Performance Analysis on Mobile Agent-based Parallel Information Retrieval Approaches

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Abstract—**The main concern of the Internet user-base has shifted from what kind of information are available to how to find the desired information on the Internet thanks to the explosive growth of the WWW and the increasing amount of data available via the Internet. Since mobile agent technology is expected to be a promising technology for information retrieval, there are a number of mobile agent based-information retrieval approaches have been proposed in recent years. For a better understanding and efficiency improvement of these approaches, performance evaluation of great importance. However, most of existing evaluation results are experimental and there is a lack of theoretical performance analysis which is helpful to reveal the insight of the working mechanisms. In this paper, we further the study in [14] in which some primary studies on the performance of several mobile agent-based information retrieval approaches are provided and provide the exact probability distributions of execution time for each approach. Our results reveal the insight of mobile agent-based information retrieval approaches and our analytical method provides a useful tool for further research to information retrieval.**

Keywords: Information retrieval, mobile agents, performance comparison.

I. INTRODUCTION

Due to the explosive growth of the WWW and the dramatically increasing amount of data available via the Internet within less than a decade, Internet search engines have completely changed how people gather information. As the Web is growing much faster than any present-technology search engine can possibly index and many web pages are updated frequently, the current search engines cannot visit the web site regularly enough to index new content [3]. New search techniques are on demand and mobile agent-based search is one of these features [9], [18].

Mobile agents are programs that can transport its state from one environment to another and resume its performing appropriately in the new environment [7], [8]. As mobile agents support intermittent connectivity, slow networks, and light-weight devices [20], mobile agent technology has been expected as a promising solution to efficient information retrieval in large dynamic environments such as the Internet.

In a large dynamic network such as the Internet, information is always separately spread over a set of nodes in the network [2]. Once a user request for retrieving a information is received by a mobile agent-based system, a number of mobile agents will be generated and dispatched to the network. The agents migrate to the nodes where the data are located rather than transmit data across the network and return back with the results to the user. Thus, the consumption on the network bandwidth will be reduced, especially when the data is located in a remote area.

In a mobile agent-based information retrieval algorithm, mobile agents will be generated and dispatched to the network frequently. Thus, they will certainly consume a certain amount of computational resources such as the network bandwidth. If there are too many agents running in the network, they will consume too much network resources, which will affect network performance and ultimately block the entire network; on the other hand, if there are too few agents running in the network, there is no guarantee that the information retrieval task will be completed quickly [11]. Therefore, it is not only important but necessary to analyze both the number of mobile agents and the execution time of mobile agents [15].

Analysis on performance of mobile agent-based information retrieval, including the number and the execution time of mobile agents, will benefit a lot to the discovery and understanding of system performance, the optimization of system designs, and the improvement of future systems. This problem has attract a lot of attentions and many works have been done in recent years [5], [10], [16]. However, most of the existing results [1], [2], [17], [22] are experimental. To the best of our knowledge, there is a lack of theoretical analysis that are useful for revealing the intrinsic characteristics of those proposed approaches. In this paper, we will evaluate the performance of mobile agent-based information retrieval approaches both theoretically and experimentally.

The remainder of this paper is organized as follows. Section II gives a brief look on related works. Section III provides a short introduction on the structure and working mechanism of a mobile agent-based information retrieval system. Section IV describes the approaches to be analyzed in this paper and Section V theoretically analyzes and compares these approaches. Section VI summarizes our work and concludes

978-1-4244-1890-9/07/$25.00

this paper.

II. RELATED WORK

There are a number of works that focus on mobile agent-based information retrieval. [2] proposed a planning algorithm for mobile agent-based information retrieval. Based on the proposed planning algorithm, mobile agents can dynamically decide their routes according to the dynamically changing traffic state of the network for the purpose of a minimum round trip time. [6] proposed a mobile multi-agent network model based on the generalized stochastic Petri-net. The Petri-net model was also used in [21] for investigating the performances of the client/server approach, remote-evaluation approach and mobile-agent approach in information retrieval application. [5] compared the energy consumption and the query response time between client/server approach and mobile agent approach for information retrieval, [19] compared these two approaches for network management, [4] compared these two approaches in component cost and migration cost, and [24] compared these two approaches for workflow systems. All the experimental results showed a promising performance of mobile agent technology.

In [17], the performance of a multi-agent architecture for geospatial data integration and conflation ([16]) is experimentally evaluated and compared with the client/server approach. The experimental results show that the clinet/server performs better than the proposed architecture only for a very small amount of data. In [1], a comparison between the remote method invocation approach and mobile agent paradigm approach used for information retrieval was provided. The experimental results showed that the mobile agent paradigm offers a superior performance compared to the remote method invocation in a lower invocation cost and a better fault-tolerant ability.

