Efficient searching and retrieval of documents in PROSA

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Abstract. Retrieving resources in a distributed environment is more difficult than finding data in centralised databases. In the last decade P2P system arise as new and effective distributed architectures for resource sharing, but searching in such environments could be difficult and time-consuming. In this paper we discuss efficiency of resource discovery in PROSA, a self-organising P2P system heavily inspired by social networks. All routing choices in PROSA are made locally, looking only at the relevance of the next peer to each query. We show that PROSA is able to effectively answer queries for rare documents, forwarding them through the most convenient path to nodes that much probably share matching resources. This result is heavily related to the small-world structure that naturally emerges in PROSA.

1 Introduction

Organisation of electronical resources and documents is of the most importance for efficient searching and retrieval. Nowadays the WWW is a (negative) example of how searching and obtaining informations from an unstructured knowledge base could really become difficult and frustrating. In the case of the World Wide Web, this problem is faced and partially resolved by centralised searching engines, such as Google, MSN–Search, Yahoo and so on, which can help users in pruning away useless resources during searches. But searching strategies used by web indexing engines cannot be easily adopted in a P2P environment, mainly because nodes of such a distributed system cannot be compared to web–servers. Each peer shares a small amount of resources, can join and leave the network many times in a week and usually searches and retrieve resources belonging to a small number of different topics. In the last few years many P2P structures have been proposed, in order to build a valuable and efficient distributed environment for resource sharing.

The problem is that existing P2P systems usually ask the user to choose between efficiency and usability. In fact, while DHT systems allow fast resource searching [3] [12] [19] introducing unnatural indexing models, unstructured and weakly structured P2P systems [5][20][2] usually allow users to easily express
queries but have poor performance with respect to bandwidth and time consumption.

In this work we analyse retrieving performance of PROSA (P2P Resource Organisation by Social Acquaintances), a P2P system heavily inspired by social networks: joining, searching resources and building links among peers in PROSA are performed in a social way. Each peer gains a certain amount of strong links to peers which share similar resources and also maintains weak links to far away peers.

The linking phase is similar to a birth: each peer is given just a couple of weak links which can be used for query forwarding. Queries for resources are forwarded through outgoing links to other peers, in accordance with a defined “similarity” between the query and shared resources. New relationships in real social networks arise because people have similar interests, culture and knowledge. In a similar way, new links among peers in PROSA are established when a query is forwarded and successful answered, so that peers which share similar resources finally get connected together.

In this paper we focus on the ability of PROSA in answering queries with a sufficient number of results, even if a small amount of existing documents match them. Matching documents are retrieved in an efficient way, forwarding queries to a small amount of nodes using just a few “right” links, thanks to small-world structure that naturally emerges in a PROSA network.

In section 2 we give a brief formal description of involved algorithms; section 3 reports simulation results, focused on retrieval of rare resources; in section 4 the efficiency of the query routing algorithm is discussed, while section 5 propose guidelines for future work.

2 PROSA: a brief description

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

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

\(\mathcal{P}\) denotes the set of peers (i.e. vertices), \(\mathcal{L}\) 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 resources it shares with other peers. In PROSA the mapping \(\mathcal{P}_r : \mathcal{P} \rightarrow 2^\mathcal{R}\), associates peers with resources. For a given peer \(s \in \mathcal{P}\), \(\mathcal{P}_r(s)\) is the set of resources hosted by peer \(s\). Given a set of resources, we define a function \(\mathcal{R}_c : 2^\mathcal{R} \rightarrow \mathcal{C}\) that provides a sort of compact description of all resources. We also define a function \(\mathcal{P}_k : \mathcal{P} \rightarrow \mathcal{C}\), such that, for a given peer \(s\), \(\mathcal{P}_k(s)\) is a compact description of the peer knowledge (PK - Peer Knowledge). It can also be obtained combining \(\mathcal{P}_r\) and \(\mathcal{R}_c\): \(\mathcal{P}_k(s) = \mathcal{R}_c(\mathcal{P}_r(s))\).

Relationships among people in real social networks are usually based on similarities in interests, culture, hobbies, knowledge and so on [7][4][1]. 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, then 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 $P_k(t)$, 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 based on previously received queries from the source peer. Different meanings of links are modelled by means of a labelling function $\text{Label}$: for a given link $l = (s, t) \in L$, $\text{Label}(l)$ 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 about the target peer; this is computed as follows:

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

In the next two sections, we give a brief description of how PROSA works. A detailed description of PROSA can be found in [6].

### 2.1 Peer Joining 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 life he doesn’t know anything about his parents and relatives. The PROSA peer joining procedure is described by algorithm 1.

