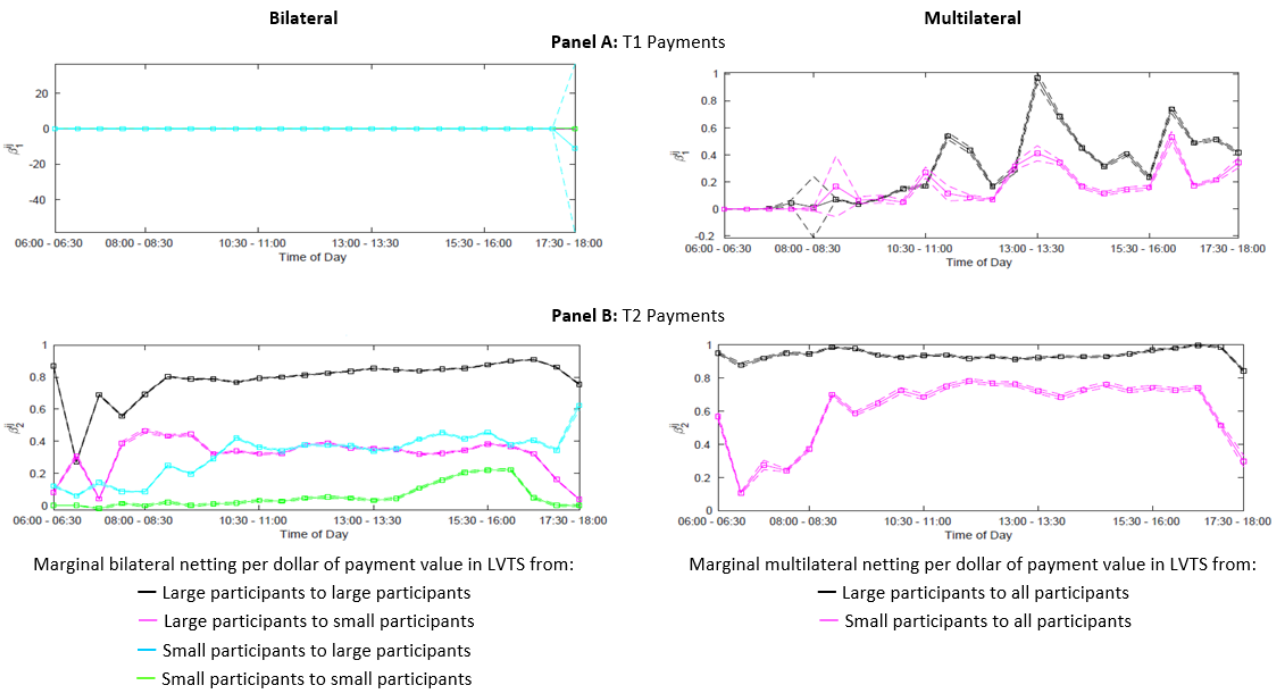
Marginal netting per dollar of payment value in LVTS from:
— All participants — All participants excluding the Bank of Canada

Dotted lines represent confidence intervals at the 95% level.

- **For T2 (unsecured exposures) banks rely on both bilateral and multilateral coordination.**
- **Banks do not see T1 (secured exposures) and T2 (unsecured exposures) as substitutes.**

Same-Tranche Marginal Netting by Participant Size

Figure 9: Same-tranche marginal netting by size of direct participant for the full sample period



Estimates are for the full sample period from March 1, 2004 to December 30, 2016. Dotted lines represent confidence intervals at the 95% level.

- **For T1 (secured exposures) banks rely almost exclusively on multilateral coordination.**
- **For T2 (unsecured exposures) banks rely on both bilateral and multilateral coordination.**
- **Large banks coordinate more and therefore net more of their exposures than small banks**
- **As settlement approaches, large banks cut their unsecured exposures to small banks**

3. Conclusion and Policy Implications

Conclusions

1. **Banks prefer to issue unsecured exposures and do not see secured and unsecured exposures as substitutes.**

2. **Banks coordinate the issuance of payments to jointly manage their liquidity and counterparty risk exposures.**
   - Small banks coordinate less and net less exposures than large banks
   - Per dollar of transaction, small banks contribute more counterparty risk to the system

3. **Banks use different coordination methods to manage secured and unsecured exposures.**
   - **Unsecured exposures:** Banks rely on both bilateral and multilateral coordination.
   - **Secured exposures:** Banks rely almost exclusively on multilateral coordination.

Policy Implications

1. **When interest rates are high, the incentive to net increases because the opportunity cost of collateral also increases**
   - Important implications for monetary policy

2. **Operational risk exposures:**
   - Large banks rely more on coordination, so they are more exposed to partial operational disruptions that disrupt marginal netting.
   - Small banks net less, so they could be more exposed to systemic operational disruptions that trigger settlement.

3. **Small banks are more exposed to changes in costs of funding**

4. **Indirect access to the payments system (i.e. corresponding banking) could increase netting efficiency**
   - The payment orders of small banks could be received and netted by big banks

Practical Policy Contributions

- **An intraday baseline of risk flows in the payments system.**

- **A monitoring tool that can be used in real time for quantifying risks and assessing the impact of regulatory changes:**
  1. Reduced form approach to measure the systemic importance of market participants.
  2. Impact of GFC, changes in interest rates, changes in collateral policies, and entry and exit of participants.
  3. Potential impact of operational disruptions.

- **A framework to help us understand liquidity and counterparty risk management:**
  - Assumptions based on empirical evidence.
  - Could help us understand **gridlock in the system.**

Thank you!

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Appendix 1: Literature Review

Why is this work important?

1. **Limited literature on joint management of risks and their interactions**
   - Particularly liquidity and counterparty risks.
   - However, these risks are central to systemic risk regulations.

2. **Secured vs. unsecured credit**
   - Limited empirical evidence on the use and degree of substitutability between secured (i.e. defaulter-pay) and unsecured (i.e., survivor-pay) credit obligations.

3. **Capital vs. collateral**
   - Limited evidence on the use and degree of substitutability between collateral and capital requirements.

4. **Coordination as a risk management tool**
   - Netting is a main determinant of counterparty risk exposures, collateral and regulatory capital.
   - If a secured exposure cannot be netted out, it must be collateralized.
   - If an unsecured exposure cannot be netted, it must be supported with regulatory capital.
   - Policymakers need to consider these interactions for collateral and capital regulations.

Contributions to the Literature

1. We integrate and expand previous literature

- **Nested framework** that jointly assesses the management of liquidity risk, secured and unsecured credit exposures in a centralized exchange.

2. Coordination and netting has received limited attention in the literature

- **McAndrews and Potter (2002)** is closest to our research.
  - They study how exogenous shocks, such as the events of 9/11, affect systemwide netting, bilateral netting, and coordination in payment systems.
  - In contrast, we emphasize how **marginal and total netting** relate to **secured and unsecured credit exposures.**
- Previous literature shows that **timing of payment orders** can increase **collateral efficiency** and make **funding relatively less costly**.
  - For example, Bech and Garratt (2002); Bech (2003); Ashcraft and Duffie (2007); Kambhu, Weidman and Krishnan (2007).
  - We show that **timing and coordination is related to marginal netting.**
  - We also show that there are different marginal netting effects for **secured and unsecured credit exposures.**

3. Our framework shows a simple link between collateral, capital requirements and liquidity

- Previous literature also shows how the **interconnectedness of participants** determines **credit exposures** and (the probability of) **contagion**.
  - For example, Furfine (1999); Bech, Chapman and Garratt (2010); McAndrews and Rajan (2000); Bech and Soramäki (2002); Soramäki, et al. (2006); Merrouche and Schanz (2008); Bech and Garratt (2012).
  - Some of these papers employ a **network approach** for modeling interconnectedness.
  - Our approach is based on a **reduced form model** of marginal risk contributions.

