Cooperative mechanisms for information dissemination and retrieval in networks with autonomous nodes

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Abstract. In this dissertation we propose, model and evaluate novel algorithms and schemes that allow information dissemination and retrieval to be performed more efficiently in a modern networking environment. Most of these schemes are examined in relation to the content management tasks of content storage and classification. An inherent challenge lies in the need to manage the autonomy of nodes while preserving the distributed, as well as open nature of the system. To this end, we examine in some cases the development of incentives for nodes to cooperate while performing communication tasks. Finally, a novel attribute of most of the proposed schemes is the exploitation of social characteristics of nodes, focusing on how common interests of nodes can be used to improve communication efficiency.

1 Introduction

The proliferation of networking technologies in our time, due mostly to the development of the Internet, cellular and ad-hoc wireless mobile networks, is associated with a huge increase in the type and volume of information transmitted through a telecommunications network. Apart from the development of new communication techniques, the number of information sources has increased significantly, with user devices able to create, reproduce and transmit content that can be interesting and useful to other users. Algorithms for information dissemination and retrieval must adapt to this new setting by exploiting the ability of user devices to communicate directly and to obtain content from different sources, while handling the problem of information explosion caused by the abundance of data.

This thesis contributes to the literature by proposing, modeling and evaluating novel information dissemination and retrieval algorithms and schemes that can render communication more efficient in a modern networking environment. Such an environment consists predominantly of mobile nodes that obtain or exchange content with other peer nodes, fixed Internet servers or sensor nodes.

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Apart from information dissemination and retrieval, related content management functions we examine are content storage, replication and classification.

1.1 Outline of the thesis

We provide an outline of the thesis, referring to the publications that were produced during our study. In [1] and [2] we study a content replication scheme in which autonomous nodes form a group, called a distributed replication group and cooperate in order to effectively retrieve information objects from a distant server. Each node locally replicates a subset of the server objects and can access objects stored by other nodes in the group at a smaller cost, compared to the cost of accessing them from the server. Given that nodes are autonomous and independently decide which objects to replicate, the problem is to construct efficient distributed algorithms for content replication that induce low overall average access cost. This problem becomes even more challenging when the group has to deal with churn, i.e., random "join" and "leave" events of nodes in the group; churn induces instability and has a major impact on cooperation efficiency. Given a probability estimate of each node being available, we propose a distributed churn-aware object placement strategy. By considering a game-theoretic approach, we identify cases where the churn-aware strategy is individually rational for all nodes, while the churn-unaware is not. Numerical results further show that the algorithm outperforms, in most cases, its churn-unaware counterpart, and allows for a more fair treatment of nodes according to their availability frequency, thus inciting nodes to cooperate.

Based on this setting, in [3] and [4] we study the impact of the similarity in nodes' preferences or interest profiles on content replication. Our aim is to investigate the kind of content placement strategy a node participating in a distributed replication group should follow in order to increase its benefits. We define a metric that captures the similarity of nodes' interest profiles, called group tightness. Using this metric and testing with different interest profiles, we are able to show the association of the degree of interest similarity within nodes in a group with the benefits they incur by applying a cooperative or selfish replication strategy.

An important as well as anticipated conclusion is that the higher the interest similarity between nodes, the higher the gains by cooperation in content management. It is therefore reasonable to attempt to organize nodes into communities where nodes share similar interests. However, in current "computerized" social networks users do not necessarily create ties based on common interests, but also on many other factors, such as friendship, kinship, professional relations, or even prestige. The result is a relatively small tightness of such groups, and relatively poor gains from cooperation. In [5], we propose a framework for the construction of communities based on common interests of users, by building a virtual graph where an edge between two nodes is weighted by the degree of similarity in their interests, and then using known community detection algorithms to establish communities. Testing on synthetic network scenarios shows that this framework helps to correctly identify interest communities, stressing that care must be taken on the proper choice of the similarity metric used to represent weights.

