Exploiting social networks dynamics for P2P resource organisation

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Abstract. In this paper we present a formal description of PROSA, a P2P resource management system heavily inspired by social networks. Social networks have been deeply studied in the last two decades in order to understand how communities of people arise and grow. It is a widely known result that networks of social relationships usually evolve to small-worlds, i.e. networks where nodes are strongly connected to neighbours and separated from all other nodes by a small amount of hops. This work shows that algorithms implemented into PROSA allow to obtain an efficient small-world P2P network.

1 Introduction

A Peer-to-Peer system consists of computing elements that are connected by a network, addressable in a unique way, and sharing a common communication protocol. All computing elements, equivalently called nodes or peers, have the same functionalities and role. In P2P networks there is no difference between "client" and "server" hosts: a peer acts as a "client" if it requests a resource from the network, while it acts as a "server" if it is requested a resource it is sharing. From this point of view, P2P networks differ a lot from World Wide Web, TCP/IP networks and, in general, from client-server networks.

Studies on P2P networks are focused on two different topics: physical P2P networks (i.e., P2P networks opposed to hierarchic and centralised TCP/IP networks) and overlay networks (i.e. networks of logical links between hosts over an existing physical network of any type). Our interest is mainly focused on overlay P2P systems: they are probably going to become the most used kind of application-level protocols for resource sharing and organisation.

In this paper we present a novel P2P overlay network, named PROSA, heavily inspired by social networks. Social networks are sets of people or groups interconnected by means of acquaintance, interaction, friendship or collaboration links. Many kinds of natural social networks have been deeply studied in the last thirty years [2], and many interesting characteristics of such networks have been discovered. In a real social network relationships among people are of the most importance to guarantee...
efficient collaboration, resources discovery and fast retrieval of remote people. Nevertheless, not all relationships in a social network are of the same importance; usually links to parents and relatives are stronger than links to friends, which are in turn stronger than links to colleagues and classmates. On the other hand, it is also interesting to note that usually links in a social group evolve in different ways. A large amount of relationships are (and remain) bare “acquaintances”; some of them evolve around time into “friendships”, while “relativeness” is typical of very strong links to really trusted people.

This suggests that a P2P network based on a social model should take into account that different kind of links among peers can exist, and that links can evolve from simple acquaintances to friendship.

Results of studies performed by Watts, Strogatz, Newman, Barabasi et al. in the last decades[7] [4] [6] [8] [1] reveal that networks of movie characters, scientific collaborations, food chains, proteins dependence, computers, web pages and many other natural networks usually exhibit emerging properties, such that of being small-worlds. A small-world is a network where distance among nodes grows as a logarithmic function of the network size and similar nodes are strongly connected in clusters. PROSA tries to build a P2P network based on social relationships, in the hope that such network could naturally evolve to a small-world.

In section 2, we describe PROSA and algorithms involved in linking peers and routing queries for resources; in section 3, we report some results about topological properties of PROSA network, obtained by simulation; in section 4, we summarise obtained results and plan future work.

2 PROSA : A brief introduction

As stated above, PROSA is a P2P network based on social relationships. More formally, we can model PROSA as a directed graph:

\[
\text{PROSA} = (P, L, P_k, \text{Label})
\]

\(P\) denotes the set of peers (i.e. vertices), \(L\) is the set of links \(l = (s, t)\) (i.e. edges), where \(t\) is a neighbour of \(s\). For link \(l = (s, t)\), \(s\) is the source peer and \(t\) is the target peer. All links are directed.

In P2P networks the knowledge of a peer is represented by the resources it shares with other peers. In PROSA the mapping \(P_k : P \rightarrow C\), associates peers with resources. For a given peer \(s \in P\), \(P_k(s)\) is a compact description of the peer knowledge (PK - Peer Knowledge).

