LETTER

Performance Evaluation of Adaptive Probabilistic Search in P2P Networks

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SUMMARY The overall performance of P2P-based file sharing applications is becoming increasingly important. Based on the Adaptive Resource-based Probabilistic Search algorithm (ARPS), which was previously proposed by the authors, a novel probabilistic search algorithm with QoS guarantees is proposed in this letter. The algorithm relies on generating functions to satisfy the user's constraints and to exploit the power-law distribution in the node degree. Simulation results demonstrate that it performs well under various P2P scenarios. The proposed algorithm provides guarantees on the search performance perceived by the user while minimizing the search cost. Furthermore, it allows different QoS levels, resulting in greater flexibility and scalability.

key words: *P2P networks, generating function, probabilistic forwarding, QoS*

1. Introduction

Search is one of the most fundamental services in peer-to-peer (P2P) file sharing networks. In highly popular P2P file sharing systems, such as Gnutella [1], peers are organized in an ad-hoc fashion. Due to the lack of global knowledge, locating a resource is one of the most challenging issues in this kind of unstructured system.

The authors have proposed the Adaptive Resource-based Probabilistic Search Algorithm (ARPS) for unstructured P2P networks [2]. ARPS considers the difference in popularity amongst the resources. In ARPS, a node uses probabilistic forwarding for query messages, varying the forwarding probability according to the popularity of the resource being searched. By introducing the probabilistic search, ARPS achieves a better tradeoff between the search cost and performance than traditional methods over a wide range of P2P scenarios.

In [2], we use the k-ary tree model to analyze the search performance in the random topology networks. However, recent measurements of Gnutella and some other unstructured P2P networks, show that the underlying network topology has a power-law node degree distribution [3]. Unlike the standard random graphs, the node degrees exhibit high variance, with a few nodes having very high degrees while many others, low ones. Thus, we need to use a more accurate model and mathematical framework to keep the analysis feasible and with satisfactory compliance to reality.

Performance issues in P2P-based file sharing applications have become increasingly important. [4] provides a classification structure of relevant issues and problems that play a role in the performance of P2P-based file sharing applications. Relative to different viewpoints, search time, success rate and search cost are among the main relevant performance metrics. To provide a guaranteed probability and delay bound to locate a particular resource is the key issue from the user's perspective, while the scalability problem is more important from the system's viewpoint.

In this letter, we investigate the search performance in P2P networks with power-law degree distribution. Based on [2], we present a simple but highly effective search algorithm with performance guarantees. The algorithm guarantees the search delay and the success rate will meet the user's targeted values, while simultaneously minimizing the search overhead.

2. Analytical Model

In order to analytically characterize the search performance, we employ generalized random graphs (GRG) [5] to model the topology of P2P networks, and use the analytical framework in [6], [7] to model the search strategies of probabilistic forwarding.

The generating function for the probability distribution of the vertex degree is

$$G_0(x) = \sum_{k=0}^{\infty} p_k \cdot x^k, \quad (1)$$

where p_k is the probability that a randomly chosen vertex has degree k.

The generating function of the degree distribution of the nodes reached by following one end of a randomly chosen edge (the starting edge is excluded) is

$$G_1(x) = \frac{G_0'(x)}{G_0'(1)} = \frac{1}{z} G_0'(x), \quad (2)$$

where $G_0'(x)$ is the first derivative of $G_0(x)$, and $z = G_0'(1)$ is the average node degree. The generating function of the number of nodes two hops away is given by

$$\sum_{k=0}^{\infty} p_k [G_1(x)]^k = G_0(G_1(x)). \quad (3)$$

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Therefore, the generating function for the number of peers h hops away from a randomly chosen node is $G_0(\underbrace{G_1(\ldots G_1(x)\ldots)}_{h-1})$.

Due to the probabilistic nature of ARPS, no query message may be propagated from the originator. To tackle this problem, we modified the message forwarding function g [6] as follows:

$$g(d) = \begin{cases} 1 & d = 0 \\ p_f & 0 < d < TTL \end{cases} \tag{4}$$

The forwarding function represents the modified probabilistic search strategy where the query originator uses the flooding mechanism while the intermediate nodes use probabilistic forwarding to forward the query message. This probabilistic search strategy ensures that at least one query is propagated from the originator while limiting the average total number of messages sent through the P2P network.