In [22], a Mobile Agent Search System (MaSS) was developed and a mobile agent-based information retrieval approach was proposed. The performance of the proposed approach was compared with five other mobile agent-based information retrieval approaches. Experimental results showed that the proposed approach required a short round trip time comparing with other approaches for retrieving same information. The performance of these approaches are also studied in [14]. Some theoretical analysis on the number of generated agents and the execution time of an user query are provided. Besides, all six approaches are compared together while in [22] the newly proposed approach is only compared to one of the five existing approaches.

III. SYSTEM DESCRIPTION AND PRELIMINARIES

A. System Structure

A brief view on the system structure in which the approaches are implemented is provide in this section for a clear impression. A detailed description can be found in [14].

An E-commerce system is user as an example for the structure of a mobile agent-based information retrieval system. As shown in Fig. 1, there is a set of service servers and a number of e-markets. Each service server has a client agent to be responsible for contacting with users and handling user tasks.

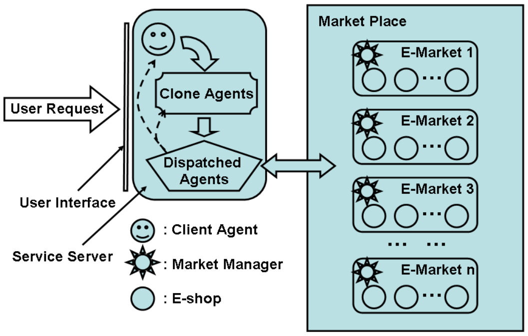

Fig. 1. System structure of mobile agent-based information retrieval.

Once a user query is received from a service server, the client agent on the server will analyze the user request and decompose the request into a number of sub-tasks if possible so that each sub-task can be completed by visiting one e-market. The a number of agents will be generated to execute the user task/sub-tasks. After the generated returns back with a report of their execution, the client agent will provide the user an integrated report.

Generally, a dispatched agent can be assigned one sub-task or a set of sub-tasks. if these tasks are semantically independent and the number of remote hosts that should be visited is large, distributing these tasks to multiple agents might be a good choice. As each dispatched agent has only one or a small number of simple task which will not take a long time to be accomplish, the user can get the feedback from the client agent in a short time. However, in case that there is a set of tasks that are semantically dependent and can only be finished serially, generating and dispatching only one agent will be more feasible.

B. The Working Mechanism of Dispatched Mobile Agents

In [14], the execution process of a dispatched agent is decomposed as five stages: generating, sending, executing, returning, and reporting. The round trip time of the k-th generated agent is defined as the time period from the client agent begin generating mobile agents for a user request to the k-th generated agent submits its report on his assigned task. The round trip time of an approach is defined as the time period from the client agent generates the first agent to the last generated agent submits its execution report. That is, $T = max_k t(k)$ where T is the round trip time of an approach and $t(k)$ is the round trip time of the k-th generated agent.

1) **Generating**, denoted by $Tg(i)$, is the time duration for generating the i-th agent.
2) **Sending**, denoted by Ts_i, is the time duration that the i-th agent arrives at its work place from the previous place, the e-market for its assigned task.

3) **Executing**, denoted by Te_i, is the time duration that the i-th agent executes its task on it work place.
4) **Returning**, denoted by Tb_i, is the time duration that the i-th agent returns back from the work place to the client agent.
5) **Reporting**, denoted by Tr_i, is the time duration that the i-th agent submits its report to the client agent.

IV. MOBILE AGENT-BASED INFORMATION RETRIEVAL APPROACHES

In this section, we give a short description on the approaches to be compared in the next section. More detailed descriptions are referred to [14], [22].

A. IQR

The working mechanism of the IQR approach can be briefly described as follows: for each user task, IQR generates one search agent. The search agent roams in the network with a timer and a collection of IP address of servers to be visited. The service server will provide the agent an itinerary for its task, but the agent can also make routing decision by itself on-the-fly. When the search agent completes its task on a server, it moves to the next one on its list and continues its execution. The search agent will return to the service server with a thorough report of its trip after it completes visiting all listed servers [1], [21].

B. PQR

For each user task, PQR generates a number of search agents such that each server to be visited will be assigned to one agent, respectively. Those agents are generated one by one and an agent will be dispatched immediately after its generation. When a search agent has completed its task, it returns to the home server and submits the report [17], [23]. Compared with IQR, PQR shortens the search time by employing more agents.

C. SHQR

For each user task, SHQR generates one search agent. The search agents roams in the network with a timer and a collection of servers to be visited. Different with IQR, the search agent returns to the home server after it completes visiting to a server, submit its report to the home server, and sent out to the next server on the list. This mechanism can greatly increase its fault-tolerant ability comparing with IQR in that the intermedial execution results will not be lost even if the agent's execution falls during its journey, while IQR losses all.

