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Identifying central bank liquidity super-spreaders in interbank funds networks[1]

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Abstract

Evidence suggests that the Colombian interbank funds market is an inhomogeneous and hierarchical network in which a few financial institutions fulfill the role of "super-spreaders" of central bank liquidity among market participants. Results concur with evidence from other interbank markets and other financial networks regarding the flaws of traditional direct financial contagion models based on homogeneous and non-hierarchical networks, and provide further evidence about financial networks' self-organization emerging from complex adaptive financial systems. Our research work contributes to central bank's efforts by (i) examining and characterizing the actual connective structure of interbank funds networks; (ii) identifying those financial institutions that may be considered as the most important conduits for monetary policy transmission, and the main drivers of contagion risk within the interbank funds market; (iii) providing new elements for the implementation of monetary policy and for safeguarding financial stability.

JEL: E5, G2, L14,

Keywords: interbank, monetary policy, contagion, networks, super-spreader, central bank.

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1 Introduction

The interbank funds market plays a central role in monetary policy transmission: *it allows banks to exchange central bank money in order to share liquidity risks* (Fricke and Lux, 2012; p.2). For that reason, *they are the focus of central banks' implementation of monetary policy and have a significant effect on the whole economy* (Allen et al., 2009; p.639), whereas the interbank rate is commonly regarded as the central bank's main target for assessing the effectiveness of monetary policy transmission. In addition, as there are powerful incentives for participants to monitor each other, the interbank funds market also plays a key role as a source of market discipline (Rochet and Tirole, 1996; Furfine, 2001).

This paper proposes an alternative approach to the analysis of the interbank funds market and its role for monetary policy transmission. The suggested approach consists of using network analysis' concepts and metrics for identifying the connective and hierarchical structure of the Colombian interbank funds market. However, as a realistic model of interbank funds market has to take the central bank into account (Georg and Poschmann, 2010), the network under analysis comprises the interbank funds market and the central bank's monetary policy transactions (i.e. open market operations vía repos).

Our main findings come in the form of the identification of an inhomogeneous and hierarchical connective (core-periphery) structure, in which a few financial institutions fulfill the role of "super-spreaders" of central bank money within the interbank funds market because of their *hub centrality* and *authority centrality*. The main results concur with those of Inaoka et al. (2004), Soramaki et al. (2006), Craig and von Peter (2010) and Fricke and Lux (2012) for the Japanese, U.S., German and Italian interbank funds markets, respectively, further supporting their argument against traditional assumptions of homogeneity in interbank direct contagion models (á la Allen and Gale, 2000), whereas the similarities across different interbank funds markets' topology support what Fricke and Lux (2012; p.41) allege *might be classified as a new "stylized fact" of modern interbank networks*.

Our research work also contributes to the existing literature by means of providing new elements for examining and understanding the structure and dynamics of interbank funds networks, and –thus- for the implementation of monetary policy and for safeguarding financial stability. These new elements may be useful for analyzing one of the most interesting phenomena marking the Global Financial Crisis (GFC), namely the "freezing" of the interbank funds market (Gale and Yorulmazer, 2011), in which money market primary dealers did not fulfill their role as liquidity conduits. In particular, identifying key players in the interbank funds market is important because their behavior contributes to determine the most effective set of policy instruments to achieve an efficient interest rate transmission, whereas characterizing the actual topology of the interbank funds network is essential for policymakers because of the relation between its structure and its resilience and efficiency.

This paper is organized in five sections. The second presents the review of existing related literature. The third section introduces the methodological approach, and presents the dataset and its main topological features from the network analysis perspective. The fourth section presents the main results. The fifth suggests a rationale for financial institutions becoming super-spreaders in the Colombian interbank funds market. The last section presents final remarks.

2 Literature review

The recent GFC evidenced a significant reduction in the intermediation of funds in the interbank market in most industrialized economies. In the case of the U.S., the fragile liquidity conditions forced the Federal Reserve (Fed) into a rapid reduction of its policy rate, and to implement several unconventional measures to bring liquidity directly to the money market primary dealers (i.e. the group of financial institutions that help the Fed implement monetary policy) in order to assure the intermediation of funds among financial institutions. However, instead of serving as liquidity conduits, primary dealers avoided counterparty risk and hoarded, thus aggravating the adverse liquidity conditions.[5] Accordingly, the Fed had to implement additional measures to grant liquidity to other participants of the interbank funds market and to participants of other markets as well. A similar strategy was implemented by most central banks from industrialized economies, including the European Central Bank, Bank of England, Bank of Canada and Bank of Japan, among others.[6]

In the Colombian case the central bank (BR – Banco de la República) faced a similar stance back in 2002. By mid-2002 a regional market crisis triggered by political stress in Brazil led to the disruption of external credit lines and to a "sudden stop" that weakened the liquidity position of financial institutions, particularly that of brokerage firms (Vargas and Varela, 2008), which were confronted with credit institutions' reluctance to supply liquidity amidst volatile and uncertain market conditions; as was the case during the GFC, in 2002 Colombian credit institutions (i.e. banking firms) with access to central bank's liquidity feared counterparty risk and hoarded. Under these circumstances, the Board of Directors of the Central Bank decided to move up its standing purchases of local sovereign securities (i.e. TES – *Títulos de Tesorería*) on the secondary market and to authorize brokerage firms and trust companies to conduct temporary expansion operations with the central bank (BDBR, 2003). Thus, after August 2002 credit institutions, brokerage firms and trust companies in the Colombian financial market have been allowed to access central bank's temporary monetary expansion operations (e.g. open market operations).

[5] As in Gale and Yorulmazer (2011), avoiding counterparty risk and hoarding are unrelated. In the first case not supplying liquidity to other financial institutions follows concerns on the credit quality of its counterparties, whereas hoarding is due to concerns on its own access to liquidity in the future.

[6] Literature has assessed the efficiency of unconventional measures adopted by central banks during the GFC, as well as the main consequences for central banks and interbank funds markets (e.g. Christensen et al., 2009; Cecchetti and Disyatat, 2010; Bech and Monnet, 2013).

One of the main lessons from the GFC is that policy makers have to properly identify the role of the "big players" in the interbank funds markets. These financial institutions may be considered as liquidity "super-spreaders", or the driving forces behind the supply and demand for funds in the interbank market. However, not only super-spreaders may be regarded as those contributing to liquidity transmission the most, but also as those that may distort the distribution of central bank's liquidity the greatest, as was the case of primary dealers in the U.S. interbank funds market or of credit institutions in the Colombian money market in 2002. This dichotomy may be linked to the elusiveness of simultaneously attaining financial and monetary stability across inflation regimes (as in Borio (2014)), and underscores the intricacy of clearly differentiating super-spreaders' role for financial stability (drivers of contagion risk) and for monetary policy transmission (conduits of central bank money).

Several studies on the topology of interbank funds market networks had been conducted, mainly to identify their properties, such as Inaoka et al. (2004) for Japan (BoJ-NET); Bech and Atalay (2008) and Soramäki et al. (2006) for the U.S. (Fedwire); Boss et al. (2004) for Austria; van Lelyveld and in 't Veld (2012) and Pröpper et al. (2008) for The Netherlands; Craig and von Peter (2010) for Germany; Fricke and Lux (2012) for Italy; Cajueiro and Tabak (2007) and Tabak et al. (2013) for Brazil; and Martínez-Jaramillo et al. (2012) for Mexico. Some of these works also implement network metrics (e.g. centrality) for analytical purposes related to financial stability and contagion. Only Boss et al. (2004) includes the central bank as a participant in the interbank funds network, but does not address its particular role within it.

There are few studies worth mentioning in the Colombian case. Regarding the formation of the interbank interest rate, Cardozo et al. (2011) and Gonzalez et al. (2013) describe the functioning of the local money market and examine how the central bank's policy rate and liquidity facilities affect the interbank interest rate.