The probability that the query originator transmits the search message to n of its neighbors is given by

$$q_n = \sum_{k=n}^{\infty} p_k \cdot \binom{k}{n} \cdot g(0)^n \cdot (1 - g(0))^{k-n} = p_n. \tag{5}$$

The generating function for the number of peers that receive the query in the neighborhood of the requester is

$$Q_1(x, g) = \sum_{n=0}^{\infty} q_n x^n = G_0(x). \tag{6}$$

The generating function for the number of peers at distance h hops from the query originator and who receive the message is

$$Q_h(x, g) = Q_1(\underbrace{\overline{Q}_1(\ldots \overline{Q}_1(x, g), g \ldots), g)}_{h-1}, \tag{7}$$

with

$$\overline{Q}_1(x, g) = G_1(1 + p_f \cdot (x - 1)). \tag{8}$$

Thus, the generating function for the total number of peers that receive the query message under the constraint of TTL is given by

$$Q(x, g, \mathrm{TTL}) = \prod_{m=1}^{\mathrm{TTL}} Q_m(x, g). \tag{9}$$

From (9), the average number $\overline{N}$ of query messages sent throughout the network is

$$\overline{N} = Q'(1, g, \mathrm{TTL}). \tag{10}$$

Let p denote the resource popularity. The probability that, among all neighbors of the query originator that receive the query message, n peers own the resource is

$$P(n, p) = \sum_{k=n}^{\infty} q_k \cdot \binom{k}{n} \cdot p^n \cdot (1 - p)^{k-n}, \tag{11}$$

with the generating function

$$H_1(x, g, p) = \sum_{n=0}^{\infty} P(n, p) x^n = Q_1(1 + p \cdot (x - 1), g). \tag{12}$$

The generating function for the total number of resource owners that receive the query message with the constraint of TTL is

$$H(x, g, p, \mathrm{TTL}) = \prod_{m=1}^{\mathrm{TTL}} H_m(x, g, p), \tag{13}$$

where $H_m(x, g, p) = Q_m(1 + p \cdot (x - 1), g)$.

From (13), the probability P_{hit} that the resource can be found (at least one hit returns) is given by

$$P_{hit}(g, p, \mathrm{TTL}) = 1 - H(0, g, p, \mathrm{TTL}). \tag{14}$$

We approximate the search delay by the average number of hops it takes for the query messages to reach the first node that has the resource. If the search fails, the delay is just the TTL value of the message.

As $H(0, g, p, h)$ is the probability that the resource is not found in h hops away from the requester, the probability that a search takes exactly h hops for the first hit is

$$F(g, p, h) = H(0, g, p, h - 1) - H(0, g, p, h). \tag{15}$$

The average number of hops it takes for the query messages to reach the first resource owner is

$$D(g, p, \mathrm{TTL}) = \sum_{h=1}^{TTL} h \cdot F(g, p, h) + (1 - P_{hit}) \cdot \mathrm{TTL}. \tag{16}$$

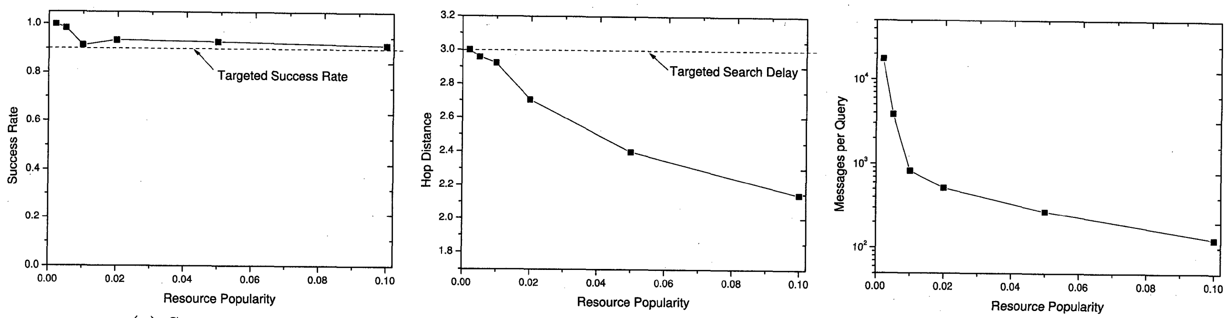
Let P_{target} and D_{target} denote the target success rate and the search delay bound separately. From the viewpoint of the user, the most relevant performance constraints are

$$\begin{aligned} &P_{hit}(g, p, (TTL)) \geq P_{target} \\ &D(g, p, \mathrm{TTL}) \leq D_{target}. \end{aligned} \tag{17}$$

3. Search Algorithm

We propose a new search algorithm following the modified probabilistic search strategy of (4). To provide guarantees on the search success rate and delay, two fundamental questions need to be answered: 1) When a peer attempts to locate an object, what is the current popularity of that resource? 2) If the popularity is known, which forwarding probability should the peer choose to propagate the query message?