Besides common interests, a major characteristic of communities is their locality, i.e., the specific neighbourhood, venue, or spot where they are located. Some localities may constitute points of attraction or hotspots with a higher node density. Mobile nodes also form social groups dynamically, as they move to different localities where they can establish communication with other nodes. Social groups that are examined from the viewpoint of the locality they are situated in, are termed locality-induced groups. In [6], we investigate the intermingling of interest and locality-induced social groups and propose an approach that can enhance content dissemination in the presence of such groups. We assume a setting where nodes have different interest distribution patterns over a set of information objects, and different frequencies of visiting a number of localities. Considering a new metric for the valuability of content, that takes into account both its usability and discoverability, we explore the conditions under which a cooperative strategy can improve the content dissemination process compared to a selfish one.

We further investigate content dissemination under node mobility in [7], by considering a so-called nomadic sensor network consisting of: a) sensor nodes (T-nodes), that are fixed at some points and collect information about states or variables of the environment, and b) mobile nodes (U-nodes) that collect and disseminate this information. Mobile nodes are assumed to be interested in different subsets of sensor node information. Similarly to custom multi-hop forwarding, dissemination of information content in such networks can be achieved at smaller costs if mobile nodes are cooperative and collect and carry information not only in their own interest, but also in the interest of other mobile nodes. A specific modeling scenario is considered where mobile nodes move randomly on a graph, collecting information from fixed nodes located at the vertices. We present a game-theoretic analysis to find conditions under which a cooperative equilibrium can be sustained.

Finally, in [8], we study gossip-based algorithms for content dissemination and search in large-scale networks with autonomous nodes. The dissemination or search process is carried out in rounds, where at each round multiple peers can be contacted. We develop an analytical model that allows us to evaluate the performance of the algorithm as well as the impact of several design parameters, such as the degree of cooperation of nodes, the number of peers contacted in each round, or the number of nodes where a searched content may be located. We also consider the degree of information a node has about the evolution of the gossiping process, meaning the number of nodes contacted so far, and study both the case where a node has complete information and the case of no information. The results provide significant insights on the design of such schemes.

1.2 Related works

Properly distributing replicas of content in multiple nodes in the network has shown to provide smaller search and retrieval times for content in peer-to-peer networks, and to decrease the overall network load [9]. In mobile networks, there has been in recent years a tremendous increase in the volume of downloaded data from the Internet, which may result in congestion in wireless access links. Replication techniques have also been proposed in this case to take advantage of device-to-device communication capabilities, reduce content retrieval times and mitigate congestion in Internet access links [10], [11], [12]. Despite the fact that in a mobile network the topology dynamically changes over time, there has been significant evidence that non-random clustered mobility characterizes human movements in outdoor environments [13]. That is, despite node mobility, there is a tendency for the formation of groups composed of nodes which are in geographical proximity for a relatively long period of time and have high connectivity. This is the key fact that allows replication strategies to be extended to such networks, since it allows nodes to rely on other nodes in order to retrieve content.

A basic model we employ in our work is the one introduced in [14], where nodes are self-organized into what we call a "replication group", i.e., a group consisting of nodes in network proximity, where the cost of each node to retrieve locally stored content from another node in the group is about the same and small compared to the cost of retrieving it from the origin server. Further, we use as a basis the work in [15], where the authors devised a cooperative content placement strategy on the basis of game-theoretic arguments, determining which objects each node should store locally so that the gain for each and every node is at least (and typically much higher than) that induced under a selfish strategy.

For some content dissemination scenarios, it was demonstrated in [16] that higher similarity in the interests/preferences of online social group members favors collaborative, and even altruistic, behavior. In order to examine if such similarity is present in social networks, we devise mechanisms and tools that can assess the similarity of interests among social group members and discover interest-based communities. In the literature, algorithms for detecting community structure have largely been applied to a given network structure, usually modeled as a graph. The most prominent algorithm thereof is that of Girvan and Newman [17], which is highly efficient and overcomes many shortcomings of previously proposed algorithms. In the thesis, we shall see that interest-based relationships in social networks can be represented in the form of weighted graphs. We use a similar algorithm for detecting communities in weighted graphs [18], based on a simple mapping from a weighted network to an unweighted multigraph.