About the local interbank funds market structure and its relation to financial stability, Estrada and Morales (2008) use transaction data from the central bank's local sovereign securities trading platform (SEN – *Sistema Electrónico de Negociación*) in order to study the structure of the Colombian interbank funds market and the resulting contagion risk, whereas Capera-Romero et al. (2013) use a truncated database of observed interbank funds transactions to examine the local interbank credit relations (á la Cocco et al. 2009) and to study contagion risk. However, as Estrada and Morales (2008) proxy for the interbank funds market comes from anonymous trading of sovereign securities among a limited number of market makers in SEN[7], and Capera-Romero et al. (2013) limit the observed interbank funds transactions to those between credit institutions, results and analysis from both research works may be determined by their choice of datasets.

[7] León and Pérez (2013) conclude that the SEN local sovereign securities trading platform is a particular case of an homogeneous and non-hierarchical network artificially designed to create a "small club" of local sovereign securities' market makers, who trade anonymously, without counterparty risk limits among them, and with requirements to quote bid and ask prices, among other requisites. These features contradict the main characteristics of a typical interbank funds market (e.g. market discipline).

To the best of our knowledge, neither all observed interbank funds market transactions in the Colombian case have been considered for network analysis purposes, nor the central bank has been taken into account as a participant of the local interbank funds network. Likewise, the use of interbank funds networks to identify central bank's liquidity super-spreaders by network analysis metrics has not been documented in related –local or foreign- literature.

Our model implements standard network analysis' metrics on a single network resulting from merging the Colombian interbank funds market and the central bank's open market operations (i.e. repos) in order to identify the topology of the Colombian interbank funds network. Afterwards, we use *authority centrality* and *hub centrality* (Kleinberg, 1998) to identify interbank funds market's "super-spreaders". Under our analytical framework a financial institution may be considered a super-spreader for central bank's liquidity if it simultaneously excels at spreading liquidity to other participants (i.e. it is a good hub) and it excels at receiving liquidity from good hubs (i.e. it is a good authority), with the central bank being among the best hubs.

The closest research work is that of Craig and von Peter (2010), Fricke and Lux (2012) and van Lelyveld and in 't Veld (2012), who document the existence of core-periphery structures in the German, Italian and Dutch interbank funds markets, respectively. Such tiered hierarchical structure not only concurs with our results, but also verifies the importance of a limited number of financial institutions for the transmission of liquidity within the money market; in this sense, the so-called "top-tier" or "money center banks" of Craig and von Peter (2010) are analogous to our liquidity super-spreaders. However, because their main objective is different from ours, none of those research works include the direct liquidity provision by the central bank as an element worth considering, nor they implement network analysis metrics to pinpoint liquidity super-spreaders. Therefore, our work makes a first contribution to the identification of central bank liquidity super-spreaders in interbank funds markets by means of network analysis.

Identifying central bank's money super-spreaders is not only key for the implementation of monetary policy, but it also coincides with the "robust yet fragile" characterization of financial networks by Haldane (2009). This characterization poses major challenges from the financial stability perspective, including the revision of traditional interbank contagion models of Allen and Gale (2000) and of most interbank direct contagion models that followed (e.g. Cifuentes et al., 2005; Gai and Kapadia, 2010; Battiston et al., 2012).

Coincidences with recent literature on the inhomogeneous and core-periphery features of interbank funds networks support that these are "stylized facts" of interbank funds markets, as claimed by Fricke and Lux (2012). Moreover, an overlooked feature common to the US, Austrian, Dutch and Colombian interbank funds market is revealed: they are "ultra-small" networks in the sense of Cohen and Havlin (2003), which is consistent with the existence of a core that provides an efficient short-cut for most peripheral participants in the network, and points out that the structure of these interbank funds networks favors an efficient spread of liquidity, but also of contagion effects.

Lastly, our results provide evidence on self-organization and complex adaptive systems in financial markets, which concurs with the view of a self-organized economy (Krugman, 1996) and of the economy as a complex adaptive system (Holland, 1998). This further underscores the perils arising from reductionist assumptions commonly employed in the modeling of financial systems (i.e. homogeneity, symmetry, linearity, normality, static equilibrium).

3 Methodological approach

Two methodological steps are necessary for assessing financial institutions' central bank liquidity spreading capabilities in the local interbank funds market. First, the corresponding network merging interbank funds and monetary policy transactions has to be built from available data. Second, appropriate metrics for assessing the spreading capabilities of financial institutions have to be chosen. Both steps are introduced next.

3.1 The interbank funds and central bank's repo network

Data from the local large-value payment system (CUD – *Cuentas de Depósito*) was used to filter two types of transactions: interbank funds and central bank repos. In the Colombian case the interbank funds market is not limited to credit institutions, and it corresponds to funds *provided (acquired) by a financial institution to (from) other financial institution without any agreement to transfer investments or credit portfolios*[8]; this is, the interbank funds market consists of all non-collateralized borrowing/lending between all types of financial institutions.

The interbank funds market is the second contributor to the exchange of liquidity between financial institutions in the Colombian money market. As of 2013, the interbank funds market represents about 15.4% of financial institutions' exchange of liquidity as of 2013, below sell/buy backs or "*simultáneas*" (84.4%) on sovereign local securities (i.e. TES), but above repos between financial institutions (0.2%).[9] Despite the contribution of the sell/buy backs between financial institutions exceeds that of the interbank funds market, analyzing the former for monetary purposes may be inconvenient because its interest rate may be affected by the presence of securities-demanding financial institutions (instead cash-demanding), and by the absence of mobility restrictions for the collateral (Cardozo et al., 2011). Hence, as the interbank funds market is the focus of central bank's implementation of monetary policy (Allen et al., 2009), it is also the focus of our analysis.

Central bank's repos correspond to the liquidity granted by Banco de la República (BR) to financial institutions on behalf of monetary policy considerations by means of standard open market operations, in which the eligible collateral is mainly local sovereign securities (i.e.

[8] Chapter XIX, *Circular Básica Contable y Financiera* (*Circular Externa* 100, 1995), Financial Superintendence of Colombia. (http://www.superfinanciera.gov.co/Normativa/normas.htm)

[9] Based on provisional figures for year 2013. Only sell/buy backs and repos with sovereign local securities (i.e. TES) as collateral are considered. Sovereign local securities acting as collaterals for borrowing between financial institutions in the money market usually account for about 80% of the total; if repos with the central bank are included, sovereign local securities represent about 90% of all collateralized liquidity sources.

TES). Access to central bank repos is open to different types of financial institutions (i.e. banking and non-banking), but is limited to those that fulfill some financial and legal prerequisites.[10] For instance, as of December 2013, 87 financial institutions were eligible for taking part in central bank's repo auctions: 42 credit institutions (CIs), 20 investment funds (IFs), 18 brokerage firms (BKs), 4 pension funds (PFs) and 3 other financial institutions (Xs). As of 2013, the value of Colombian central bank's repo facilities was about 6 times that of interbank funds transactions.