Appendix 2: Payment Systems

A quick introduction to payment systems

- A **payments system** is "a set of instruments, procedures, and rules for the **transfer of funds** between or among participants; the system includes the **participants** and the **entity operating the arrangement**" (BIS, 2012).

- A **large value payment system (LVPS)** is "a funds transfer system that typically handles **large-value and high-priority payments**" (BIS, 2012).

- **Netting** is "the **offsetting of obligations** between or among participants … thereby reducing the number and value of payments or deliveries needed to settle a set of transactions" (BIS, 2012).

- All payments systems rely on **two common functions** (or stages) to transfer funds:
    1. Clearing
    2. Settlement

Common Types of Payments Systems

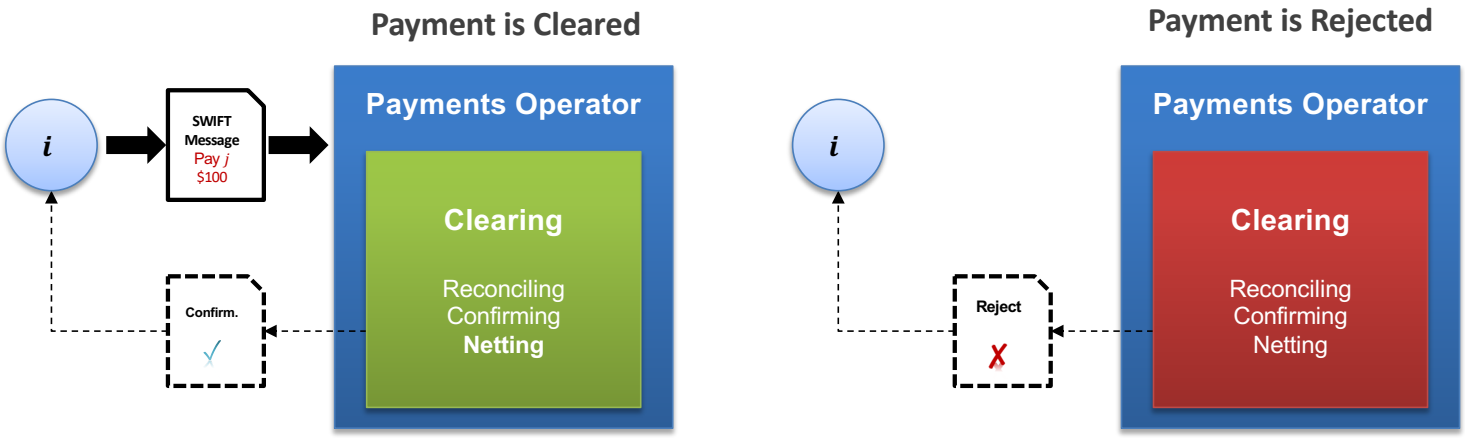
- **Real Time Gross Settlement (RTGS) systems**
  - **Clearing and settlement functions occur simultaneously and on a gross basis.**
  - There is immediate transfer of settlement funds across the accounts of direct participants (DPs).
  - Because settlement is immediate, defaults cannot occur inside the system.
  - Lack of (or limited) netting makes these systems inefficient in terms of collateral.

- **Deferred net settlement (DNS) systems**
  - **Messages are submitted and cleared, but settlement takes place at the end of the payments cycle.**
  - Separation of clearing and settlement allows for netting of payments.
  - Because settlement is not immediate, defaults can occur inside the system.
  - Use of bilateral or multilateral netting increases collateral efficiency.

The Clearing Function

1. Clearing

- "The process of transmitting, reconciling and, in some cases, confirming transactions prior to settlement, potentially including the **netting** of transactions and the establishment of final positions for settlement." (BIS, 2012).
- **"Sometimes this term is also used (imprecisely) to cover settlement"** (BIS, 2012).

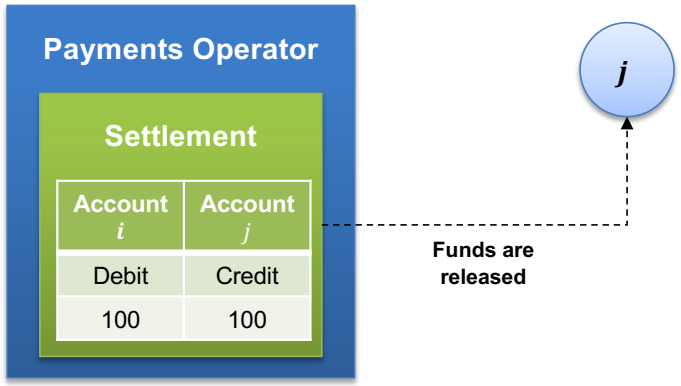


The Settlement Function

2. Settlement

- "The discharge of an obligation in accordance with the terms of the underlying contract" (BIS, 2016).
- "The release of payment obligations between two or more parties by transferring funds between them" (Bank of Canada, 2016).

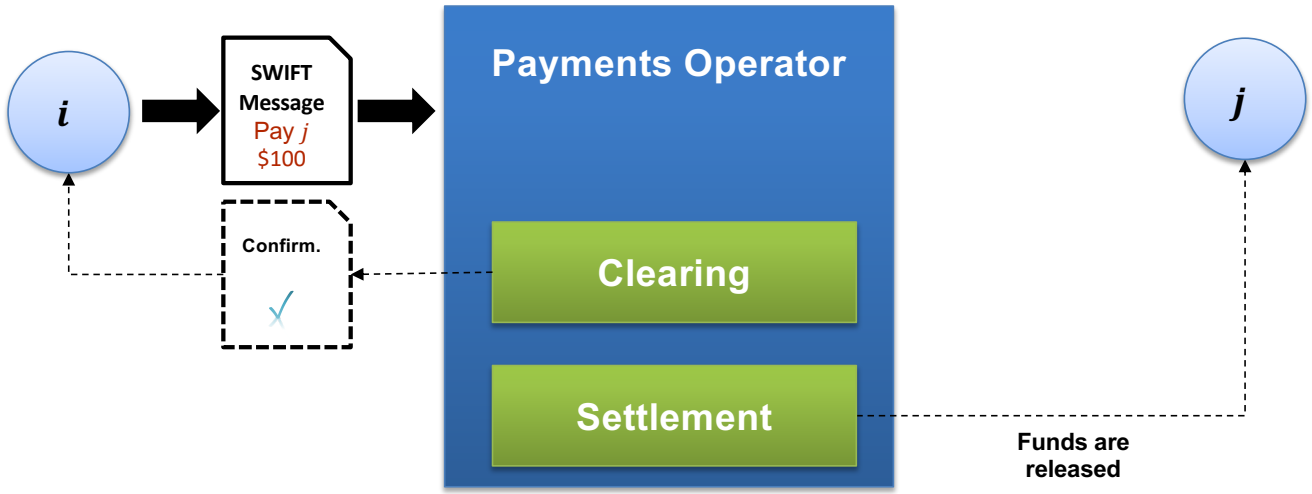
- **Example:**
  - Assume the **PO clears the payment order** in our previous example.
  - The PO transfers **"settlement funds"** (usually central bank reserves) from i to j to settle the obligation.