D. SQR

SQR approach is similar to the SHQR approach in that only one search agent will be dispatched to collect a query results. The agent self-clone mechanism is adopt in this approach. When the search agent completes its execution on a server, it clones itself on the server and returns back to the home server to report the query results. The cloned replica will move to the next server in the visiting list and continue this process, until all listed server are visited.

E. HQR

HQR approach is based on the self-clone ability of mobile agents. There are three kinds of agents in HQR approach, i.e., the client agent, the clone agent, and the dispatched agent. Once a user request is arrived at a service server through a user interface, a client agent is generated and take responsible for the user request. The client agent firstly decomposes the user request into a set of simple tasks that each task can be accomplished by visiting a single place in the system. Then the client agent generates a number of clone agents one by one. If the number of generated agents of this generation is not enough, the generated agents will self-clone more agents with a given generating rate. After enough agents are generated at a generation, the agents of this generation will be dispatched to a workplace with a task. These agents work on their own workplaces synchronously and return their execution results to the client agent.

F. EHQR

In EHQR, a clone agent will work as a dispatched agent after its clone task is completed. Therefore, comparing with the HQR approach, less agents will be generated for a same number of dispatched agents. Thus, both the time consumption for generating a given number of dispatched agents and the computational resources consumed by these agents are reduced.

V. THEORETICAL ANALYSIS

In this section, we will analyze and compare the performance of 7 mobile agent-based algorithms mainly through two parameters, i.e., the number of generated agents and the execution time for an information retrieval task.

A. IQR

The execution process of the IQR approach is shown in Fig. 2 from which it can be seen that this approach generates only one agent for an user request. Thus, the round trip time of the agent is the round trip time of the IQR approach, which can be expressed as [14]

$$T_{IQR} = t(1) = Tg(1) + \sum_{i=1}^{N}(Ts_i + Te_i) + Tb_N + Tr_N. \quad (1)$$

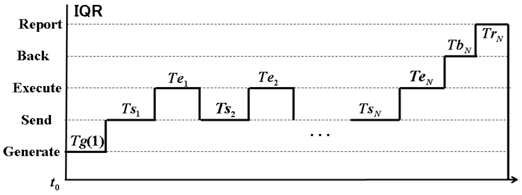

Fig. 2. The execution process of the IQR approach

Let $\Omega_i = Ts_i + Te_i$ and $\omega(t)$ be the pdf of Ω_i. Since Ts_i and Te_i are two independent random variables, the pdf of Ω_i,

$\omega(t)$, can be expressed as the convolution of $s(t)$ and $e(t)$, i.e., $\omega(t) = s(t) * e(t)$. Let $\Omega = \sum_{i=1}^{N} \Omega_i$, then, the Laplace transform of Ω, Ω^*, satisfies

$$\Omega^*(s) = E\left(e^{-s\sum_{i=1}^{N}\Omega_i}\right) = \left[S^*(s) \cdot E^*(s)\right]^N \tag{2}$$

due to the fact that $\Omega_i (i = 1, \cdots, N)$ are independent random variables. Here, $S^*(s)$ and $E^*(s)$ are Laplace transforms of Ts_i and Te_i, respectively.

$$\begin{aligned} S^*(s) &= E\left(e^{-sTs_i}\right) = \int_0^\infty s(t)e^{-st}dt, \\ E^*(s) &= E\left(e^{-sTe_i}\right) = \int_0^\infty e(t)e^{-st}dt. \end{aligned} \tag{3}$$

Let IQR^* be the Laplace transform of T_{IQR}, the distribution of the round trip time of the IQR approach satisfies

$$\begin{aligned} IQR^*(s) &= E\left(e^{-sT_{IQR}}\right) \\ &= E\left(e^{-s\left[Tg(1)+\sum_{i=1}^{N}(Ts_i+Te_i)+Tb_N+Tr_N\right]}\right) \\ &= E\left(e^{-s[Tg(1)+\Omega+Tb_N+Tr_N]}\right) \\ &= G^*(s) \cdot \left[S^*(s) \cdot E^*(s)\right]^N \cdot B^*(s) \cdot R^*(s) \end{aligned}$$

where $G^*(s)$, $B^*(s)$, and $R^*(s)$ are the Laplace transforms of Tg_i, Tb_i, and Tr_i, respectively. Thus, the distribution of the round trip time of the IQR approach can be easily gained by a reverse Laplace transform. Based on the analysis in [13], the mean and the variance of T_{IQR} can be given as follows:

$$\begin{aligned} &E(T_{IQR}) = -\left.\frac{\mathrm{d}F^*(s)}{\mathrm{d}s}\right|_{s=0}, \text{ and} \\ &D(T_{IQR}) = E\left(T_{IQR}^2\right) - \left[E\left(T_{IQR}^2\right)\right]^2 \\ &= \left.\frac{\mathrm{d}^2F^*(s)}{\mathrm{d}s^2}\right|_{s=0} - \left[\left.\frac{\mathrm{d}F^*(s)}{\mathrm{d}s}\right|_{s=0}\right]^2. \end{aligned} \tag{4}$$