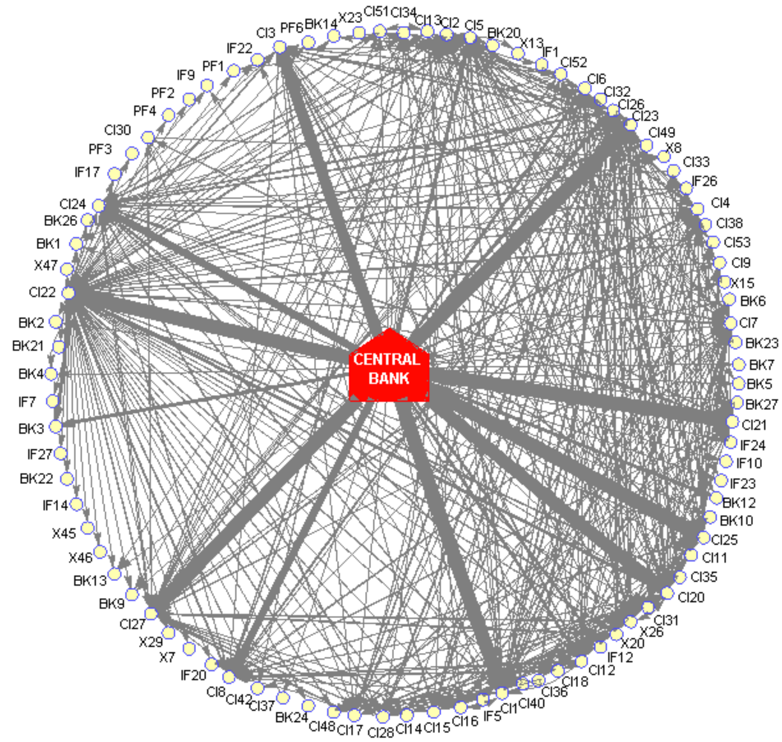
Merging the interbank funds market and the central bank's repos into a single network follows several reasons. First, by construction, the central bank is the most important participant of the interbank funds market, in which its intervention determines the efficient allocation of money among financial institutions, as underscored by Allen et al. (2009) and Freixas et al. (2011). Second, merging both networks allows for comprehensively assessing how central bank's liquidity spreads across financial institutions in the interbank funds market; therefore, as in Georg and Poschmann (2010; p.2), *a realistic model of interbank markets has to take the central bank into account*. Third, as the access to central bank's repos is open to all types of financial institutions, identifying which institutions effectively access the central bank's open market operations facilities may provide useful information designing liquidity facilities and implementing monetary policy.

Accordingly, based on CUD data from January 2 to December 17 2013, Figure 1 displays the graph resulting from merging the interbank funds market and the central bank's repo facilities.[11] As usual, the direction of the arrow corresponds to the direction of the funds transfer (i.e. towards the borrower), whereas its width represents its monetary value. Only the original transaction (i.e. from the lender to the borrower) is considered; transactions consisting of borrowers paying back for interbank or repo funds are omitted; intraday repos, pursuant the smooth functioning of the payment system –with no monetary aim- are not considered.

[10] Financial institutions fulfilling those prerequisites are known as ACOs (*Agentes Colocadores de OMA*).

[11] The database was extracted from the large-value payment system (CUD) by means of filtering the corresponding transaction codes; transaction codes are assigned by the central bank (i.e. the owner and operator of CUD), and financial institutions and financial infrastructures are obliged to use them to report their transactions.

Figure 1
The interbank funds and central bank's repo network*



(*) Credit institution (CI); brokerage firm (BK); investment fund (IF); pension fund (PF); other (X)
Source: authors' calculations.

Some salient features of Figure 1 are worth mentioning. First, the widest links correspond to funds from the central bank to some credit institutions (e.g. CI22, CI21, CI20, CI1, CI8, CI27, CI3, CI23), which corresponds to the role of the central bank as liquidity provider within 2013's expansionary monetary policy framework. Second, there is a noticeable concentration of interbank links in credit institutions receiving funds from the central bank. Third, most weakly connected institutions correspond to non-credit institutions.

Standard statistics for this network are presented in Table 1. Evidence advocates that the network under analysis is (i) sparse, with low density resulting from the number of observed links being much smaller than the potential number of links, and with an average degree (i.e. mean of links per institution) much smaller than the number of participants; (ii) "ultra-small" in the sense of Cohen and Havlin (2003), in which the average minimal number of links required to connect any two financial institutions (i.e. the mean geodesic distance) is particularly low (i.e. ~2) with respect to the number of participants; (iii) somewhat clustered, in which the probability of two counterparties of a financial institution being themselves counterparties is higher than expected in a random network (i.e. ~0); (iv) inhomogeneous, in which the dispersion, asymmetry, kurtosis and the order of the power-law exponent for the distribution of links and their monetary values suggest the presence of a few financial institutions that are heavily connected and large contributors to the system, whereas most institutions are weakly connected and minor contributors, with the distribution of degree and strength presumably approximating a scale-free distribution;[12] (v) *assortative mixing by degree*, which means that heavily (weakly) connected financial institutions tend to be connected with other heavily (weakly) connected, especially for the in-degree case.

Table 1
Standard statistics for the interbank funds and central bank's repo network

Statistic	Including the central bank	Excluding the central bank
Participants	92	91
Density	0.07 [a]	0.07
Mean geodesic distance	2.04	2.05
Clustering (non-weighted | weighted)	0.13 | 0.11	0.16 | 0.16
Degree	(In | Out)	(In | Out)
Mean	6.62 | 6.62	6.16 | 6.16
Standard deviation	8.35 | 10.68	8.17 | 10.00
Skewness	1.59 | 2.55	1.59 | 2.64
Kurtosis	4.78 | 11.33	4.81 | 13.11
Power-law exponent	1.60 | 3.50*	1.60 | 1.71
Assortativity index	0.54 | 0.06	0.57 | 0.15
Strength	(In | Out)	(In | Out)
Mean	1.09 | 1.09	1.10 | 1.10
Standard deviation	3.35 | 8.49	3.16 | 3.02
Skewness	5.37 | 9.37	6.40 | 4.29
Kurtosis	37.24 | 89.24	51.32 | 24.99
Power-law exponent	1.43 | 2.00[b]	3.14[b] | 1.41
Assortativity index	0.04 | -0.05	0.05 | -0.01

[a] The calculation of density is adjusted for the exclusion of financial institutions' payback for the repo. [b] Based on Clauset et al. (2009) goodness-of-fit tests there is a strong case for a power-law distribution with the estimated exponent.
Source: authors' calculations.

Altogether, these features concur with the scale-free and assortative mixing by degree connective structure of social networks reported by Newman (2010), and suggest the presence of a core-periphery structure within the network under analysis. Moreover, as the interbank funds network is "ultra-small" in the sense of Cohen and Havlin (2003), the process of liquidity spreading within the interbank funds network is highly efficient; nevertheless, it

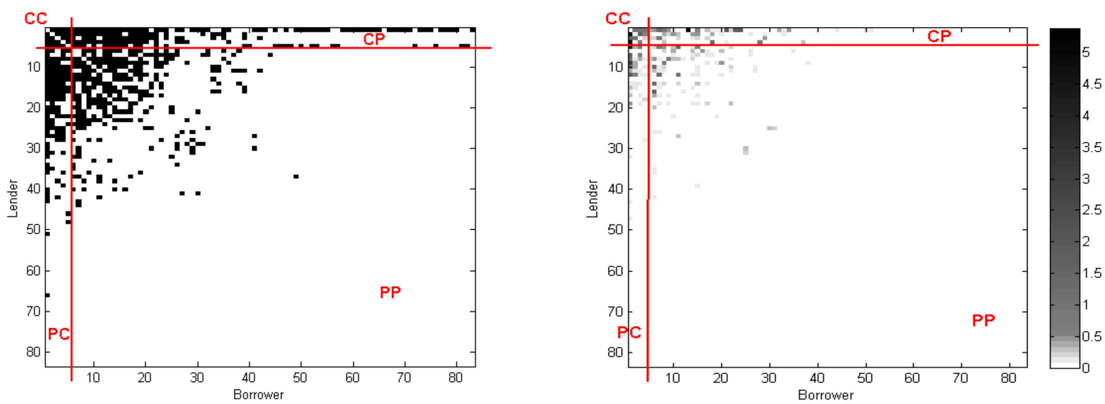
[12] The estimation of the power-law exponent was based on the maximum likelihood method proposed by Clauset et al. (2009); this method is preferred to the traditional ordinary least-squares due to documented issues regarding the latter (as in Clauset et al. (2009), Stumpf and Porter (2012)). Despite some of the estimated power-law exponents do not make a strong case based on the goodness-of-fit tests of Clauset et al. (2009), the level of the exponent provides enough evidence of the alleged inhomogeneity in the distribution of degree and strength.

means that contagion effects within the network are efficiently spread as well.[13] These main features are robust to the exclusion of the central bank.