There has also been some research on how locality-induced node encounters and the nodes' own (content) interests can be jointly exploited to improve information dissemination in social networks. In this respect, the closest work to ours is in [19], where the authors introduce a dynamic scheme for deciding which objects (content) of a certain content type to replicate locally based on the encounters with other nodes. In that work each node appends a value to each object that is a function of its access probability and its availability in a locality, its size and the weight of the locality; this weight represents the relationship between the node and the locality (e.g., how often a node visits this locality).

A nomadic sensor network is a networking paradigm that was introduced in [20]. Compared to traditional sensor networks where communication to end-users is realized in a multi-hop fashion, this paradigm exploits user mobility to conserve limited sensor energy, prolonging the lifetime of the network and making it more cost-efficient. Previous applications of game-theoretic methods in examining cooperation between mobile nodes have focused mainly on traditional ad hoc networks, where cooperation consists of each node acting as a relay and forwarding packets of other nodes, at the expense of an increased processing and energy cost. This kind of cooperation is the main subject of the papers in [21], [22], [23], [24]. A work with a similar subject to ours is [25]. Therein, the authors consider a general delay-tolerant network where information is disseminated in a store-carry-and-forward manner.

Finally, the term "gossiping algorithm" encompasses any communication algorithm where messages between two nodes are exchanged opportunistically, with the intervention of other nodes that act as betweeners or forwarders of the message. Attractive characteristics of gossiping algorithms include simplicity, scalability and robustness to failures, as well as a speed of dissemination that is easily configurable. Gossiping can be identified with the spreading of rumors in a network, the dynamics of which are investigated in [26], [27]. The process of communication consists of one or more rounds, in which a number of nodes that carry the message contact their peers, until the message reaches the intended recipient(s). In this respect, Pittel [26], Karp et al. [28] and Kempre et al. [29] studied a simpler model in which each peer selects a single neighbour in the network to communicate with at every round.

2 Results and Discussion

In the content replication scenario, let $\mathcal{N} = \{1, 2, ..., N\}$ denote the set of the nodes (or players) in a replication group and let $\mathcal{M} = \{1, 2, ..., M\}$ denote the set of objects (or items) these nodes are interested in. Let R^n_m denote the preference rate of node n for object m, and let $R^n = \{R^n_1, R^n_2, ..., R^n_M\}$ be the global preference vector. By P_n, we denote the placement at node n, defined to be the set of objects stored locally at that node with storage capacity C_n. Let t_l, t_r and t_s denote the cost for accessing an object from the node's local memory, from another remote node within the replication group and from nodes outside the replication group or distant server, respectively; $t_l < t_r < t_s$. Given an object placement $\mathcal{P}$, and node churn data, expressed in the form of ON probabilities $\pi_k, k = 1, ..., N,\ k \neq n$, the mean access cost incurred to node n per unit time for accessing its requested objects is given by:

$$
\begin{aligned}
\mathcal{C}_n(P) = &\sum_{i \in P_n} R_i^n t_l + \sum_{\substack{i \notin P_n,\\ i \notin P_{-n}}} R_i^n t_s \\
&+ \sum_{\substack{i \notin P_n,\\ i \in P_{-n}}} \left[R_i^n [t_r (1 - \prod_{\substack{k=1,\\ k \neq n, k: i \in P_k}}^{N} (1 - \pi_k)) + t_s \prod_{\substack{k=1,\\ k \neq n, k: i \in P_k}}^{N} (1 - \pi_k)] \right] .
\end{aligned}
\tag{1}
$$

In the churn-aware strategy proposed in [1] and [2], each node n stores objects with the aim to minimize its access cost shown by (1), given the placements of other nodes. We show that in the majority of test cases, this strategy decreases both individual and total access costs of nodes in a replication group, compared to the strategy which does not consider other nodes' placements (called "greedy local") or the strategy which considers other nodes' placements but is unaware of churn (called "churn-unaware strategy").