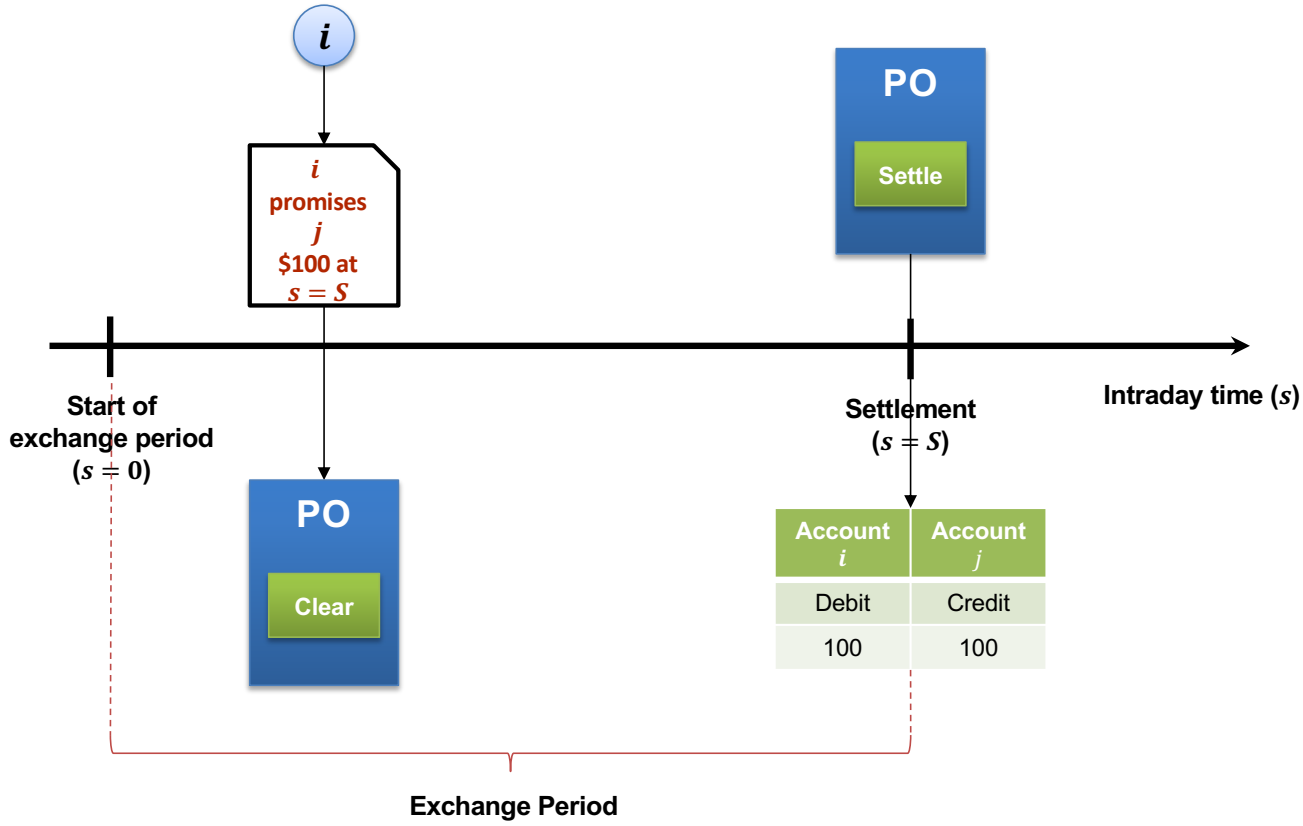
Payment Systems in a Nutshell

- **Real Time Gross Settlement (RTGS) System:** Clearing and settlement take place simultaneously
  - No counterparty risk
  - Might be inefficient in terms of liquidity and collateral

- **Deferred Net Settlement (DNS) System:** Clearing first and settlement at the end of a predetermined period
  - Leads to **counterparty risk**
  - The **payments operator** manages credit risk with **collateral requirements** and **loss-sharing provisions.**

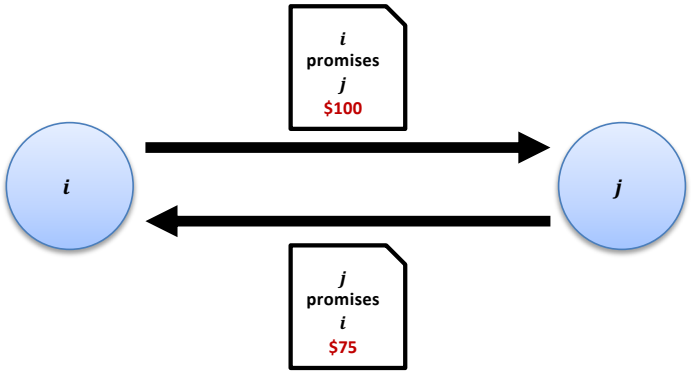


A Deferred Net Settlement (DNS) System

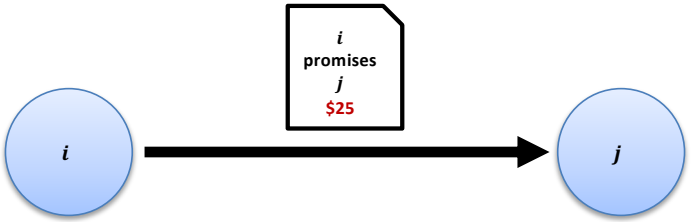


Bilateral Netting

Gross credit obligations



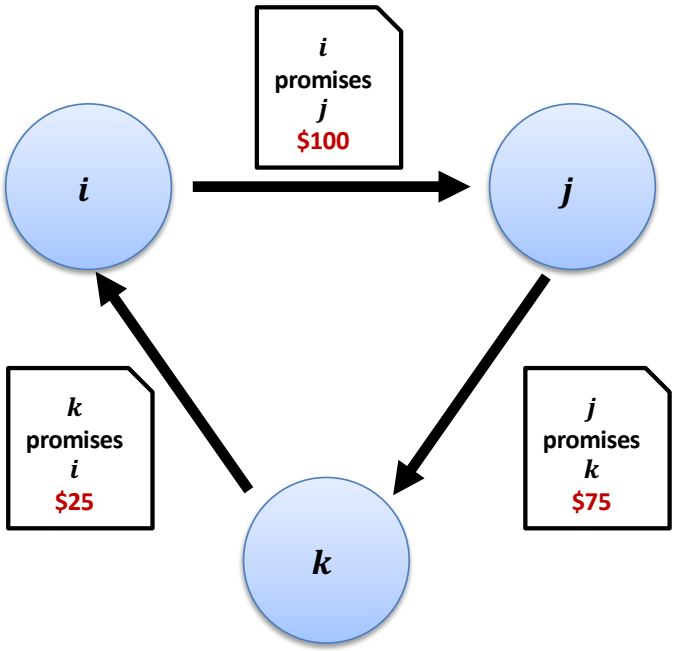
Net credit obligations



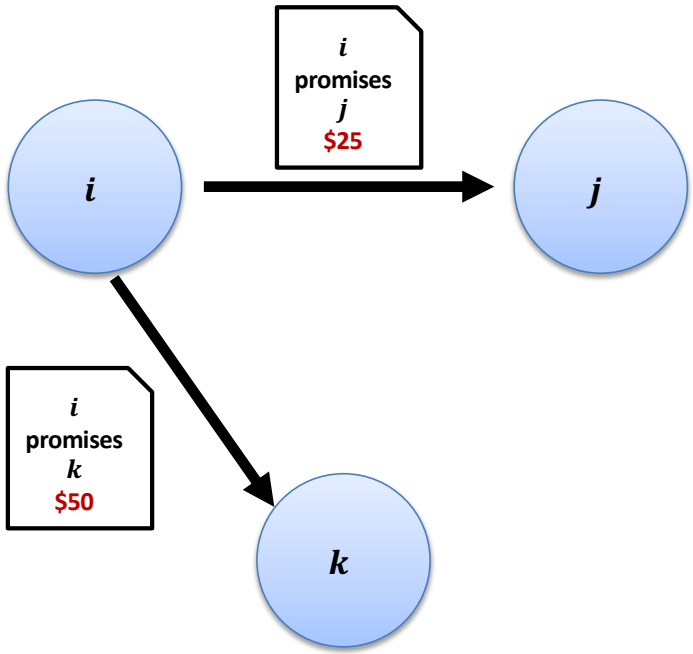
Netting is "the **offsetting of obligations** between or among participants … thereby reducing the number and value of payments or deliveries needed to settle a set of transactions" (BIS, 2012).