A synthetic version of the *blockmodel* proposed by Craig and von Peter (2010) also suggests the presence of a core-periphery structure for the Colombian interbank funds market. A blockmodel is a theoretical reduction that decomposes the whole network block into different types of sub-blocks. The blockmodel of Craig and von Peter consists of four sub-blocks: (i) a core-core (CC) block, corresponding to top-tier institutions densely interconnected; (ii) a core-periphery block (CP), corresponding to connections from top-tier to low-tier institutions; (iii) a periphery-core block (PC), corresponding to connections from low-tier to top-tier institutions; and (iv) a periphery-periphery (PP) block, corresponding to low-tier interconnections. The synthetic blockmodel was fitted by ordering financial institutions by their degree (Figure 2, left panel) and by their strength (Figure 2, right panel); hence, high-degree and high-strength institutions are located in the upper-left corner of each blockmodel, respectively.[14]

Figure 2
Blockmodel of Colombian interbank funds market

By degree (presence or absence of a link) | By strength (contribution to total payments, in %)



Source: authors' design

[13] Cohen and Havlin (2003) point out that scale-free networks (i.e. approximating a power-law distribution by degree) have a very small average distance between participants, thus they are "ultra-small". Let n be the number of participants in the network, the mean geodesic distance for "ultra-small" networks approximate $\ln \ln n$, whereas for homogeneous networks it approximates $\ln n$.

[14] Other methods for fitting the blockmodel may be used. For instance, it is possible to force the blocks to obey some expected features of the blockmodel, such as CC consisting of a complete network and forcing CP and PC to be row-regular (i.e. each column should have at least one element different from zero) and column-regular (i.e. each row should have at least one element different from zero), respectively, as in Craig and von Peter (2010). However, ordering institutions according to their degree and strength is not only intuitive and easier to implement, but also allows to work with a weighted network (Figure 1, right panel); therefore the "synthetic" nature of our implementation of the –more complicated- blockmodel designed by Craig and von Peter (2010) or Fricke and Lux (2012).

As expected, either by degree or by strength, it is evident that there is a small group of financial institutions that tend to be densely interconnected in the core (CC block in the upper-left corner), and that appear to intermediate between peripheral financial institutions, whereas the block corresponding to inter-peripheral connections (or their monetary values) tend to be sparse. In the by-degree blockmodel (Figure 2, left panel) there are 5 financial institutions densely interconnected in the CC block (i.e. CI22, CI23, CI20, CI7, CI5), whereas in the by-strength block model (Figure 2, right panel) there are 4 (i.e. CI22, CI20, CI23, CI5).

A remarkable but overlooked coincidence between the blockmodel and the quantitative results in Table 1 is worth noting. A mean geodesic distance around 2 not only agrees with "ultra-small" networks (Cohen and Havlin, 2003), but also suggests that the bulk of financial institutions require about two links (i.e. circa one financial institution in-between) to connect to any other financial institution in the interbank funds network, meaning that the core provides an efficient short-cut for most peripheral participants in the network; again, the spreading capabilities of the network are particularly high. Interestingly, mean geodesic distances reported by Boss et al. (2004), Soramäki et al. (2006), Bech et al. (2008) and Pröpper et al. (2008) for the Austrian, US and Dutch interbank funds networks are about 2, consistent with "ultra-small" networks and with the role of a core providing an effective short-cut for the network; likewise, mean geodesic distances reported by León and Berndsen (2013) for the Colombian large-value payment system (CUD) and the main local sovereign securities settlement system (DCV – *Depósito Central de Valores*) is also about 2.

All in all, these findings concur with those of Craig and von Peter (2010) about the presence of interbank funds tiering and money center banks in the German banking system. Moreover, as also highlighted by Craig and von Peter (2010), these features verify that the connective structure of financial networks departs from traditional assumptions of homogeneity and representative agents (as in Allen and Gale (2000), Freixas et al. (2000), Cifuentes et al. (2005), Gai and Kapadia (2010)), and further supports the need to achieve the main goal of this paper: identifying which financial institutions are particularly relevant for the network.

3.2 Identifying super-spreaders in financial networks[15]

Whenever financial networks' observed connectedness structure is inhomogeneous the issue of the resiliency of the system arises. In those networks the extraction or failure of a participant will have significantly different outcomes depending on how the participant is selected. When randomly selected, the effect will be negligible, and the network may withstand the removal of several randomly selected participants without significant structural changes; however, if selected because of their high connectivity, the effect of extracting a small number of participants may significantly affect the network's structure. In this sense, a rising amount of financial literature is devoted to encouraging the usage of network metrics of importance (e.g. centrality) for identifying "super-spreaders" (Markose et al., 2012; Markose, 2012; Haldane and May, 2011; Haldane, 2009).

[15] This section is based on León and Berndsen (2013).

Most literature on financial super-spreaders seeks to identify those institutions that may lead contagion effects due to their network connectivity, *high-infection individuals* (Haldane, 2009), or those that *dominate in terms of network centrality and connectivity* (Markose et al., 2012). Despite the traditional negative connotation of super-spreaders in financial networks, in the present case the super-spreader financial institution is considered a good conduit for monetary policy as well.

There are many approaches for assessing the importance of individuals or institutions within a network. However, centrality is the most common concept, with many definitions and measures available. The simplest measures are related to local metrics of centrality such as degree (i.e. number of links) or strength (i.e. weighted links), but they fall short to take into account the global properties of the network; this is, the centrality of the counterparties is not taken into account as a source of centrality.

The simplest global measure of centrality is eigenvector centrality, whereby the centrality of a vertex is proportional to the sum of the centrality of its adjacent vertices; accordingly, the centrality of a vertex is the weighted sum of centrality at all possible order adjacencies. Hence, in this case centrality arises from (i) being connected to many vertices; (ii) being connected to central vertices; (iii) or both.[16] Alternatively, as put forward by Soramäki and Cook (2012), eigenvector centrality may be thought of as the proportion of time spent visiting each participant in an infinite random walk through the network.

Eigenvector centrality is based on the *spectral decomposition* of a matrix. Let Ω be an adjacency matrix (weighted or non-weighted), Λ a diagonal matrix containing the eigenvalues of Ω, and Γ an orthogonal matrix satisfying $\Gamma\Gamma' = \Gamma\Gamma = \mathrm{I}_n$, whose columns are eigenvectors of Ω, such that

$$\Omega = \Gamma\Lambda\Gamma' \qquad [\S1]$$

If the diagonal matrix of eigenvalues (Λ) is ordered so that $\lambda_1 \geq \lambda_2 \cdots \lambda_n$, the first column in Γ corresponds to the principal eigenvector of Ω. The principal eigenvector (Γ_1) may be considered as the leading vector of the system, the one that is able to explain the most of the underlying system, in which the positive n-scaled scores corresponding to each element may be considered as their weights within an index.

Because the largest eigenvalue and its corresponding eigenvector provide the highest accuracy (i.e. explanatory power) for reproducing the original matrix and capturing the main features of networks (Straffin, 1980), Bonacich (1972) envisaged $\Gamma_1$as a global measure of popularity or centrality within a social network.

However, eigenvector centrality has some drawbacks. As stated by Bonacich (1972), eigenvector centrality works for symmetric structures only (i.e. undirected graphs); however, it is possible to work with the right (or left) eigenvector (as in Markose et al., 2012), but this

[16] For instance, Markose et al. (2012) use eigenvector centrality to determine the most dominant financial institutions in the U.S. credit default swap market, and to design a super-spreader tax that mitigates potential socialized losses.

may entail some information loss. Yet, the most severe inconvenience from estimating eigenvector centrality on asymmetric matrices arises from vertices with only outgoing or incoming edges, which will always result in zero eigenvector centrality, and may cause some other non-strongly connected vertices to have zero eigenvector centrality as well (Newman, 2010). In the case of acyclic graphs, such as financial market infrastructures' networks (León and Pérez, 2014), this may turn eigenvector centrality useless; this is also our case because the central bank has no incoming links, and because some peripheral financial institutions are weakly connected.