Relationships among people are usually based on similarities in interests, culture, hobbies, knowledge and so on. Usually these kind of links evolve from simple “acquaintance–links” to what we called “semantic–links”. To implement this behaviour three types of links have been introduced: Acquaintance–Link (AL), Temporary Semantic–Link (TSL) and Full Semantic–Link (FSL). TSLs represent relationships based on a partial knowledge of a peer. They are usually stronger than ALs and weaker than FSLs.
In PROSA, if a given link is a simple AL, it means that the source peer does not know anything about the target peer. If the link is a FSL, the source peer is aware of the kind of knowledge owned by the target peer (i.e., it knows the $P_k(t) <$, where $t \in \mathcal{P}$ is the target peer). Finally, if the link is a TSL, the peer does not know the full $P_k(t)$ of the linked peer; it instead has a Temporary Peer Knowledge ($TP_k$) which is built based on previously received queries from the source peer. Different meanings of links are modelled by means of a labelling function $Label$: for a given link $l = (s, t) \in L$, $Label(l)$ is a vector of two elements $[e, w]$: the former is the link label and the latter is a weight used to model what the source peer knows of the target peer; this is computed as follow:

- if $e = AL \Rightarrow w = \emptyset$
- if $e = TSL \Rightarrow w = TP_k$
- if $e = FSL \Rightarrow w = P_k(t)$

In the next two sections, we give a brief description of how PROSA works. A detailed description of PROSA can be found in [3].

2.1 Peer Joining to PROSA

The case of a node that wants to join an existing network is similar to the birth of a child. At the beginning of his life a child “knows” just a couple of people (his parents). A new peer which wants to join, just looks for $n$ peers at random and establishes ALs to them. These links are ALs because a new peer doesn’t know anything about its neighbours until he doesn’t ask them for resources. This behaviour is quite easy to understand: when a baby comes to live he doesn’t know anything about his parents. The PROSA peer joining procedure is represented in algorithm 1.

| Algorithm 1 JOIN: Peer s joining to PROSA ($\mathcal{P}, \mathcal{L}, P_k, Label$) |
|---|
| **Require:** PROSA ($\mathcal{P}, \mathcal{L}, P_k, Label$), Peer s |
| 1: $RP \leftarrow \text{rnd}(\mathcal{P}, n)$ \{Randomly selects $n$ peers of PROSA\} |
| 2: $\mathcal{P} \leftarrow \mathcal{P} \cup s$ \{Adds s to set of peers\} |
| 3: $\mathcal{L} \leftarrow \mathcal{L} \cup \{(s, t), \forall t \in RP\}$ \{Links s with the randomly selected peers\} |
| 4: $\forall t \in RP \Rightarrow Label(p, q) \leftarrow [AL, \emptyset]$ \{Sets the previously added links as AL\} |

2.2 PROSA dynamics

In order to show how PROSA works, we need to define the structure of a query message. Each query message is a quadruple:

$$Q_M = (qid, q, s, n_r) \quad (2)$$

where $qid$ is a unique query identifier to ensure that a peer does not respond to a query more than once; $q$ is the query, expressed according
to the used knowledge model; $s \in P$ is the source peer and $n_r$ is the number of required results. \textit{PROSA} dynamic behaviour is modelled by Algorithm 2 and is strictly related to queries. When a user ($U$) of \textit{PROSA} asks for a resource on a peer $s$, the inquired peer $s$ builds up a query $q$ and specify a certain number of results he wants to obtain $n_r$. This is equivalent to call $ExecQuery(\textit{PROSA}, s, \emptyset, n_r)$.

Algorithm 2 $ExecQuery$: query $q$ originating from peer $s$ executed on peer $cur$

\begin{algorithm}
\caption{$ExecQuery$}
\begin{algorithmic}[1]
\Require $\textit{PROSA} (P, \mathcal{L}, P_k, \text{Label})$
\Require $cur, prev \in P$, $qm \in \text{QueryMessage}$
\State $\text{Result} \leftarrow \emptyset$
\If{$prev \neq \emptyset$} 
\State $UpdateLink(\textit{PROSA}, cur, prev, q)$
\EndIf
\State $(\text{Result}, \text{numRes}) \leftarrow \text{ResourcesRelevance}(\textit{PROSA}, q, cur, n_r)$
\If{$\text{numRes} = 0$} 
\State $f \rightarrow SelectForwarder(\textit{PROSA}, cur, q)$
\If{$f \neq \emptyset$} 
\State $ExecQuery(\textit{PROSA}, f, cur, qm)$
\EndIf
\Else 
\State $\text{SendMessage}(s, cur, \text{Result})$
\State $\mathcal{L} \leftarrow \mathcal{L} \cup (s, cur)$
\State $\text{Label}(s, cur) \leftarrow [\text{FSL}, P_k(cur)]$
\If{$\text{numRes} < n_r$} 
\State \{ Semantic Flooding \}
\ForAll{$t \in \text{Neighborhood}(cur)$} 
\State $rel \rightarrow PeerRelevance(P_k(t), q)$
\If{$rel > \text{Threshold}$} 
\State $qm \leftarrow (qid, q, s, n_r - \text{numRes})$
\State $ExecQuery(\textit{PROSA}, t, cur, qm)$
\EndIf
\EndFor
\EndIf
\EndIf
\end{algorithmic}
\end{algorithm}