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**Algorithm 1 JOIN:** Peer $s$ joining to $\text{PROSA}(\mathcal{P}, \mathcal{L}, P_r, \text{Label})$

**Require:** $\text{PROSA}(\mathcal{P}, \mathcal{L}, P_r, \text{Label}), \text{Peer } s$

1. $\mathcal{R}\mathcal{P} \leftarrow \text{rnd}(\mathcal{P}, n)$ \{Randomly selects $n$ peers of PROSA\}
2. $\mathcal{P} \leftarrow \mathcal{P} \cup s$ \{Adds $s$ to set of peers\}
3. $\mathcal{L} \leftarrow \mathcal{L} \cup \{(s, t), \forall t \in \mathcal{R}\mathcal{P}\}$ \{Links $s$ with the randomly selected peers\}
4. $\forall t \in \mathcal{R}\mathcal{P} \Rightarrow \text{Label}(p, q) \leftarrow [\text{AL}, \emptyset]$ \{Sets the added links as AL\}
2.2 **PROSA dynamics**

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

\[ Q_M = (qid, q, s, n_r) \]  \hspace{1cm} (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\(^1\); \( s \in P \) is the source peer and \( n_r \) is the number of required results. **PROSA** dynamic behaviour is modelled by algorithm 2 and is strictly related to queries. When a user of **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 \( \text{ExecQuery}(\text{PROSA}, s, (qid, q, s, n_r)) \).

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| Algorithm 2 ExecQuery: query \( q \) originating from peer \( s \) executed on peer \( \text{cur} \) |
|---------------------------------------------------------------|
| **Require:** **PROSA**\((P, L, P_r, \text{Label})\), \( \text{cur} \in P \), \( q \in QM \) |
| **1:** \( \text{Result} \leftarrow \emptyset \) |
| **2:** if \( \text{cur} \neq s \) then |
| **3:** \( \text{UpdateLink}(\text{PROSA}, \text{cur}, s, q) \) |
| **4:** end if |
| **5:** \( (\text{Result}, \text{numRes}) \leftarrow \text{ResourcesRelevance}(\text{PROSA}, q, \text{cur}, n_r) \) |
| **6:** if \( \text{numRes} = 0 \) then |
| **7:** \( f \rightarrow \text{SelectNextPeer}(\text{PROSA}, \text{cur}, q) \) |
| **8:** if \( f \neq \text{null} \) then |
| **9:** \( \text{ExecQuery}(\text{PROSA}, f, qm) \) |
| **10:** end if |
| **11:** else |
| **12:** \( \text{SendMessage}(s, \text{cur}, \text{Result}) \) |
| **13:** \( L \leftarrow L \cup (s, \text{cur}) \) |
| **14:** \( \text{Label}(s, \text{cur}) \leftarrow \left[ \text{FSL}, P_k(\text{cur}) \right] \) |
| **15:** if \( \text{numRes} < n_r \) then |
| **16:** \{ Semantic Flooding \} |
| **17:** for all \( t \in \text{Neighborhood}(\text{cur}) \) do |
| **18:** \( \text{rel} \rightarrow \text{PeerRelevance}(P_k(t), q) \) |
| **19:** if \( \text{rel} > \text{Threshold} \) then |
| **20:** \( qm \leftarrow (qid, q, s, n_r - \text{numRes}) \) |
| **21:** \( \text{ExecQuery}(\text{PROSA}, t, qm) \) |
| **22:** end if |
| **23:** end for |
| **24:** end if |
| **25:** end if |

\(^1\) 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.
The first time *ExecQuery* is called, *cur* is equal to *s* and this avoids the execution of instruction #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(*TPk*) based on the received query message. Note that a *TPk* can be considered as a “good hint” for the current peer, in order 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 eventually download some of the 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 *TPk* is updated. If the requesting peer is a FSL, no updates are necessary.

The relevance of a query with respect to the resources hosted by a 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 *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 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 < *nr*). 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 builds a new FSL to the answering peer and then presents results to the user. If the user decides to download a certain resource from another peer, the requesting peer directly contacts the peer owning that resource asking for download. If download is accepted, the resource is sent to the requesting peer.
3 Information Retrieval in PROSA

Other studies about PROSA [6] [18] revealed that it naturally evolves to a small–world network, with a really high clustering coefficient and a relatively small average path length between peers.

The main target of this work is to show that PROSA does not only has desirable topological properties, but also that resource searching can be massively improved exploiting those characteristics. The fact that all peers in PROSA are connected by a small number of hops does not guarantees anything about searching efficiency. In this section we show that searching resources in PROSA is really fast and successful, mainly because peers that share resources in the same topic usually results to be strongly connected with similar peers.