Multilateral Netting

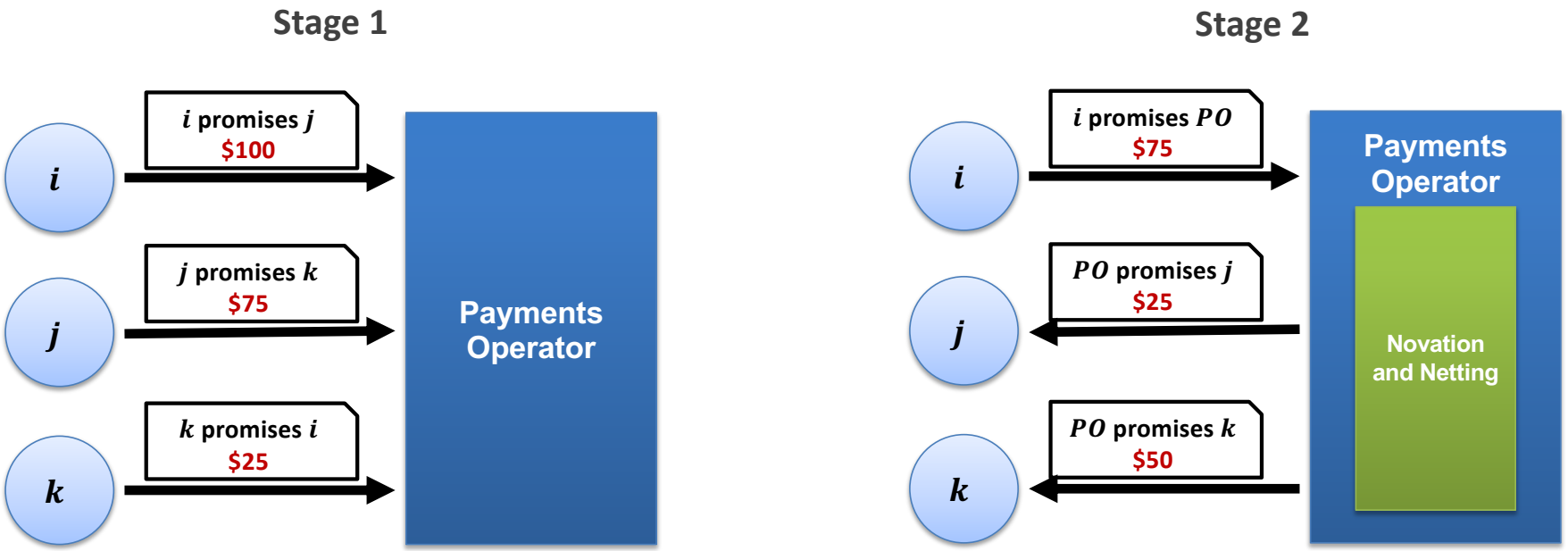
Gross credit obligations



Possible Arrangement of Net credit obligations



Multilateral Netting



Appendix 3: Liquidity Flows and Clearing Capacity

Liquidity Flows

- Let $Val_{t,s}^{ij}$ be the sum of the value of all payments sent from DP i to j up to time s on calendar date t.

$$\boldsymbol{Val_{t,s}^{ij} = \sum_{d=0}^{s} P_{t,d}^{ij}}$$

- The net bilateral liquidity inflow of DP i from j up to time s on calendar date t is:

$$\boldsymbol{NBI_{t,s}^{ji} = Val_{t,s}^{ji} - Val_{t,s}^{ij}}$$

- The net multilateral liquidity inflow of DP i up to time s on calendar date t is:

$$\boldsymbol{NMI_{t,s}^{i} = \sum_{j \neq i}^{N} NBI_{t,s}^{ji} = \sum_{j \neq i}^{N} \left(Val_{t,s}^{ji} - Val_{t,s}^{ij} \right)}$$

- **Note:**
  - NMO includes all NBOs across participants.
  - A correction is needed when payment values are not continuous (i.e., payment orders cannot be partially settled).
  - Novation is needed for multilateral netting.
  - If payments are not continuous and matching is not perfect, settlement needs to happen on a gross basis.

Clearing Capacity

- The **clearing function** and **liquidity flows** determine the **clearing capacity** of direct participants (DPs).

- **Clearing capacity:**
  - The maximum order value that a payments processor would agree to clear for a DP immediately, without delays or queuing, given a set of risk management conditions.
  - It is a type of **funding liquidity** with **limits and costs determined by the structure of the payment system.**

- There are two types of clearing capacity depending on the configuration of the payments system:

1. **Bilateral Clearing Capacity:**

$$BCC_{t,s}^{i} = BDC_{t,s}^{ij} + NBI_{t,s}^{ji}$$

2. **Multilateral Clearing Capacity:**

$$MCC_{t,s}^{i} = MDC_{t,s}^{i} + NMI_{t,s}^{i}$$

LVTS T1 Clearing Capacity

- **Let $Val_{t,s}^{ij}$ be the sum of the value of all payments sent from DP i to j up to time s on calendar date t.**

$$Val_{t,s}^{ij} = \sum_{d=0}^{s} P_{t,d}^{ij}$$

- **T1 uses full collateralization:**

$$T1MDC_{t,s}^{i} = \sum_{d=0}^{s} T1C_{t,d}^{i} \times \psi_{t,d}^{i}$$

  - Where $\psi_{t,d}^{i} \epsilon [0,1]$ is the haircut parameter.
  - T1MDC is the T1 **multilateral net debit cap** (also known as T1 Net Debit Cap)

- **The T1 Multilateral Clearing Capacity of i:**

$$\boldsymbol{T1MCC_{t,s}^{i} = \sum_{d=0}^{s} T1C_{t,d}^{i} \times \psi_{t,d}^{i} + \sum_{j \neq i}^{N} \left(T1Val_{t,s}^{ji} - T1Val_{t,s}^{ij} \right)}$$

LVTS T2 Clearing Capacity

- **The debit caps in T2 are:**

$$T2BDC_{t,s}^{ij} = BCL_{t,s}^{ji} \quad \text{and} \quad T2MDC_{t,s}^{i} = \sum_{j\neq i}^{N} BCL_{t,s}^{ji}(\theta)$$

- **Therefore, the clearing capacity in T2 is defined by:**

$$\boldsymbol{T2BCC_{t,s}^{i} = BCL_{t,s}^{ji} + \left(T2Val_{t,s}^{ji} - T2Val_{t,s}^{ij}\right)}$$

$$\boldsymbol{T2MCC_{t,s}^{i} = \sum_{j\neq i}^{N} BCL_{t,s}^{ji}(\theta) + \sum_{j\neq i}^{N}\left(T2Val_{t,s}^{ji} - T2Val_{t,s}^{ij}\right)}$$

- **Notice that the collateral contribution after haircuts is**

$$T2C_{t,d}^{i} = \frac{maxASO_{t,s}^{i}}{\psi_{t,d}^{i}} = \frac{max\left(BCL_{t,s}^{ij}\right)\theta}{\psi_{t,d}^{i}}$$

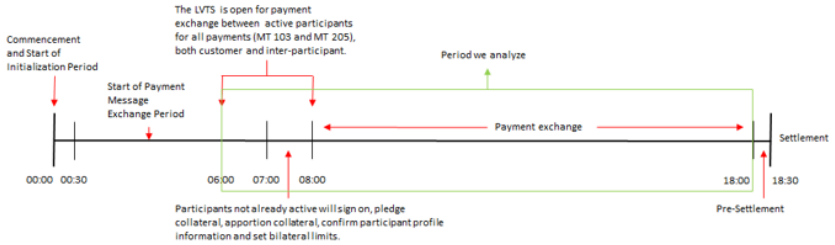
  - Where **θ is the system-wide percentage**.