The first time $ExecQuery$ is called, $prev$ is equal to $\emptyset$ and this avoids the execution of instruction number 3. Following calls of $ExecQuery$, i.e. when a peer receives a query forwarded by another peer, use function $UpdateLink$, which updates the link between current peer $cur$ and the forwarding peer $prev$, if necessary. If the requesting peer is an unknown peer, a new TSL link to that peer is added having as weight a Temporary Peer Knowledge($TP_k$) based on the received query message. Note that a $TP_k$ can be considered as a “good hint” for the current peer, in order

\footnote{1 If knowledge is modelled by Vector Space Model, for example, $q$ is a state vector of stemmed terms. If knowledge is modelled by ontologies, $q$ is an ontological query, and so on}
to gain links to other remote peers. It is really probable that the query would be finally answered by some other peer and that the requesting peer will download all resources that matched it. It would be useful to record a link to that peer, just in case that kind of resources would be requested in the future by other peers. If the requesting peer is a TSL for the peer that receives the query, the corresponding TPV (Temporary Peer Vector) in the list is updated. If the requesting peer is a FSL, no updates are performed.

The relevance of a query with respect to the resources hosted by the user’s peer is evaluated calling function ResourcesRelevance. Two possible cases can hold:

- If none of the hosted resources has a sufficient relevance, the query has to be forwarded to another peer \( f \), called “forwarder”. This peer is selected among \( s \) neighbours by the function SelectForwarder, using the following procedure:
  - Peer \( s \) computes the relevance between query \( q \) and the weight of each links connecting itself to his neighbourhood.
  - It selects the link with the highest relevance, if any, and forward the query message to it.
  - If the peer has neither FSLs nor TSLs, i.e. it has just ALs, the query message is forwarded to one link at random.

This procedure is described in Algorithm 2, where the subsequent forwards are performed by means of recursive calls to ExecQuery.

- If the peer hosts resources with sufficient relevance with respect to \( q \), two sub-cases are possible:
  - The peer has sufficient relevant documents to full-fill the request. In this case a result message is sent to the requesting peer and the query is no more forwarded.
  - The peer has a certain number of relevant documents, but they are not enough to full-fill the request (i.e. they are \(< n_r\) ). In this case a response message is sent to the requester peer, specifying the number of matching documents. The message query is forwarded to all the links in the neighbourhood whose relevance with the query is higher than a given threshold (semantic flooding). The number of matched resources is subtracted from the number of total requested documents before each forward step.

When the requesting peer receives a response message it presents the results to the user. If the user decides to download a certain resource from another peer, the requesting peer contacts the peer owning that resource asking for download. If download is accepted, the resource is sent to the requesting peer.

### 3 Topological properties

Algorithms described in section 2 are inspired by the way social relationships among people evolve, in the hope that a network based on those simple rules could naturally become a small-world. That of being a small-world is one of the most desirable properties of a P2P network, since resource retrieval in small-worlds is really efficient. This is mainly
due to the fact that small-world networks have a short Average Path Length (APL) and a high Clustering Coefficient (CC). APL is defined as the average number of hops required to reach any other node in the network: if APL is small, all nodes of the network can be easily reached in a few steps starting from whichever other node.

CC can be defined in several ways, depending on the kind of “clustering” you are referring to. We used the definition given in [7], where the clustering coefficient of a node is defined as:

$$CC_n = \frac{E_{n, real}}{E_{n, tot}}$$

where $n$’s neighbours are all the peers to which $n$ is linked to, $E_{n, real}$ is the number of edges between $n$’s neighbours and $E_{n, tot}$ is the maximum number of possible edges between $n$’s neighbours. Note that if $k$ is in the neighbourhood of $n$, the vice-versa is not guaranteed, due to the fact that links are directed. The clustering coefficient of the whole network is defined as:

$$CC = \frac{1}{|V|} \sum_{n \in V} CC_n$$

i.e. the average clustering coefficient over all nodes.