3.1 Two words about simulations

In order to show that PROSA can be used to efficiently share resources in a P2P environment, we developed a event-driven functional simulator written in Python. The knowledge base used for simulations is composed by scientific articles in the field of math and philosophy. Articles about math come from “Journal of American Mathematical Society”[15], “Transactions of the American Mathematical Society”[17] and “Proceedings of the American Mathematical Society”[16], for a total amount of 740 articles. On the other hand, articles in the field of philosophy come from “Journal of Social Philosophy” [9], “Journal of Political Philosophy” [8], “Philosophical Issues” [10] and “Philosophical Perspectives” [11], for a total amount of 750 articles.

The simulator uses a Vector Space [13] knowledge model for resources. Each document is represented by a state vector which contains the highest 100 TF–IDF [14] weights of terms contained into the document.

Each peer contains, on average, 20 ± 5 articles in the same topic. Nodes perform 80% of queries in the same topic of the hosted resources and the remaining 20% in the other topic. We choose to do so after some studies about queries distribution in a Gnutella P2P system [5] and with real social communities in mind, where the most part of requests for resources are focused on a really small amount of topics.

3.2 Number of retrieved documents

One of the most relevant quality measure of a resource searching algorithm is the number of documents retrieved by each query. In this paragraph we examine results obtained with PROSA, using the query mechanism described in section 2. We also compare PROSA to other searching strategies, such as random walk and flooding.

Figure 1(a) shows a comparison of average number of retrieved documents in a PROSA network for different number of nodes, when each node performs 15 queries on average.
As showed in figure 1(a), the best performance is obtained by flooding, since the average number of retrieved documents per query is about 10, that is the number of documents required by each query \( n_r \). Nevertheless, \texttt{PROSA} is able to retrieve about 4 documents per query, on average, and this result is still better than that obtained with a random walk, which usually retrieves only 2.8 documents per query.

This suggests that the query routing algorithm, based on local link ranking, is really efficient and usually let queries “flow” in the direction of nodes that can probably answer them. We note that \texttt{PROSA} is able to retrieve a relatively high number of documents also if compared with a simple flooding. This is a good result, since flooding is known as being the optimal searching strategy: queries are actually forwarded to all nodes, so all existing and matching documents are retrieved, until the number of required documents has not been obtained.

In figure 1(b) the average number of retrieved documents per successful query is reported. The best performance is once again obtained by flooding, while \texttt{PROSA} retrieves an average of 4.2 documents for each successful query over 10 documents required. Random walk has, once again, the worst performance.

Looking only at the number of retrieved documents could be misleading: it is not important to have a small amount of queries answered with a high number of documents. It is desirable having almost all feasible queries \(^3\) answered by a sufficient number of documents. Figure 1(c) shows the percentage of retrieved documents for \texttt{PROSA}, flooding and random walk, on the same \texttt{PROSA} network with different network sizes. Note that in every case the average amount of unfeasible queries is around 6%.

The highest percentage of answered queries is obtained by flooding the network, since about 94% of queries have an answer. This means that practically all the queries are answered, if we except those that have no matching documents. A valuable result is obtained also by \texttt{PROSA}: 84% to 92% of all queries are answered, while random walk usually returns result for less than 80% of issued queries \(^4\). The percentage of answered queries increases with network size, for all searching strategies, because all nodes have an average number of 20 documents: more nodes means more documents, i.e. an higher probability of finding matching documents.

### 3.3 Query recall

Either if it is an important parameter for a resource searching and retrieving strategy, the number of retrieved documents is not the best measure of how

\(^2\) A query is no more forwarded if a sufficient number of documents has been retrieved, as explained in 2

\(^3\) A query is feasible if there exist matching documents to answer it. Otherwise it is considered unfeasible

\(^4\) If a query eventually enters an unconnected component, it cannot be further forwarded.
much documents a searching algorithm is able to retrieve. Since not all queries match the same number of documents, it is better to measure the percentage of retrieved documents over all matching documents. A valuable measure is the so–called “recall”, i.e. the percentage of distinct retrieved documents over the total amount of distinct existing documents that match a query. In figure 2(a) we show the recall distribution for PROSA, flooding and random walk when each node performs 15 queries on average.

The best performance is obtained, once again, flooding the network: about 60% of queries have a recall of 100%, and about 80% of queries have a recall of 50%. Searching by flooding could not return all documents because PROSA is a directed graph, and unconnected components could still exist. Also PROSA has high recall: about 20% of queries obtain all matching documents, while 45% of queries are answered with one half of the total amount of matching documents. Random walk is the worst case: about 80% of queries has a recall of less than 50% and only 8% of queries obtain all matching documents.