- Therefore, **there is no one-to-one correspondence between collateral contribution and clearing capacity.**

Appendix 4: LVTS

LVTS Cycle

Figure 1: Daily operating schedule of the LVTS



Time	LVTS Cycle
23:00	**Commencement and Start of Initialization Period** DPs wishing to exchange CLS-related or bilaterally agreed upon non-CLS related payments will sign-on, pledge collateral, apportion collateral, confirm DP profile information and set bilateral limits. The Bank of Canada will value DP collateral. CLS-related payments are those payments to/from Bank of Canada for the benefit of the CLS Bank, payments delivered between DPs to fund a DP's position or a client's position for whom a DP is acting as the client's... agent.
00:30 - 18:00	**Start of Payment Message Exchange Period** LVTS is open for exchanging payments.1 There must be bilateral agreement between Sending and Receiving DPs to send non-CLS related payments prior to 06:00 hours.
07:00-08:00	**Sing-on Period** DPs not already active will sign-on, pledge collateral, apportion collateral, confirm DP profile information, and set bilateral limits.
18:00	**End of Payment Message Exchange Period/Start of Pre-Settlement** Start of Inter-DP Payment Message Exchange Period LVTS is open for bilaterally agreed upon inter-DP payments (MT 205 only). This period is to be used by the DPs to bring their Multilateral Net Positions closer to zero.
18:30	**End of Pre-Settlement** No further payment messages may be exchanged through the LVTS.
By 19:30	**Settlement** The Bank of Canada will settle all DPs' Multilateral Net Positions. All DPs' Multilateral Positions are settled simultaneously.

Note: This figure describes the LVTS Cycle as reported in Payments Canada (2017).

Suggested Guidelines for Payment Transmissions

Table 2: Payments Canada suggested guidelines for payment transmissions

Time	Daily Payment Order Dollar Value	Daily Payment Order Volume
10:00 (Local)	25%	40%
13:00 (Local)	60%	60%
16:30 (EST)	80%	80%

Note: According to Rule 6 of the LVTS, DPs, excluding the Bank of Canada, are currently encouraged to meet these minimum targets by the specified time on a best effort basis. However, if DPs do not meet these targets and this situation prevents the smooth operation of the LVTS, the targets could become mandatory or the intraday fee structure could be changed to encourage DPs to meet the targets (Payments Canada, 2017).

Appendix 5: Data

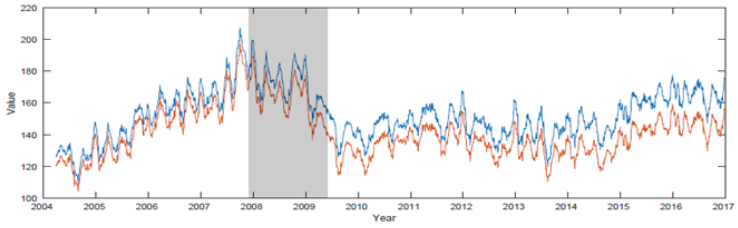
Summary of the data

- **Historical LVTS data**
  - All payment orders from March 1st, 2004 to December 30th, 2016.
  - On average, 18 DPs including the Bank of Canada.

- **Important periods of exogenous variation**
  - The Great Financial Crisis:
    - Pre-crisis period (March 1, 2004 to December 1, 2007)
    - Crisis period (December 2, 2007 to June 1, 2009)
    - Post-crisis period (June 2, 2009 to December 30, 2016)
  - Change in collateral policy:
    - System wide percentage parameter from 0.24 to 0.30 on May 1, 2008.
  - Entry and exit of DPs

Figure 2: System-wide gross value and gross volume of payment orders for the full sample period

Panel A: Gross value of payment orders (in billions of Canadian dollars)



Panel B: Gross volume of payment orders (in thousands)

Payments from:

— All participants — All participants excluding the Bank of Canada

Panel A and B report the rolling moving average (21 trading days) of the aggregate gross value and the aggregate gross volume of payment orders processed in the LVTS, respectivelly, for the full sample period from March 1, 2004 to December 30, 2016. The shaded area corresponds to the Great Financial Crisis (from December 2, 2007 to June 1, 2009, NBER, 2010).

LVTS Participants

Table 1: Direct participants in the LVTS

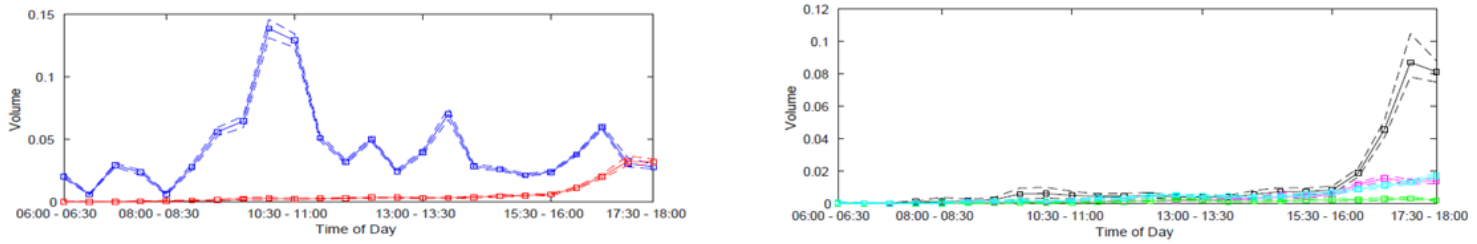
Number	Direct Participant	Partners
1	Alberta Treasury Branches	0
2	Bank of America National Association	0
3	Bank of Canada	0
4	Bank of Montreal	14
5	BNP Paribas	0
6	Caisse Centrale Desjardins	4
7	Canadian Imperial Bank of Commerce	9
8	Central 1 Credit Union	13
9	HSBC Bank Canada	0
10	ICICI Bank Canada	0
11	Laurentian Bank of Canada	1
12	Manulife Bank of Canada	0
13	National Bank of Canada	0
14	Royal Bank of Canada	21
15	State Street	0
16	The Bank of Nova Scotia	2
17	Toronto-Dominion Bank	1

Note: The table lists the direct participants in the LVTS as of December 31, 2017. It also reports the number of non-participant partners associated to each direct participant. Non-participant partners are institutions that access the LVTS indirectly through a direct participant.