The CC is an estimate of how strongly nodes are connected to each other and to their neighbourhood. In particular, the definition given in Equation 3 measures the percentage of links among a node neighbours with respect to the total possible number of links among them. In the following two subsections we show that PROSA has both a small APL and a considerable high CC.

### 3.1 Average path length

Since we are focusing on topological properties of a PROSA network to show that it is a small-world (i.e. that queries in PROSA are answered in a small amount of steps), we estimate the APL as the average length of the path traversed by a query. It is interesting to compare the APL of PROSA with the APL of a correspondent random graph, since random graphs usually have a really small average path length.

Given a graph $G(V,E)$ with $|V|$ vertices (nodes) and $|E|$ edges (links) among nodes, the correspondent random graph is a graph $G_{rand}$ which has the same number of vertices (nodes) and the same number of edges (links) of $G$, and where each link between two nodes exist with a probability $p$. Note that the APL of a random graph can be calculated using equation (5), as reported in [5], where $|V|$ is the number of vertices (nodes) and $|E|$ is the number of edges (links).

$$APL = \frac{\log |V|}{\log (|V|/|E|)}$$

Figure 1 shows the APL for PROSA and the correspondent random graph for different number of nodes in the case of 15 performed queries per node. The APL for PROSA is about 3.0, for all network sizes, while
the APL for the correspondent random graph is between 1.75 and 2.0: the average distance among peers in PROSA seems to be independent from the size of the network. This is quite common in real small-world networks.

![Fig. 1. APL for PROSA and random network](image1)

It is also interesting to analyse how APL changes when the total number of performed queries increases. Results are reported in Figure 2, where the APL is calculated for windows of 300 queries, with an overlap of 50 queries. Note that the APL for PROSA decreases with the number of performed queries. This behaviour heavily depends on the facts that new links among nodes arise whenever a new query is performed (TSLs) or successfully answered (FSLs). The higher the number of performed queries, the higher the probability that a link between two nodes does exist.

![Fig. 2. Running averages of APL for PROSA with different network size](image2)
3.2 Clustering Coefficient

The clustering (or transitivity) of a network is a measure of how strongly nodes are connected to their neighbourhood. Since links among nodes in PROSA are established as a consequence of query forwarding and answering, we suppose that peers with similar knowledge will be eventually linked together. This means that usually peers have a neighbourhood of similar peers, and having strong connections with neighbours could really speed-up resource retrieval.

In Figure 3 the CC of PROSA for different number of performed queries is reported, for a network of 200 nodes. Note that the clustering coefficient of the network increases when more queries are performed. This means that nodes in PROSA usually forward queries to a small number of other peers so that their aggregation level naturally gets stronger when more queries are issued.

![Fig. 3. PROSA CC for PROSA](image)

It could be interesting to compare PROSA clustering coefficient with that of a corresponding random graph. The clustering coefficient of a random graph with $|V|$ vertices (nodes) and $|E|$ edges (links) can be computed using equation 6.

$$CC_{rnd} = \frac{|E|}{|V| \cdot (|V| - 1)}$$ (6)

Figure 4 shows the CC for PROSA and a correspondent random graph for different network sizes, in the case of 15 performed queries per node. The CC for PROSA is from 2.5 to 6 times higher that that of a correspondent random graph, in accordance with CC observed in real small-world networks. This result is quite simple to explain, since nodes in PROSA are linked principally to similar peers, i.e. to peers that share the same kind of resources, while being linked to other peers at random. Due to the linking strategy used in PROSA, it is really probable that neighbours of a peer are also linked together, and this increases the clustering coefficient.
4 Conclusions and future work

PROSA is a P2P system mainly inspired by social networks and behaviours. Topological properties of PROSA suggest that it naturally evolves to a small-world network, with a very short average path length and a high clustering coefficient. More results about query efficiency are reported in [3]. Future work includes deeply examining the internal structure of PROSA networks and studying the emergence of communities of similar peers.

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