Among some alternatives to surmount the drawbacks of eigenvector centrality (e.g. PageRank, Katz centrality), the HITS (Hypertext Induced Topic Search) algorithm by Kleinberg (1998) is convenient for several reasons. The HITS algorithm has two main advantages in our case: (i) it provides two separate centrality measures, *authority centrality* and *hub centrality*, which correspond to the eigenvector centrality as recipient and as originator of links, respectively, and (ii) it avoids introducing stochastic or arbitrary adjustments to the network (as in PageRank and Katz centrality) that may be undesirable from an analytical point of view.

The estimation of authority and hub centrality results from estimating standard eigenvector centrality [§1] on two modified versions of the adjacency matrix, $\mathcal{A}$ and $\mathcal{H}$, as in [§2].

$$\mathcal{A} = \Omega^T \Omega \qquad\qquad \mathcal{H} = \Omega\Omega^T \qquad\qquad [§2]$$

Multiplying the adjacency matrix with a transposed version of itself allows identifying directed (*in* or *out*) second order adjacencies. Regarding $\mathcal{A}$, multiplying Ω^T with Ω sends weights backwards –against the arrows, towards the pointing node-, whereas multiplying Ω with Ω^T (as in $\mathcal{H}$) sends scores forwards –with the arrows, towards the pointed-to node (Bjelland et al., 2008). Thus, the HITS algorithm works on a circular thesis: the authority centrality of each participant is defined to be proportional to the sum of the hub centrality of the participants that point to it, and the hub centrality of each participant is defined to be proportional to the sum of the authority centrality of the participant it points-to.

The circularity of the HITS algorithm is most convenient for identifying super-spreaders of central bank's liquidity. An institution may be considered a good conduit for central bank's liquidity if it simultaneously is a good hub (i.e. it excels at spreading liquidity within the interbank funds market) and a good authority (i.e. it excels at receiving liquidity from good hubs, with the central bank being among the best hubs). On the other hand, if an institution is a good authority but a meager hub it may be regarded as a poor conduit for central bank's liquidity; likewise, if an institution is a good hub but a modest authority its central bank's liquidity transmission capabilities may be regarded as low.

The eigenvector centrality framework behind the estimation of authority centrality and hub centrality allows both metrics to capture the impact of liquidity on a global scale. Accordingly, all financial institutions that are connected to the central bank and the most important hubs, either directly or indirectly, inherit some degree of authority centrality depending on the intensity of the links to those providers of liquidity. Likewise, all financial institutions that spread liquidity in the system inherit some degree of hub authority depending on the intensity of the links to all those receiving liquidity.

In this sense, an institution simultaneously displaying a high score in both authority and hub centrality is expected to be a dominant participant in the transmission of funds from the central bank to the interbank funds market and within the interbank funds market. Therefore, the liquidity spreading index of an i-financial institution (LSI_i) corresponds to the product of both normalized centrality measures, as in [§3].[17]

$$LSI_i = \frac{\left(\frac{\mathcal{A}_i}{\sum_{i=1}^{n}\mathcal{A}_i} \times \frac{\mathcal{H}_i}{\sum_{i=1}^{n}\mathcal{H}_i}\right)}{\sum_{i=1}^{n}\left(\frac{\mathcal{A}_i}{\sum_{i=1}^{n}\mathcal{A}_i} \times \frac{\mathcal{H}_i}{\sum_{i=1}^{n}\mathcal{H}_i}\right)} \qquad [\S3]$$

where

$$LSI = \sum_{i=1}^{n} LSI_i = 1$$

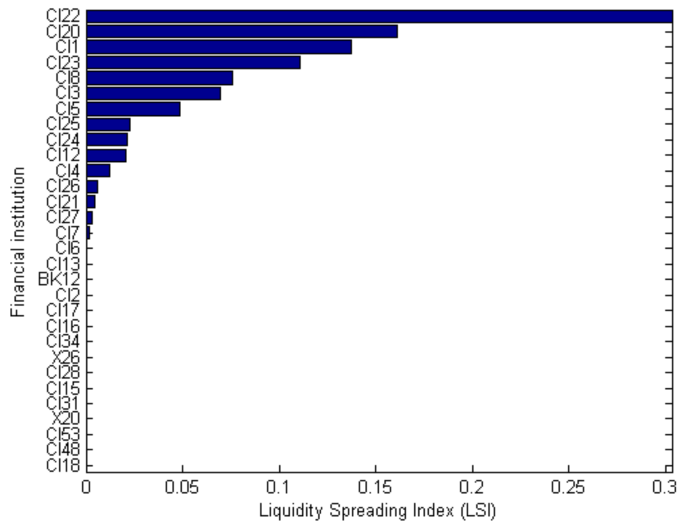
Since LSI_i is a measure of the contribution of an individual financial institution to the product of all financial institutions' hub and authority centrality, super-spreaders may be defined as those contributing the most to LSI.

4 Main results

Based on the methodological approach described in the previous section, the liquidity-spreading index (LSI_i) was estimated for the interbank funds and central bank's repo network comprising data from January 2 to December 17 2013. Figure 3 presents the top-30 financial institutions by their estimated LSI_i.

[17] The choice of the product operator is consistent with the aim of identifying institutions that simultaneously are a good hub and a good authority. Other conjunction mathematical operators may be chosen, such as $min(\cdot)$. Using the average of hub centrality and authority centrality is feasible, but may fail to discard institutions that are good authorities but mediocre hubs, or vice versa.