To answer the first question, nodes in the network update the estimated popularity of each resource periodically. Specifically, let $p_s(k)$ denote the current popularity estimate of the resource r after the kth update. During the new round of search for resource r, if the search is successful, suppose there are N_{hit} backward hits passing along the reverse path to the originator. The instantaneous estimated popularity is given by the ratio of N_{hit} to N_{query}. N_{query}, which can be



(a) Success rate (b) Search delay (c) Messages per query

Fig. 1 Search performance vs. resource popularity (with $P_{target} = 90\%, D_{target} = 3$).

obtained from (10), is the number of query messages generated. The estimated popularity after the $(k + 1)$th update is in the form of:

$$p_s(k+1) = \beta \cdot p_s(k) + (1-\beta) \cdot \Delta_k \quad (18)$$

$$\Delta_k = \left(\frac{N_{hit}}{N_{query}}\right). \quad (19)$$

The second question above can be answered from (17). In ARPS, when a node initiates a query for a resource with estimated popularity p_s, it chooses the minimal forwarding probability p_{min} which satisfies (17). If p_{min} does not exist, the query messages are flooded across the overlay network.

The analytical model is based on the assumption that the number of newly visited peers at each hop is independent, and the results for a GRG represent the average over the entire set of possible graph instances. To compensate for the the independence assumption of the analytical model and the deviation between GRG and one specific topology of the P2P file sharing network, we add a revision factor γ. With the revision factor, (17) becomes:

$$P_{hit}(g, p_s, (TTL)) \geq (1+\gamma) \cdot P_{target}$$
$$D(g, p_s, \text{TTL}) \leq (1-\gamma) \cdot D_{target}. \quad (20)$$

The originator uses the flooding mechanism while all the intermediate nodes choose the minimal forwarding probability p'_{min}, which satisfies the inequality (20) to forward the query message.

4. Simulation Results

To simulate the P2P network topology, we generate the power-law graph with degree distribution $p_k = \frac{\kappa^{-\tau} e^{-k/\kappa}}{Li_\tau(e^{-1/\kappa})}$, where $Li_n(x)$ is the nth poly-logarithm of x, and τ, κ are the power-law exponent and cutoff, respectively. We fit the parameters to obtain an average degree equal to 3.5 (with $\tau = 2.041289, \kappa = 500$). The default graph has 100000 nodes. In order to simulate the resource with popularity p, $\lfloor p \times 10^5 \rfloor$ nodes are randomly selected and marked as the resource owners in the network. The default values for TTL is 4, and the revision factor γ in the simulation is a random variable uniformly distributed in the range $[0, 0.05]$. The verification and evaluation of the search algorithm are based on the metrics of success rate, search delay and the number of messages generated per query.

Table 1 Search performance comparison.

Constraint	Message no.	Success rate	Search delay
(0.9,2.5)	7219.85	96.09%	2.27
(0.8,3)	1432.93	84.55%	2.64

Figure 1 shows the average results for the search of resources with different popularity. The targeted search performance from the user-oriented viewpoint is set to $P_{target} \geq 90\%, D_{target} \leq 3$. We simulate the search strategy with resources of various popularity. The forwarding probability of the modified probabilistic search is adjusted according to the constraints (20). As Figs. 1(a) and 1(b) illustrate, both the average values of success rate and search delay obtained from simulations satisfy the user's constraints. Thus, our algorithm succeeds in giving a guaranteed search performance under various circumstances, and this characteristic is popularity invariant. For unpopular resource (popularity less than 0.01), the constraint of search delay plays a key role in choosing the forwarding probability p_f. To find a resource owner in 3 hops, peers have to function similarly to flooding, which achieves a success rate much higher than 90%. With the increase of the popularity, the constraint of success rate becomes more crucial, which results in a search delay far less than 3 hops.

Figure 1(c) shows how the average number of messages generated decreases adaptively with the increasing popularity. As popularity increases, the forwarding probability p_f in (4) decreases accordingly. The average number of messages sent throughout the overlay network can be reduced by more than two orders of magnitude for popular resources compared with unpopular ones.

The success rate and the search delay are the most effective measures to evaluate the QoS perceived by the user of a P2P-based file sharing application. As shown in Fig. 1, the modified algorithm succeeds in minimizing the search overhead with QoS guarantees.

As the distribution of queries in P2P file sharing systems follows a Zipf-like distribution, we model the query process by using a distribution similar to [2]. Table 1 gives the overall search performance under different user-level constraints. Again, the modified adaptive probabilistic search algorithm fulfills its objective in performance guarantees. As the constraint of $(0.8, 3)$ is much looser than the one of $(0.9, 2.5)$, the number of messages generated is less than 20% that of the tighter constraint. As Table 1 illustrates, the search algorithm allows different QoS levels while minimizing the number of messages generated accordingly.

5. Conclusion

In this letter, we propose a modified adaptive probabilistic search algorithm for P2P networks. Unlike ARPS, the analytical model takes the power-law topology into account, rendering the algorithm more efficient in practical applications. Furthermore, the proposed algorithm adaptively chooses the forwarding probability according to the user-level performance constraints. The simulation results show that our modified algorithm fulfills its objective of providing QoS guarantees, while minimizing the search overhead. Additionally, our approach allows different QoS levels, providing flexibility for the P2P file-sharing system to meet different user requirements and rendering it more scalable.

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