An example of the importance of churn-awareness in such a distributed algorithm is shown in Fig. 1. Consider two nodes, node 1 and node 2, with capacities $C_1 = 4$, $C_2 = 1$ and 5 distinct objects $\{1, 2, 3, 4, 5\}$. Nodes 1 and 2 have corresponding request rates[1] $R^1 = \{0.5, 0.4, 0.3, 0.2, 0.1\}$ and $R^2 = \{0.4, 0.3, 0.5, 0.2, 0.1\}$. Node 1 is a relatively reliable node with $\pi_1 = 0.9$ and node 2 has a variable probability between 0 and 1 for the purpose of the example. We assume that $t_l = 1$, $t_r = 10$ and $t_s = 100$.

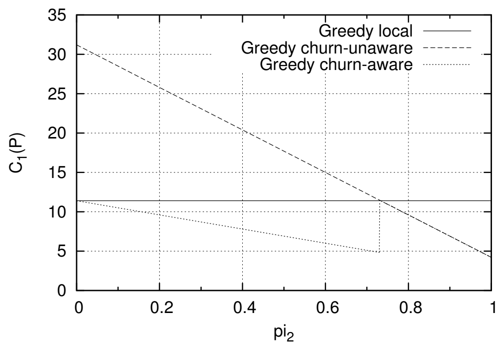


Fig. 1. Violation of the participation constraints of node 1 for $\pi_2 < 0.74$ when using the churn-unaware strategy.

Suppose that node 1 plays first in the game. It is shown in the results of Fig. 1, that for $\pi_2 < 0.74$ the access cost of node 1 under the churn-unaware strategy is greater than that of the greedy local strategy, and thus the churn-unaware strategy is not individually rational (i.e., node 1 is mistreated). This happens

[1] It is noted that request rates in the examples used here are not normalized.

because node 1 erroneously considers node 2 to be reliable. On the contrary, the churn-aware strategy always performs better than the greedy local one.

By easier satisfying individual rationality constraints and providing fairer access costs to nodes according to their reliability, the churn-aware strategy incites nodes to collectively store data. The churn-aware and churn-unaware strategies are also called "self-aware cooperative" in the thesis, as they are a mixture of selfish and cooperative behaviour.

In [3] and [4], we examined the impact of the level of similarity between node preferences within a social group on the replication strategy that nodes follow. The definition of *tightness* draws on the symmetrized Kullback-Leibler (KL) divergence [30], a well-known measure of divergence between two distributions. The Kullback-Leibler divergence of distribution R^i from R^j is defined as:

$$D_{R^i,R^j} = \sum_m R^i_m log \frac{R^i_m}{R^j_m}.$$

and its symmetrized counterpart is $D(R^i||R^j) = D_{R^i,R^j} + D_{R^j,R^i}$. Finally, we define *tightness* T to be the inverse of the average divergence of nodes' preferences within the group:

$$T = \frac{1}{\frac{\sum_{(i,j)} D(R^i||R^j)}{N(N-1)/2}}. \quad (2)$$

Our results showed that similarity is key for deciding which content placement strategy (i.e., what kind of behaviour) to follow in a replication group. We examined 3 different strategies in an environment without churn: a) the selfish (greedy local) strategy where a node stores objects based solely on its own interests, b) the self-aware cooperative strategy discussed previously, and c) the altruistic strategy which allocated object replicas in order to minimize the total access cost of the group.

In summary, our evaluation shows that the benefits of cooperation increase with the group tightness. Fig. 2 plots the total access cost values for different tightness values of the group, for a rank-preserving preference similarity scenario. Altruism emerges as a suitable strategy in very tight social groups: it minimizes the content access cost not only collectively for the whole group but also for each individual node. As tightness decreases, the collective group gain under the altruistic strategy fades out, while certain nodes may even be mistreated. For low-tightness groups, the selfish strategy is more reasonable. The performance of the self-aware cooperative strategy lies between the two; it is a suitable alternative to the altruistic strategy because it does not lead to mistreatment, and has a smaller complexity.

Based on the above results we proposed a framework called ISCoDe for the clustering of users (nodes) according to common interests. Communities in online social networks do not usually exhibit a high degree of interest similarity; thus the framework can be used as a guide for the formation of more interest-coherent communities in online social networks.