Figure 3
Top-30 financial institutions by estimated LSI_i*

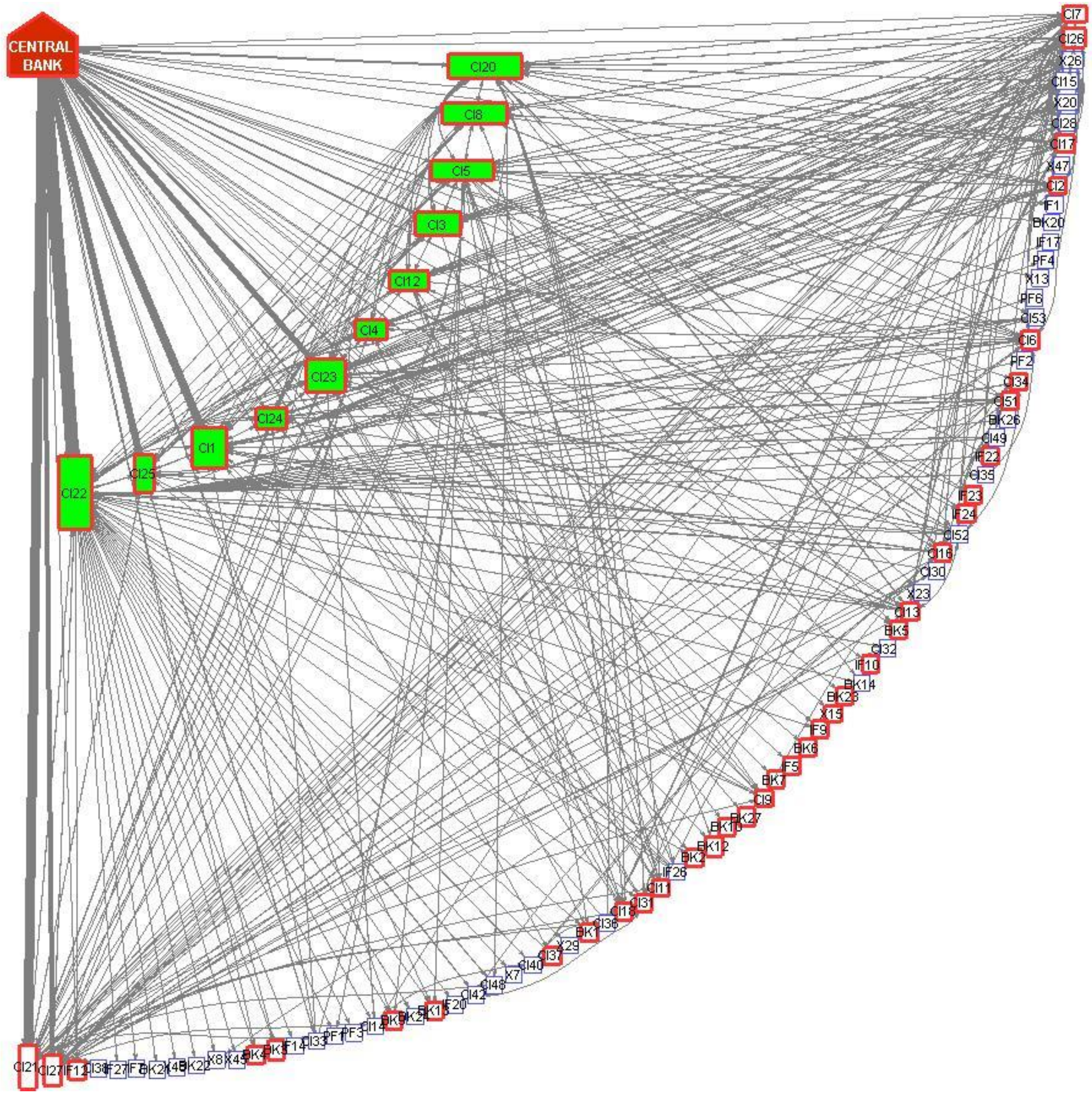


(*) Credit institution (CI); brokerage firm (BK); investment fund (IF); pension fund (PF); other (X)
Source: authors' calculations.

The first 17 are credit institutions (CIs), which together contribute with 99.98% of LSI. The concentration in the top-ranked financial institutions is clear, with the first (CI22) contributing with about 30% of the LSI, and the top-five (CI22, CI20, CI1, CI23, CI8) contributing with about 79%. Hence, results suggest that CIs provide the main conduit for central bank's liquidity within the Colombian financial system; as reported in the annex, CIs providing the main conduit for central bank's liquidity is robust to other samples (i.e. 2010, 2011, 2012).

Figure 4 (next page) displays a hierarchical visualization of how liquidity spreads from the central bank throughout the interbank funds market. The hierarchies introduced correspond to different levels of contribution to the LSI. Two levels were chosen for illustrative purposes: the first layer (green boxes) corresponds to those financial institutions in the 99th percentile of LSI_i, whereas the second layer corresponds to those whose contribution is less than 1% of the LSI. Additionally, the height of the boxes corresponds to the authority centrality, whereas their width to the hub centrality, with those financial institutions receiving liquidity directly from the central bank (i.e. via repos) appearing with a thicker (red) border; as usual, the width of the arrows correspond to the monetary value of the transactions, whereas their direction corresponds to the direction of the funds (i.e. towards the borrower).

Figure 4
The interbank funds and central bank's repo network*
(Hierarchical visualization by individual contribution to LSI)**

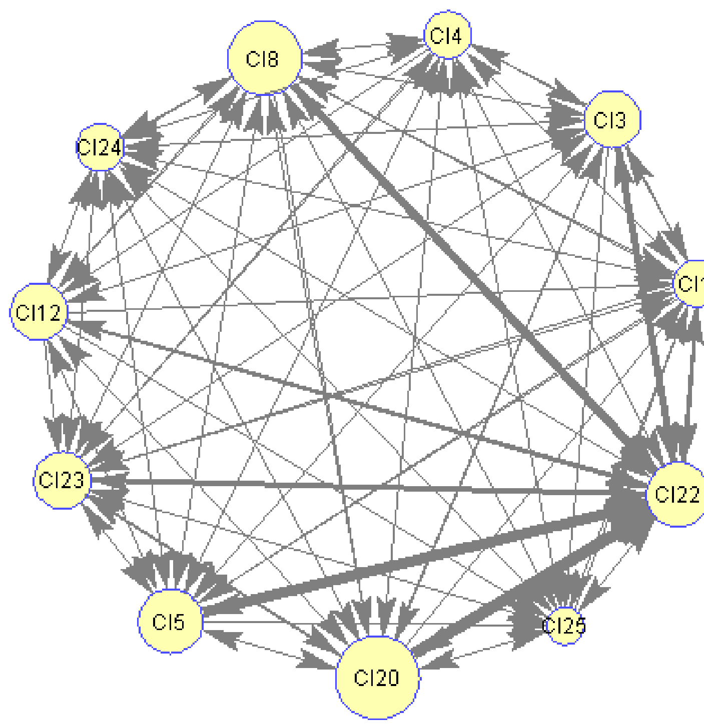


(*) Credit institution (CI); brokerage firm (BK); investment fund (IF); pension fund (PF); other (X).
(**) The height of the boxes corresponds to the authority centrality, width to the hub centrality; the first layer of institutions (in green) corresponds to the 95th percentile of the LSI_i; financial institutions receiving liquidity directly from the central bank are marked with a thicker (red) border; as usual, the width of the arrows corresponds to the monetary value of the transactions, whereas their direction corresponds to the direction of the funds (i.e. towards the borrower). Source: authors' design.

Visual inspection of Figure 4 yields some interesting remarks. Regarding the layers, it is unmistakable that the first one (green boxes) congregates the biggest (i.e. highest and widest) boxes, which signals their superior liquidity spreading capabilities within the network; in this sense, under the arbitrarily chosen percentiles, the first layer gathers what could be considered as central bank's liquidity super-spreaders: CI22, CI25, CI1, CI24, CI23, CI4, CI12, CI3, CI5, CI8, CI20. It is noticeable that the first layer congregates credit institutions (CIs) only, whereas the second displays a mixed composition. Also, financial institutions in the first layer tend to coincide with those that directly receive the most liquidity from the central bank (i.e. by the width of the arrows), and they all have direct linkages to the central bank (i.e. boxes with red borders).

Figure 5 displays the graph corresponding to the interbank funds transactions between the institutions in the first layer (i.e. the core) of Figure 4. The diameter of the circles corresponds to the value of each financial institution's lending within the network; as usual, the width of the arrows corresponds to the monetary value of the transactions, whereas their direction corresponds to the direction of the funds (i.e. towards the borrower).The sum of transactions within the core represents 52.07% of the whole interbank funds network.

Figure 5
The interbank funds core network*,**



(*) Credit institutions (CIs) here included correspond to those in the first layer of Figure 4
(**) The diameter of the circles corresponds to the value of the lending within the network; as usual, the width of the arrows corresponds to the monetary value of the transactions, whereas their direction corresponds to the direction of the funds (i.e. towards the borrower). Source: authors' design.

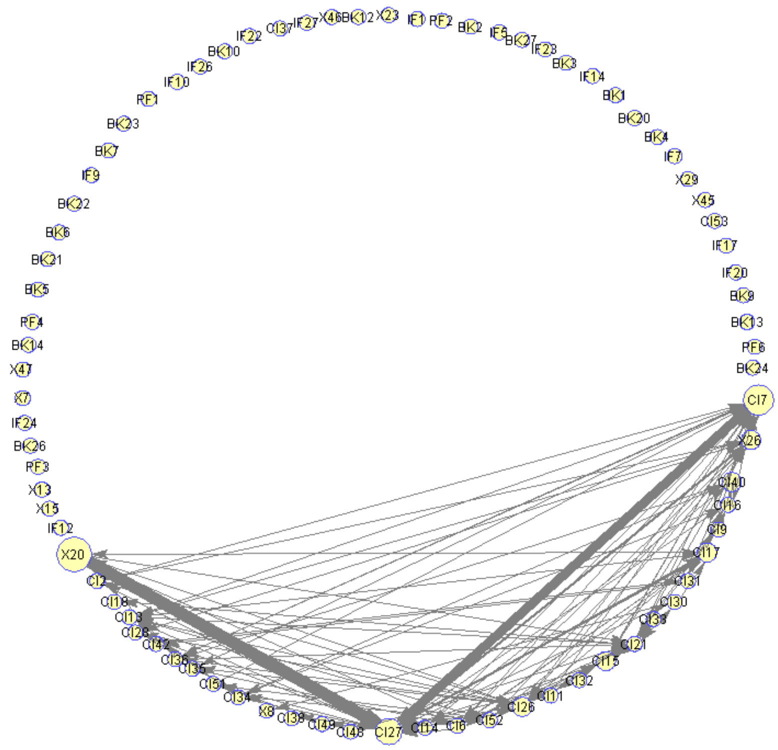
As expected, the core is a dense graph (i.e. 93.6% of the potential connections is observed), with a mean geodesic distance about 1.06, in which the degree is evenly distributed (i.e. mean degree 9.36; standard deviation about 1.00). Nevertheless, the strength displays inhomogeneity, with the diameter of each financial institution and the width of arrows varying in cross section; for instance, the total lending of CI20 is about 14.85 times that of CI25, whereas the total borrowing of CI22 is about 176.69 times that of CI12.