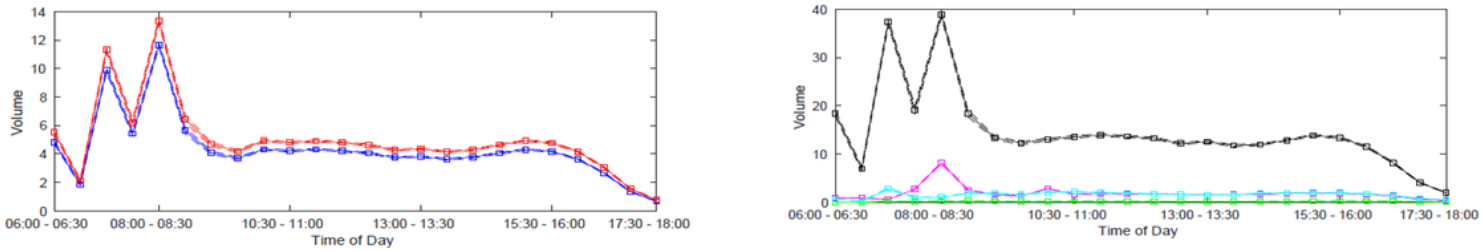
Gross Payment Order Volume

Figure 5: Bilateral volume of payment orders sent by direct participants for the full sample period

Panel A: T1 Payments



Panel B: T2 Payments



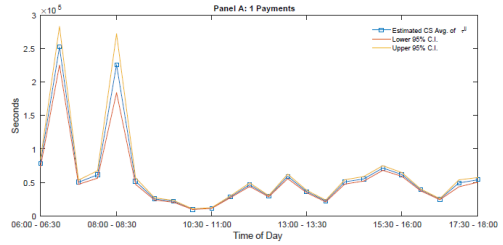
Bilateral gross volume sent by:
- All participants
- All participants excluding the Bank of Canada

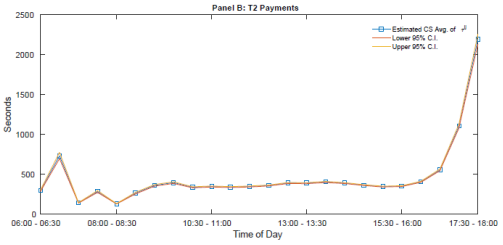
Bilateral gross volume from:
- Large participants to large participants
- Large participants to small participants
- Small participants to large participants
- Small participants to small participants

All values in thousands. Estimates are for the full sample period from March 1, 2004 to December 30, 2016.
Dotted lines represent confidence intervals at the 95% level.

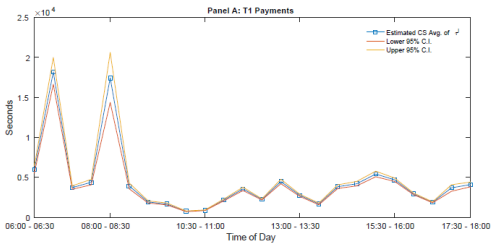
Arrival Times of Payments (CSA)

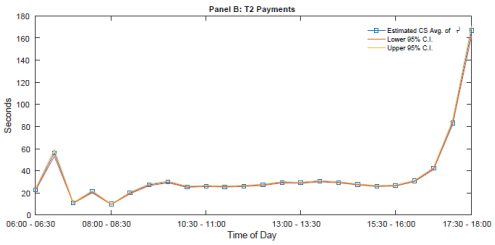
Bilateral



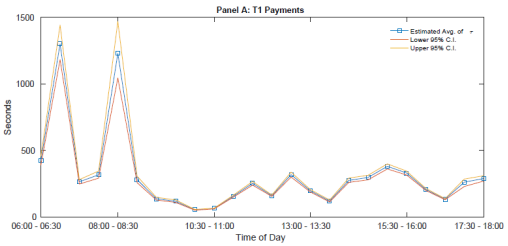


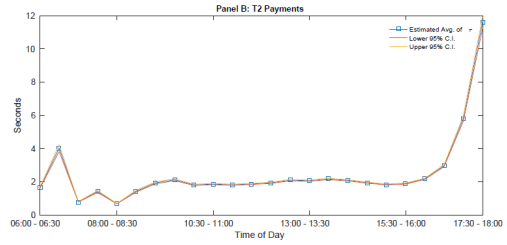
Multilateral





Systemwide





Aggregate Daily Payment Order Values and Volumes

Table 3: Aggregate daily payment order values and volume

	Full Sample			Pre-Crisis Period			Crisis Period			Post-Crisis Period		
	N	**VAL**	**VOL**	**N**	**VAL**	**VOL**	**N**	**VAL**	**VOL**	**N**	**VAL**	**VOL**
Panel A: T1 Payments												
All	18	29.17	0.24	15	20.61	0.20	15	27.45	0.23	18	33.71	0.26
		(13.09)	(0.05)		(7.68)	(0.03)		(10.14)	(0.04)		(13.53)	(0.05)
Large	8	13.42	0.04	8	9.33	0.03	8	12.84	0.05	8	15.55	0.05
		(7.04)	(0.03)		(4.47)	(0.02)		(6.06)	(0.03)		(7.34)	(0.03)
Small	9	1.54	0.03	6	1.43	0.03	6	1.48	0.03	9	1.60	0.03
		(0.96)	(0.01)		(0.84)	(0.01)		(0.82)	(0.01)		(1.03)	(0.01)
Bank of Canada	1	14.21	0.16	1	9.85	0.14	1	13.13	0.15	1	16.57	0.17
		(5.77)	(0.03)		(2.99)	(0.01)		(4.08)	(0.02)		(5.79)	(0.03)
Panel B: T2 Payments												
All	18	130.25	23.94	15	135.88	18.57	15	150.26	21.96	18	123.54	26.95
		(24.58)	(5.91)		(26.92)	(3.21)		(25.53)	(3.60)		(19.91)	(5.22)
Large	8	121.25	21.71	8	126.43	16.97	8	138.21	19.88	8	115.36	24.40
		(22.61)	(5.37)		(24.80)	(2.96)		(23.53)	(3.30)		(18.64)	(4.84)
Small	9	8.99	2.22	6	9.44	1.60	6	12.05	2.07	9	8.17	2.56
		(2.51)	(0.58)		(2.74)	(0.28)		(2.55)	(0.33)		(1.76)	(0.45)
Bank of Canada	1	0.00	0.00	1	0.01	0.00	1	0.00	0.00	1	0.00	0.00
		(0.01)	(0.00)		0.03	0.00		(0.02)	(0.00)		(0.01)	(0.00)

Note: The table reports the time series average of aggregate payment order values and volumes. VAL is payment order values in billions of Canadian dollars. VOL is payment order volumes in thousands. Numbers in in brackets are standard deviations. The All category includes all DPs in the LVTS. The Large and Small categories group DPs above and below the cross-sectional median value of payment orders during the sample period, respectively. These categories exclude the Bank of Canada.

Aggregate Collateral and BCLs

Table 4: Aggregate collateral and bilateral credit lines

	Full Sample		Pre-Crisis Period		Crisis Period		Post-Crisis Period	
	N	**Collateral**	**N**	**Collateral**	**N**	**Collateral**	**N**	**Collateral**
				Panel A: T1 Collateral				
All	17	11.37	14	8.37	14	10.61	17	13.00
		(3.69)		(2.12)		(2.90)		(3.45)
Large	8	8.94	8	6.22	8	7.09	8	10.63
		(3.49)		(1.64)		(2.83)		(3.23)
Small	9	2.44	6	2.15	6	3.51	9	2.36
		(0.91)		(1.06)		(0.58)		(0.72)
				Panel B: T2 Collateral				
All	17	4.63	14	3.63	14	4.64	17	5.11
		(0.74)		(0.49)		(0.53)		(0.19)
Large	8	3.78	8	3.01	8	3.83	8	4.15
		(0.58)		(0.38)		(0.45)		(0.15)
Small	9	0.84	6	0.63	6	0.81	9	0.95
		(0.19)		(0.18)		(0.11)		(0.10)
	N	**BCL**	**N**	**BCL**	**N**	**Collateral**	**N**	**Collateral**
				Panel C: BCL Received				
All	17	75.26	14	75.26	14	81.41	17	92.19
		(7.76)		(7.76)		(2.01)		(4.03)
Large	8	39.35	8	39.35	8	69.10	8	77.19
		(3.22)		(3.22)		(1.71)		(2.76)
Small	9	10.90	6	10.90	6	12.31	9	14.99
		(1.83)		(1.83)		(0.58)		(1.47)
				Panel D: BCL Sent				
All	17	71.68	14	71.68	14	77.53	17	87.80
		(7.39)		(7.39)		(1.91)		(3.84)
Large	8	37.55	8	37.55	8	65.49	8	73.65
		(3.01)		(3.01)		(1.65)		(2.83)
Small	9	10.79	6	10.79	6	12.05	9	14.14
		(1.73)		(1.73)		(0.52)		(1.24)