The framework is shown schematically in Fig. 3. Input to ISCoDe are the

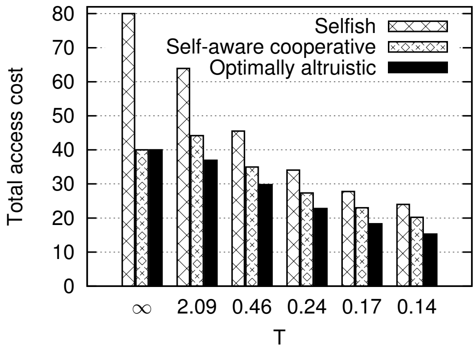


Fig. 2. Total access cost vs. *tightness* T.

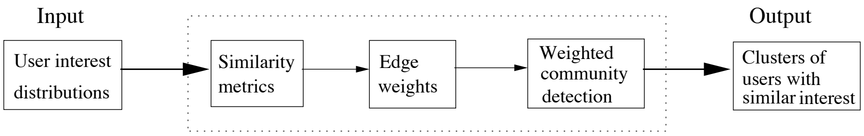


Fig. 3. The *ISCoDe* framework.

interests of the communities' member nodes in certain thematic areas. ISCoDe then proceeds in two steps. First, it quantifies the interest similarity between node pairs through the use of interest similarity metrics. Outcome of this step is a weighted graph representation of the social network, with edge weights corresponding to the similarity metric values. In a second step, ISCoDe invokes a greedy agglomerative algorithm to iteratively find the communities with the highest modularity. We have investigated two similarity metrics, Proportional Similarity (PS) and Inverse Kullback-Leibler distance (InvKL), for weighting edges according to the similarity of preferences of node-pairs in a virtual graph.

Our analytical results in the thesis suggest that both metrics produce reasonable partitions for strong community structure. However, the PS metric is more sensitive in identifying partitions in networks with less apparent interest community structure. On the other hand, InvKL has a higher resolution in networks of nodes with highly similar interests, i.e., it is able to identify smaller-sized communities.

The basic network graph model studied in [7] is as follows: U-nodes move on the graph according to a random waypoint model, with constant velocity v. Each node incurs a cost for collecting T-node content in which it is not interested. However, if all nodes are cooperative and carry content for other nodes, the benefits for all nodes outweigh the costs. We show that the following strategy of each U-node can result in a cooperative equilibrium: initially, a U-node is cooperative and copies unwanted content. However, if it meets a selfish U-node somewhere on a leg, it will only transmit its acquired content with a certain probability.

The proposed strategy may easily be applied, provided that upon meeting each other, U-nodes exchange messages that contain the list of information objects stored in their memory.

For a U-node moving on leg from T_i to T_j, the cooperative equilibrium condition is

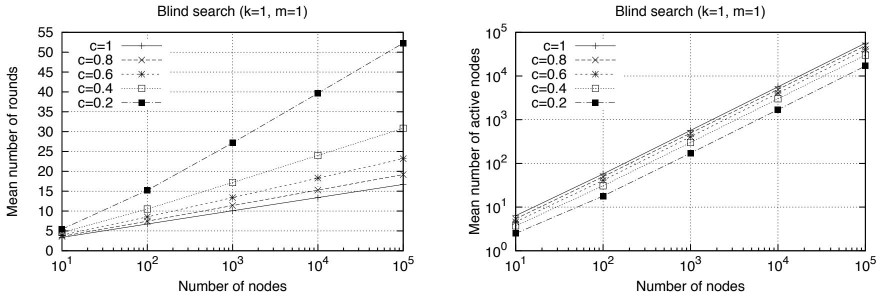
$$\begin{aligned} N \geq & 1 + \frac{2}{\alpha} + \frac{2(1-\alpha)}{\alpha}\Big\{\frac{1}{\alpha N} - (1-p)^{N-1} \\ & - \frac{1}{aNp}\big[1-(1-p)^N\big] + (1-\alpha p)^{N-1} + \frac{cv}{d}\Big\} , \end{aligned} \tag{3}$$

where N is the number of nodes, p is the content delivery probability (same for all nodes), and α is the probability a U-node meets with another U-node before hitting T_j.