Regarding the periphery, it is evident that most financial institutions in Figure 4 display small boxes (i.e. low authority and hub centrality), whereas a few (most in the first layer) display big boxes; this not only concurs with previous evidence of inhomogeneity in the network under analysis, but also with literature on financial networks. It is also noticeable that many financial institutions in the second layer maintain very few connections with the rest of the network, most of them as borrowers, which suggests that during the period under analysis (i.e. almost a yearlong) they had a limited number of counterparties in the interbank funds market, either by choice or by market constraints; on the other hand, all financial institutions in the first layer appear to be heavily connected to the network, as borrowers and lenders, as expected from core financial institutions in a core-periphery structure.

Figure 6 displays the graph corresponding to the interbank funds transactions between the institutions in the second layer (i.e. the periphery) of Figure 4. The sum of transactions within the periphery represents 10.66% of the whole interbank funds network. As expected, the periphery is a sparse graph (i.e. 2.4% of the potential connections is observed), in which degree and strength are unevenly distributed; mean degree is about 1.9, with a standard deviation about 3.5, whereas mean strength is about 1.3% with a 4.0% standard deviation.[18] Most institutions (48) have no links with other peripheral institutions during the period under analysis (i.e. about one year), which means that their liquidity sources were restricted to borrowing from core financial institutions or the central bank. The residual, comprised by 32 institutions, are well-connected between them, and most of them (30) are credit institutions.

[18] As is customary to exclude non-reachable (i.e. unconnected) participants from the calculation of the mean geodesic distance, and because most of the financial institutions are non-reachable, the mean geodesic distance of the periphery may not be informative, thus it is not reported.

Figure 6
The interbank funds periphery network*,**



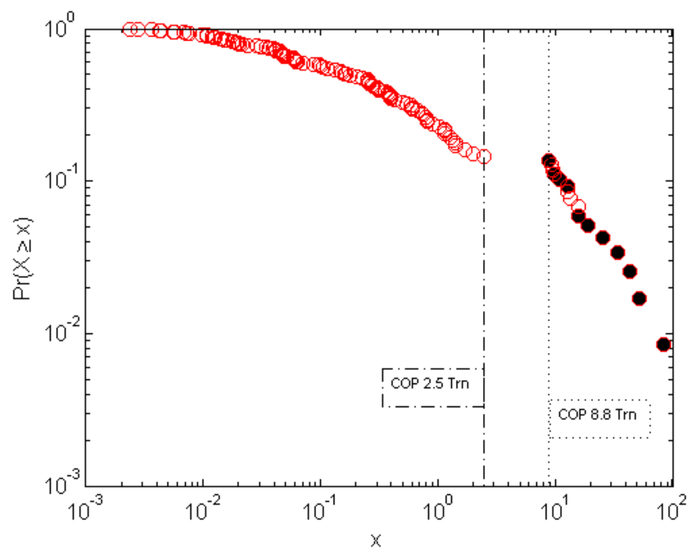
(*) Credit institution (CI); brokerage firm (BK); investment fund (IF); pension fund (PF); other (X). Financial institutions here included correspond to those in the second layer of Figure 4.
(**) The diameter of the circles corresponds to the value of the lending within the network; as usual, the width of the arrows corresponds to the monetary value of the transactions, whereas their direction corresponds to the direction of the funds (i.e. towards the borrower). Source: authors' design.

5 What makes a super-spreader in the Colombian interbank funds market?

The size of institutions in financial markets is known to be inhomogeneous, with a few that may be regarded as "too-large" and many "too-small", presumably approximating a power-law distribution (Gabaix et al., 2003; Fiaschi et al., 2013), even for the Colombian case (León, 2014). By means of an econometric model Craig and von Peter (2010) verify that there is a significant relation between financial institutions' size and their position in the interbank funds' hierarchy, in which large banks tend to be in the core, whereas small banks are found in the periphery. Such verification is consistent with Cocco et al. (2009), who report that bank size is an important determinant of interbank lending relationships, with smaller banks being less likely to act as intermediaries.

Regarding the Colombian case the relation between size and the role as super-spreader in the interbank funds market is evident. Figure 7 exhibits the double logarithmic scale plot for Colombian financial institutions' assets value, in which the horizontal axis corresponds to the logarithm of assets value, the vertical axis to the logarithm of the cumulative frequency for each asset value, and each circle represents a single local financial institution. As also reported by Fiaschi et al. (2013) for the U.S. financial market, such double logarithmic plot exhibits an interesting feature: it is an “interrupted” plot (León, 2014). Such interruption, which yields two different size regimes with two different distributional forms, verifies that in the Colombian financial market there are large (i.e. above COP 8.8 Trillion) and small (i.e. below COP 2.5 Trillion) financial institutions, and that they may be pinpointed rather objectively.

Figure 7
Distribution of Colombian financial institutions’ size*
(Double logarithmic scale)



(*) Size corresponds to the 2013 average asset value reported by the Colombian Financial Superintendence; filled circles correspond to super-spreaders in Figure 4.
Source: authors’ calculations, based on León (2014)

Filling (in black) the circles corresponding to the super-spreaders in Figure 4 (i.e. financial institutions in the 95th percentile of LSI_i) yields an obvious observation: in the Colombian interbank funds market all super-spreaders pertain to the largest financial institutions. The average size of super-spreaders is about 33 times that of other financial institutions; this agrees with evidence reported by Craig and von Peter (2010) for the German interbank funds market (i.e. about 51 times). Therefore, two distinctive features may determine super-spreading capabilities of financial institutions in the Colombian interbank funds market, namely being a credit institution and being large.

Together, the numerical evidence of the interbank funds network being approximately a scale-free network in the sense of Barabási and Albert (1999) and the distinctive firm-specific features of super-spreaders (i.e. large credit institutions), suggest that there is a dynamical process of *preferential attachment*. This means that financial institutions in the local interbank funds market do not connect to each other randomly, but they are adaptive and select their counterparties based on some metric of *fitness*, with this fitness coming in the form of large credit institutions. Large credit institutions may be considered particularly fit in the local financial market due to several features: (i) privileged access to last-resort lending from the central bank; (ii) seniority; (iii) liquidity; (iv) economies of scale; (v) market power; (vi) pertaining to a financial conglomerate or corporate group; (vii) long-term stable relationships; and (viii) market's assessment of systemic importance, among others.[19] Such selective process by financial institutions yields an inhomogeneous network that may be the result of a *fit-get-fitter* phenomenon, in which there is an adaptive evolutionary process that favors the existence of a few super-spreaders or core financial institutions.

Accordingly, based on the scale-free approximate features of the interbank funds network and the preliminary evidence of a fitness-driven preferential attachment process, it is feasible to conclude that the local interbank funds market is a *self-organized* system in the sense of Krugman (1996), Bak (1996), Barabási and Albert (1999) or Strogatz (2003), as also suggested by Leon and Berndsen (2013) for other Colombian financial networks. If this is the case, the Colombian interbank funds system may be characterized as a *complex adaptive system* (Holland, 1998; Anderson, 1999), and traditional reductionist approaches to its modeling (i.e. homogeneity, symmetry, linearity, normality, static equilibrium) are invalid and potentially misleading.