Note: The table reports the time series average of daily aggregates of collateral in T1 and T2 and BCLS received and sent. Collateral and BCL values are in billions of Canadian dollars. Numbers in in brackets are standard deviations. The All category includes all DPs in the LVTS. The Large and Small categories group DPs above and below the cross-sectional median value of payment orders during the sample period, respectively. All these categories exclude the Bank of Canada because the Bank of Canada does not post collateral or extend BCLs.

Average BCL

Table 5: Average bilateral credit line

	Full Sample		Pre-Crisis Period		Crisis Period		Post-Crisis Period	
	N	**Average**	**N**	**Average**	**N**	**Average**	**N**	**Average**
				Panel A: BCL Received				
All	17	5.06	14	5.38	14	5.82	17	5.42
		(0.55)		(0.55)		(0.14)		(0.24)
Large	8	9.06	8	8.04	8	8.64	8	9.65
		(0.88)		(0.78)		(0.21)		(0.34)
Small	9	1.50	6	1.82	6	2.05	9	1.67
		(0.27)		(0.30)		(0.10)		(0.16)
				Panel B: BCL Sent				
All	17	4.82	14	5.12	14	5.54	17	5.16
		(0.52)		(0.53)		(0.14)		(0.23)
Large	8	8.62	8	7.61	8	8.19	8	9.21
		(0.87)		(0.74)		(0.21)		(0.35)
Small	9	1.44	6	1.80	6	2.01	9	1.57
		(0.23)		(0.29)		(0.09)		(0.14)

Note: The table reports the time series average of cross-sectional average of BCLS received and sent. BCLs are in billions of Canadian dollars. Numbers in brackets are standard deviations. The All category includes all DPs in the LVTS. The Large and Small categories group DPs above and below the cross-sectional median value of payment orders during the sample period, respectively. All these categories exclude the Bank of Canada because the Bank of Canada does not extend BCLs.

LVTS Participants

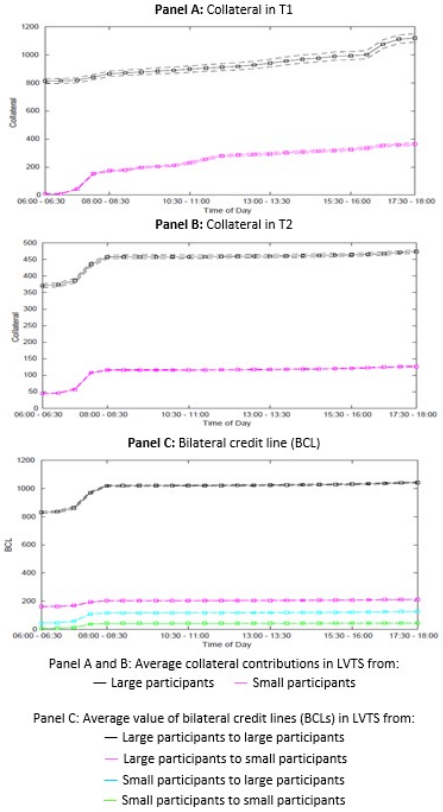
Table 1: Direct participants in the LVTS

Number	Direct Participant	Partners
1	Alberta Treasury Branches	0
2	Bank of America National Association	0
3	Bank of Canada	0
4	Bank of Montreal	14
5	BNP Paribas	0
6	Caisse Centrale Desjardins	4
7	Canadian Imperial Bank of Commerce	9
8	Central 1 Credit Union	13
9	HSBC Bank Canada	0
10	ICICI Bank Canada	0
11	Laurentian Bank of Canada	1
12	Manulife Bank of Canada	0
13	National Bank of Canada	0
14	Royal Bank of Canada	21
15	State Street	0
16	The Bank of Nova Scotia	2
17	Toronto-Dominion Bank	1

Note: The table lists the direct participants in the LVTS as of December 31, 2017. It also reports the number of non-participant partners associated to each direct participant. Non-participant partners are institutions that access the LVTS indirectly through a direct participant.

Collateral and BCL by Participant Size

Figure 3: Average collateral and bilateral credit lines by size of direct participant for the full sample period



Panel A and B: Average collateral contributions in LVTS from:
— Large participants — Small participants

Panel C: Average value of bilateral credit lines (BCLs) in LVTS from:
— Large participants to large participants
— Large participants to small participants
— Small participants to large participants
— Small participants to small participants

All values are in millions of Canadian dollars. Estimates are for the full sample period from March 1, 2004 to December 30, 2016. Dotted lines represent confidence intervals at the 95% level. The Bank of Canada will value the collateral of all DPs prior to 00:30 hours regardless of when they become active.

Appendix 6: Empirical Results

Total Netting (non-parametric)

- **Total Bilateral Netting:**

$$\eta_{t,s}^{ij} = \eta_{t,s}^{ji} = min\left(\frac{Val_{t,s}^{ji}}{Val_{t,s}^{ij}}, \frac{Val_{t,s}^{ij}}{Val_{t,s}^{ji}}\right)$$