Recall measured as the simple percentage of retrieved document over the total amount of matching documents does not take into account the fact that in PROSA queries are requested to retrieve \( n_r \) documents and no more. This fact could practically influence the recall measure for PROSA networks, since queries are no more forwarded if a sufficient number of documents has been
retrieved. On the other hand, it is important to analyse the recall in the case of “rare” queries. Note that we consider a query as being “rare” when the total number of matching documents is lower than the number of requested documents; similarly a query is considered “common” if it matches more than $n_r$.

Figure 2(b) shows the cumulative normalised distribution of recall for rare queries, while figure 2(c) reports the cumulative distribution for common queries.

Results reported in figure 2(b) are really interesting: **PROSA** answers 35% of rare queries by retrieving all matching documents, while 75% of queries retrieve at least 50% of the total amount of matching documents; less than 10% of queries obtain less than 30% of matching documents. Performance of a random walk is worse than that obtained by **PROSA**: only 20% of queries obtain all matching documents, while more than 30% of them obtain less than 30% of matching results.

The situation is slightly different for common queries. As reported in figure 2(c), **PROSA** is able to retrieve at least 10 documents for 20% of issued queries and, in every case, at least one document is found for 99% of queries, and at least

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5 Reported results are relative to $n_r = 10$
3 documents for 85% of queries. We think that this behaviour is also affected by
the chosen value of \( n_r \).

In order to better understand benefits of using PROSA, it is interesting
to look also at other measures that could clarify some PROSA characteristics. For instance, recall results are of poor relevance without a measure of how fast
answers are obtained. A feasible measure of speed could be the average query
deapness, defined as the average number of “levels” a query is forwarded far
away from the source node.

In figure 2(d) we show average deepness of successfull queries for PROSA,
flooding and random walk on the same PROSA network for different number
of peers.

Query deepness for PROSA is around 3 and is not heavily affected from the
network size, while that of flooding and random walk is much higher (from 30
to 60 and from 120 to 600, respectively). Better results obtained by PROSA
cannot be simply explained by network clustering coefficient, since all simulation
are performed on the same network. We suppose that it is mainly due to the
searching algorithm implemented by PROSA itself: it is able to find a convenient
and efficient route to forward queries along, avoiding a large number of forwards
to non-relevant nodes.

4 Energetical Considerations

An important parameter to take in account in order to quantify the efficiency of
a searching strategy is the “energy” needed to forward and answer each query.
In a theoretical model it is probably of no great importance how much power
is needed in order to answer a query. But for real systems this is a crucial
parameter. One of the main issues with unstructured P2P networks such as
Gnutella [5] is that queries waste a lot of bandwith, since a large fraction of the
network is flooded and a great amount of nodes are involved in answering each
query. It is possible to roughly define the average “energy” required for each
query using equation 3, where \( N_q \) is the number of nodes to which the query has
been forwarded and \( L_q \) is the number of links used during query routing. \( b \) and
\( c \) are dimensional scaling factors.

\[
E_q = b \cdot L_q + c \cdot N_q
\]

The definition given here for query energy is quite simple: it takes into ac-
count the required bandwith, represented by the factor \( b \cdot L_q \), and the com-
putational power needed by nodes in order to process queries, represented by
\( c \cdot N_q \).

To estimate the amount of energy required to answer queries, we could look
at the average number of nodes and the average number of links involved in each
query. Note that \( N_q \) and \( L_q \) are usually different, since a node can be reached
using many paths: either if it processes the query only once \(^6\), the bandwith
wasted to forward the query to it cannot be saved.

\(^6\) requests with the same query id are ignored
Figure 3(a) and 3(b) show, respectively, the average number of nodes involved and the average number of links used by successful queries, both for PROSA and a simple random walk search.

Since random walk uses a higher number of nodes and a higher number of links in order to answer the same queries, it is clear that PROSA requires less energy. On the other hand, since PROSA is able to retrieve more matching documents than a random walk (as shown in section 3.2), we can state that PROSA is really efficient with respect to average “energy” required to answer queries.

5 Conclusions and Future Work

This work presented a formal description of PROSA, a self-organising system for P2P resource sharing heavily inspired by social networks. Simulations show that resource searching and retrieving in PROSA is really efficient, because of the ability of peers in making good local choices that result in fast and successful global query routing. Interesting results are obtained for query recall measured on rare documents: PROSA is able to route queries for those documents directly to nodes that probably can successfully answer them. Since PROSA results to be a small-world, all nodes are reached in a few steps, avoiding to waste bandwidth and processing power. Future works include further studying PROSA in order to discover emerging structures, such as semantic groups and communities of similar peers.

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