6 Final remarks

In this paper we find that the Colombian interbank funds market displays an inhomogeneous and hierarchical (core-periphery) connective structure, in which a few financial institutions fulfill the role of "super-spreaders" of central bank money within the interbank funds market. Thus, our research work not only contributes to central banks' efforts to analyze the structure and functioning of interbank funds markets, but also contributes to designing liquidity facilities and implementing monetary policy.

Five particular contributions of our research work are worth stating. First, we propose a methodological approach that explores the connective structure of the interbank funds network and identifies those financial institutions that may be considered as the most important conduits for monetary policy transmission.

Second, our results support recent findings about the existence of some "stylized facts" in financial networks, namely an inhomogeneous and hierarchical connective structure that contradicts traditional assumptions in interbank contagion models (i.e. homogeneity, symmetry, linearity, normality, static equilibrium). Thus, our findings provide new elements for understanding the structure and dynamics of financial networks.

Third, as is the case of interbank funds networks in the U.S., The Netherlands and Austria, and consistent with the existence of a core-periphery hierarchy, the Colombian interbank funds network is "ultra-small", with an average geodesic distance around 2. This means that the core

[19] The access to deposit accounts in the central bank –a typical privilege of credit institutions- is excluded from our preliminary list of fitness sources. In Colombia such access is open to all types of financial institutions.

provides an efficient short-cut for most peripheral participants in the network, in which most financial institutions connect to each other through only one intermediate financial institution, presumably a super-spreader or a top-tier participant. This also means that the spreading capabilities of interbank funds network are particularly high, either for liquidity or for contagion effects.

Fourth, the Colombian interbank funds network topology coincides with the "robust yet fragile" characterization by Haldane (2009). This characterization entails major challenges for financial authorities contributing to financial stability. For instance, as argued after the crisis (e.g. Kambhu et al. (2007); May et al. (2008); Haldane and May (2011); León and Berndsen (2013)), the most evident challenge comes in the form of focusing financial authorities' preventive actions on super-spreaders, which requires shifting from institution-calibrated to system-calibrated prudential regulation.

Fifth, our results provide further evidence about financial networks' self-organization emerging from complex adaptive financial systems. Financial institutions do not connect to each other randomly in the interbank funds market, but they are adaptive and select their counterparties based on some metric of fitness, with such fitness presumably resulting from being large credit institutions. This may suggest that there is a dynamical process of preferential attachment in which relevant firm-specific characteristics and market conditions (e.g. privileged access to last-resort lending from the central bank, market power, conglomerates, and systemic importance) may explain the self-organization of financial markets under the inhomogeneous and hierarchical connective structure here documented. However, this analysis is preliminary, and some robust tests could provide support to this intuitive rationale.

Further related research work may come in several forms. First, it is imperative to test the robustness of results under stringent financial liquidity conditions; we attempted such test, but available data does not cover periods that could be fair examples of such conditions (e.g. 2002). Second, despite monetary policy transmission has been assumed to correspond to an expansionary stance, it may be useful to test the robustness of results under contractionary stances; again, lack of available data impeded such test. Third, due to the sparseness and inhomogeneity of the periphery, further research on how the bulk of financial institutions face regular and extraordinary liquidity strains is advisable; research results may provide useful information for designing liquidity facilities for monetary and financial stability purposes. Fourth, as results confirm that the interbank funds market is tiered despite the non-tiered (i.e. open) access to money market borrowing, central bank's accounts and temporary monetary expansion operations, the preferential attachment process beneath the core-periphery (i.e. tiered) structure should be examined. Fifth, due to the importance of sell/buy backs (*simultáneas*) in the local money market, it is advisable to implement a similar exercise on the corresponding dataset for comparative purposes. Sixth, it is advisable to consider intraday funding between financial institutions as a source of liquidity as well.

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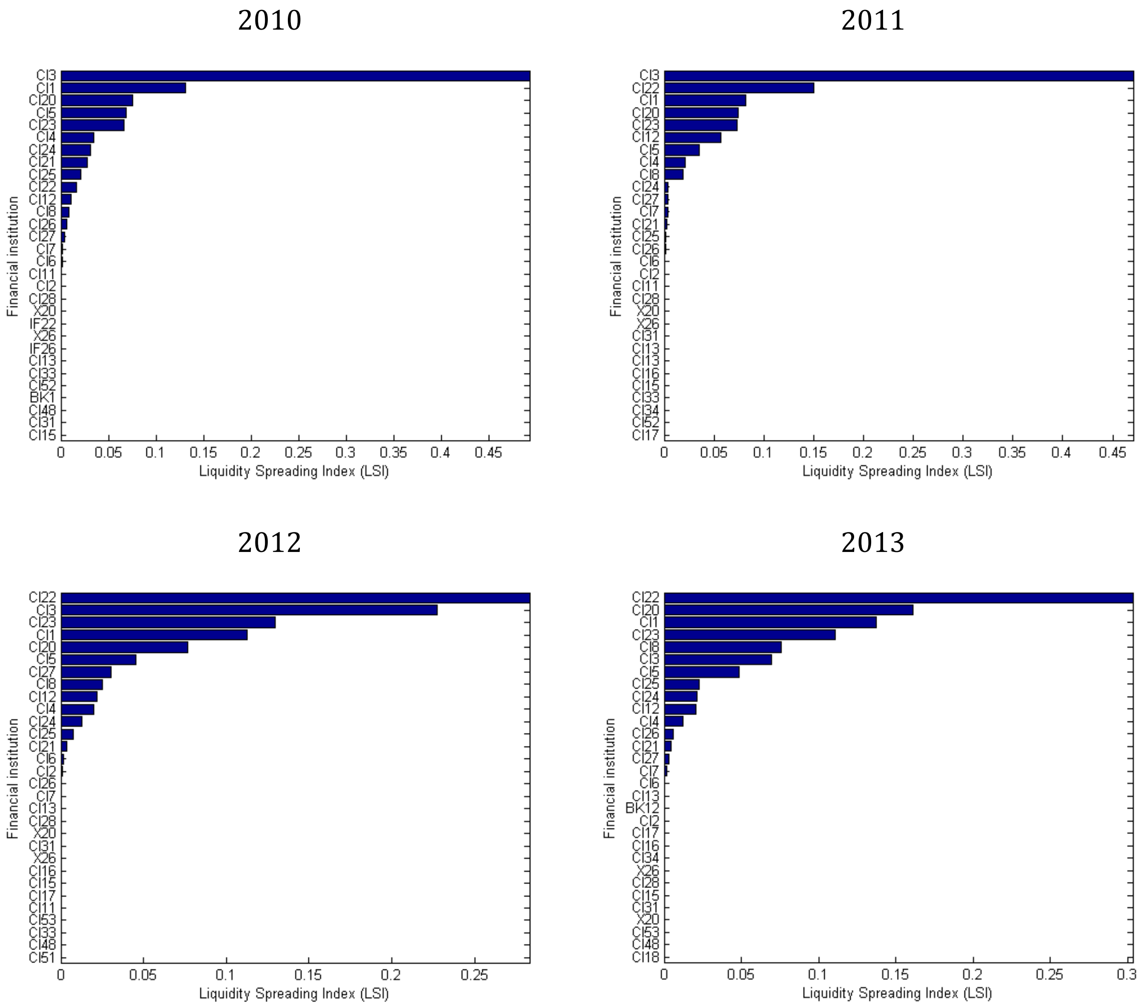
8 Annex

Top-30 financial institutions by estimated LSI_i*
(2010, 2011, 2012, 2013)



(*) Credit institution (CI); brokerage firm (BK); investment fund (IF); pension fund (PF); other (X)
Source: authors' calculations.