For reasonable network topology parameter, it is shown that a small number of U-nodes following this strategy (less than 10 nodes) is sufficient to sustain an equilibrium, even with a high content delivery probability.

In the study of gossiping algorithms presented in [8], we consider an initiator node I, and N other nodes on a graph. In the search case, there is a file f located in m of the other nodes of the graph ($m < N$) that the initiator wants to find. In the first round ($r = 1$) the initiator selects randomly k neighbours or gossiping targets, $1 \leq k \leq N$, to forward the message to. In each round, all the informed nodes select k gossiping targets randomly and independently to forward the message to. In the case of dissemination the objective is to inform all nodes in the network or a significant portion of them in the shortest possible time. In the case of search the query can be stopped when the object is found for the first time. A queried or informed node may or may not accept to forward the message. If it accepts, we say that this node is cooperative, otherwise non-cooperative. Cooperative nodes which are queried or informed become "active" and participate in the search or dissemination.

Some results from this analysis are shown in Fig. 4, where we plot the mean number of rounds and the mean number of active nodes until a file is found, as a function of the number of nodes in the network, N, and the cooperation probability c. We assume the search is blind, in that a node may query the same node more than once. We observe that the scaling performance of the search is remarkably simple. The mean number of rounds increases linearly with $\log N$, while the mean number of active nodes increases linearly with N. This is true for almost the whole range of values of c. Similar scaling results are derived for other cases, for example smart search (where nodes remember contacted peers) or different cooperation behaviors (e.g., stifling). The analysis also reveals interesting results for dissemination gossiping algorithms, and additionally a 0-1 bimodal behavior: the probability of informing all nodes in the network increases very abruptly from 0 to 1 after a critical round value, dependent on the size of the network.



(a) (b)

Fig. 4. Scaling performance of blind search in the plain non-cooperative case, for $k = 1$, $m = 1$: (a) mean number of rounds, (b) mean number of active nodes.

3 Conclusions

We end this summary by providing the major conclusions of the thesis.

In a distributed replication scenario, we showed that an algorithm where each node selfishly replicates objects from a distant server based on other nodes' placements and their reliability, can achieve good performance with minimal cost. Our results further evidence that the level of similarity of nodes' preferences within a social group is key for deciding which content placement strategy to follow within a replication group. The defined metrics of tightness which can be used as decision criteria when choosing content placement strategies under given group membership or, more broadly, for carrying out performance-driven group management operations such as group formation, merging or splitting.

The study of content dissemination in a networking environment comprised of interest and locality-induced social groups shows that when nodes exhibit the same preferences, mobility helps in the dissemination of content, and nodes attain an improvement even if they store content selfishly. Similarly, in a nomadic sensor network rational mobile nodes will exhibit cooperative behaviour on legs of the network, given that they actually transmit acquired sensor data with a probability p when they meet a selfish U-node. In a more realistic scenario, this content delivery probability would correspond to the reputation value of each U-node of being cooperative.

When disseminating or searching for content, we conclude that remarkably simple scaling behavior occurs with gossiping algorithms. Further, we discover tradeoffs between "smart" and "blind" gossiping schemes and algorithms. A smart gossiping algorithm where each node has full information about the informed or queried nodes in each round is, in nature, more effective than the blind selection scheme where no information is available. However, there is a trade-off between speed, cost and redundancy between these two schemes. A blind search process with smaller cost of managing information could compensate for the smaller speed in disseminating or finding a certain content, by querying more nodes in each round. Further, a smart gossiping scheme actually burdens cooperative nodes with more redundant messages than a blind scheme, without producing an analogous gain in dissemination or search speed.

Based on the work conducted in this thesis, in future research we can proceed to study information dissemination and retrieval at a smaller level of detail, by taking into account the semantic and freshness characteristics of objects. Semantic characteristics are important for determining the relevance of an information object (owned by some node) with a certain data query, while freshness is important for determining the current value of an object, i.e., its depreciation due to its age. Ultimately, the goal is to design an information filtering algorithm that makes part of a dissemination or retrieval scheme, and assists in maximizing the benefit we attain from this procedure.

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