- **Total Multilateral Netting:**

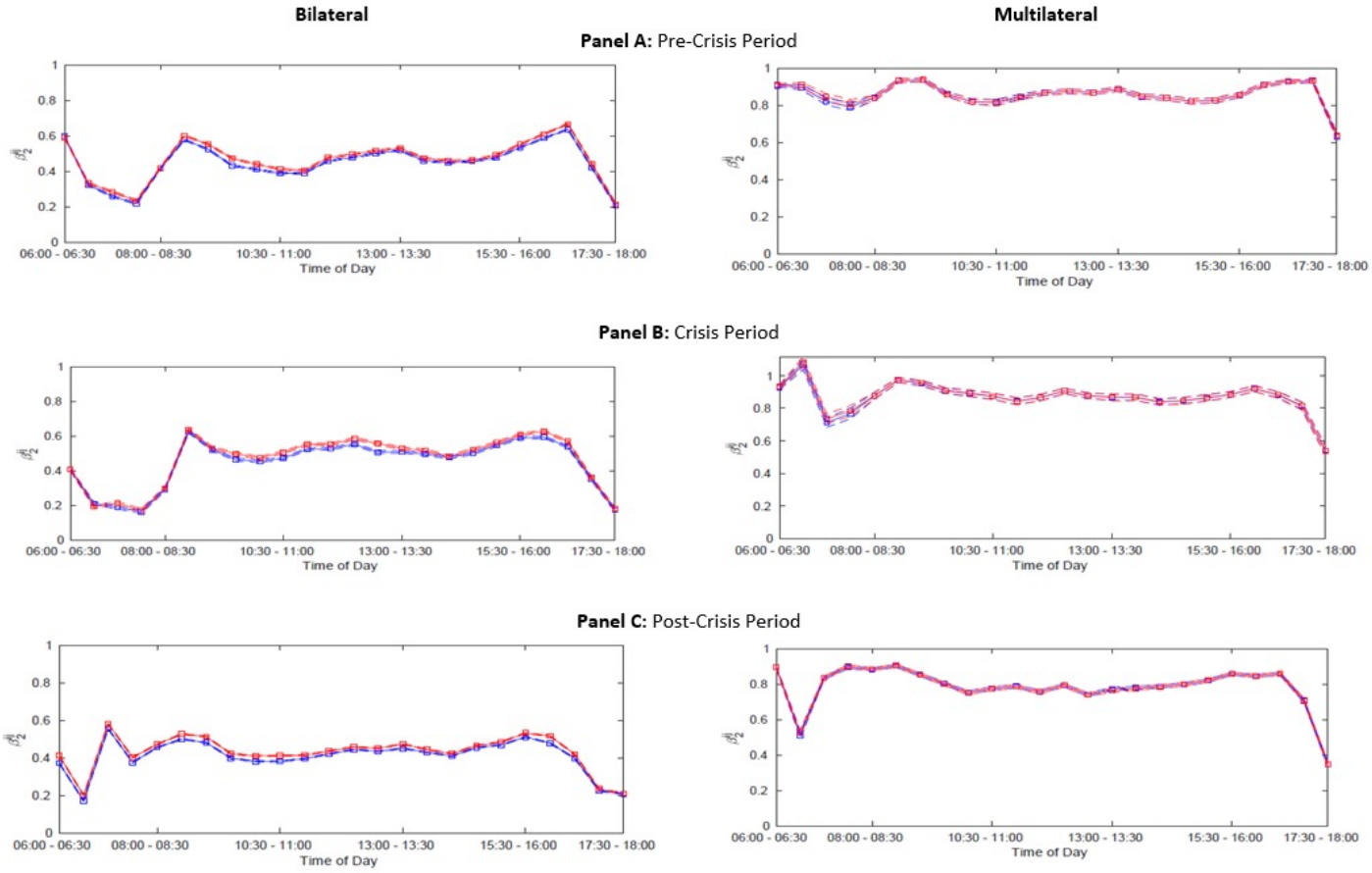
$$\eta_{t,s}^{i} = min\left(\frac{\sum_{j\neq i}^{N} Val_{t,s}^{ji}}{\sum_{j\neq i}^{N} Val_{t,s}^{ij}}, \frac{\sum_{j\neq i}^{N} Val_{t,s}^{ij}}{\sum_{j\neq i}^{N} Val_{t,s}^{ji}}\right)$$

Marginal Netting Specification

Same-tranche, cross-tranche and mixed-tranche marginal netting strategies and their *perfect* variations:

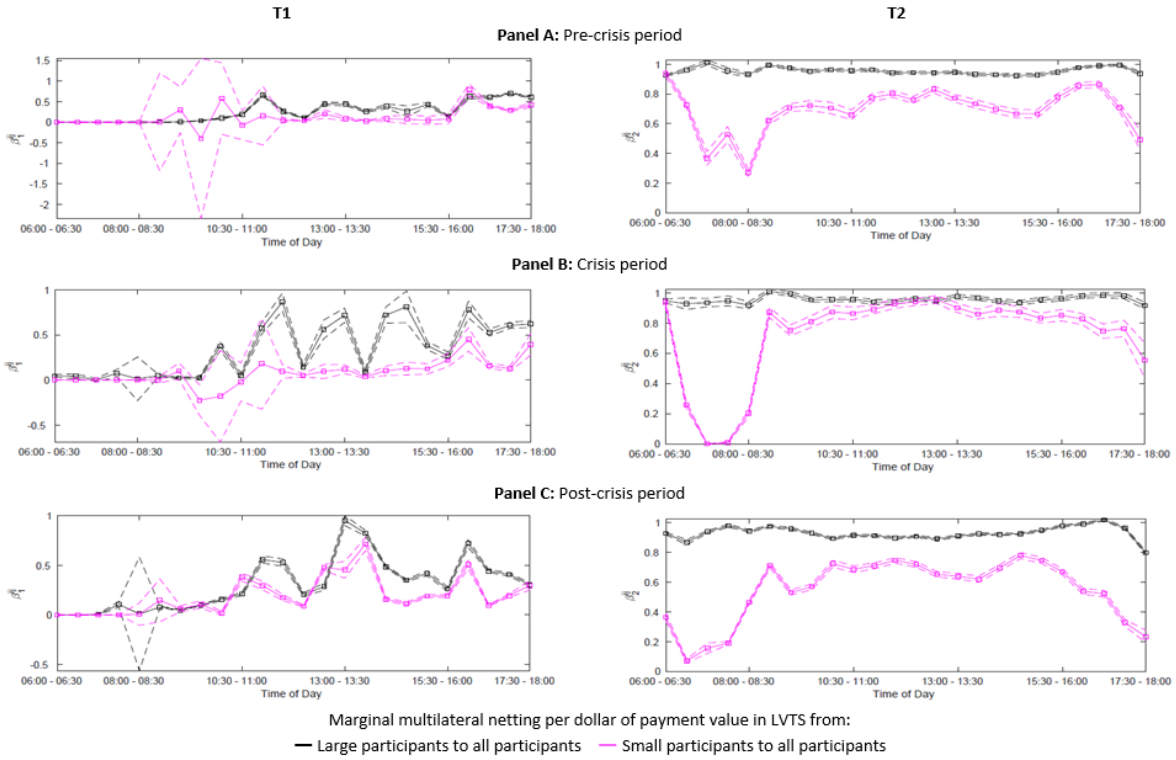
H_1 : $\boldsymbol{Same\ Tranche}$ $Marginal\ Netting$ $(\beta_1 > 0\ and\ \beta_2 = 0)$ H_1^P: $\boldsymbol{Perfect\ Same\ Tranche}$ $Marginal\ Netting$ $(\beta_1 = 1\ and\ \beta_2 = 0)$	(H1)
H_2 : $\boldsymbol{Cross\ Tranche}$ $Marginal\ Netting$ $(\beta_1 = 0\ and\ \beta_2 > 0)$ H_2^P: $\boldsymbol{Perfect\ Cross\ Tranche}$ $Marginal\ Netting (\beta_1 = 0\ and\ \beta_2 = 1)$	(H2)
H_3 : $\boldsymbol{Mixed\ Tranche}$ $Marginal\ Netting$ $(\beta_1 > 0\ and\ \beta_2 > 0)$ H_3^P: $\boldsymbol{PerfectMixed\ Tranche}$ $Marginal\ Netting$ $(\beta_1 + \beta_2 = 1)$	(H3)

Same Tranche Marginal Netting in T2



Same-Tranche Multilateral Marginal Netting

Figure 10: Same-tranche marginal multilateral netting by size of direct participant for the pre-crisis, crisis and post-crisis periods



Panel A, B and C show estmates for the pre-crisis period (March 1, 2004 to December 1, 2007), crisis period (December 2, 2007 to June 1, 2009) and post-crisis period (June 2, 2009 to December 30, 2016), respectively. Dotted lines represent confidence intervals at the 95% level.

- **Large banks coordinate more and therefore net more exposures than small banks**
  - The gap in coordination and netting between large and small banks has increased after the GFC
- **Transactions with small banks require more collateral and settlement funds per dollar of payment order.**
- **Coordination and netting incentives increase with risk exposures and the cost of funding**
  - Large banks have larger risk exposures
  - Liquidity has become relatively cheaper after the GFC

Same Tranche Marginal Netting in T2