B. PQR

The execution process of the PQR approach is shown in Fig. 3 from which it can be seen that the k-th agent in PQR approach, denoted by $t(k)$, can be expressed as [14]

$$t(k) = \sum_{j=1}^{k} Tg(j) + Ts_k + Te_k + Tb_k + Tr_k. \tag{5}$$

and the round trip time of the PQR approach, denoted by T_{PQR}, satisfies

$$T_{PQR} = \max_{1 \le i \le N} t(k). \tag{6}$$

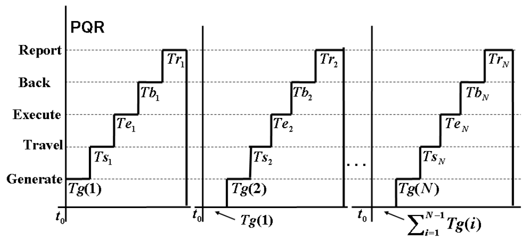

Fig. 3. The execution process of the PQR approach

Let $\phi_k = \sum_j^k Tg(j)$ where k is the sequence number of the agent's generation. Furthermore, let $\phi(t)$ be the pdf of ϕ_k and $\Phi^*(s)$ be the Laplace transform of ϕ_k. Then, the distribution of ϕ_k satisfies

$$\begin{aligned} \Phi^*(s) &= E\left(e^{-s\phi_k}\right) = \int_0^\infty \phi(t)e^{-st}\mathrm{d}t \\ &= \sum_{\ell=1}^{N} E\left(e^{-s\phi_k}\middle| k=\ell\right) P(k=\ell) \\ &= \sum_{\ell=1}^{N} E\left[e^{-s\sum_{j=1}^{k}Tg(j)}\middle| k=\ell\right] P(k=\ell) \\ &= \sum_{\ell=1}^{N} E\left[e^{-s\sum_{j=1}^{\ell}Tg(j)}\right] P(k=\ell) \\ &= \sum_{\ell=1}^{N} \left[G^*(s)\right]^\ell P(k=\ell) \end{aligned}$$

where N is the total number of agents to be generated. To analyze the probability $P(k = \ell)$, we define a random variable as follows [13]: let X_i be a 0 or 1 valued random variable with probability $\rho = P(X_i = 1)$ for $i = 1, 2, \cdots$. The event $\{X_i = 1\}$ indicates that the agent is the i-th generated. Based on the fact that $\{i = \ell\}$ is equivalent to $\{X_i = 1, X_{i-1} = \cdots = X_1 = 0\}$, we have $P\{i = \ell\} = \rho(1-\rho)^{\ell-1}$ for $1 \le \ell \le N$, which is a geometric distribution. Therefore, we have

$$\begin{aligned} \Phi^*(s) &= \sum_{\ell=1}^{N} \left[G^*(s)\right]^\ell \rho(1-\rho)^{\ell-1} \\ &= \rho G^*(s) \sum_{\ell=0}^{N} \left[(1-\rho)G^*(s)\right] \\ &= \rho G^*(s) \cdot \frac{1-\left[(1-\rho)G^*(s)\right]^N}{1-(1-\rho)G^*(s)} \end{aligned}$$

Let PQR^* be the Laplace transform of $t(k)$, the distribution of the round trip time of agents in the PQR approach satisfies

$$\begin{aligned} PQR^*(s) &= E(e^{-st(k)}) \\ &= E\left[e^{-s\left(\sum_{j=1}^{k}Tg(j)+Ts_k+Te_k+Tb_k+Tr_k\right)}\right] \\ &= \Phi^*(s) \cdot S^*(s) \cdot E^*(s) \cdot B^*(s) \cdot R^*(s) \\ &= \rho G^*(s) \cdot S^*(s) \cdot E^*(s) \cdot B^*(s) \cdot R^*(s) \\ &\quad \cdot \frac{1-\left[(1-\rho)G^*(s)\right]^N}{1-(1-\rho)G^*(s)}. \end{aligned}$$

Thus, the distribution of the round trip time of agents in the PQR approach can be gained by a reverse Laplace transform.

The mean and the variance of can be given from (4), respectively.

C. SHQR

The execution process of the SHQR approach is plotted in Fig. 4. From Fig. 4, it can be seen that similar to the IQR approach, there is only one agent being generated. Thus, the round trip time of the SHQR approach equals to the round trip time of the agent, which can be expressed as [14]

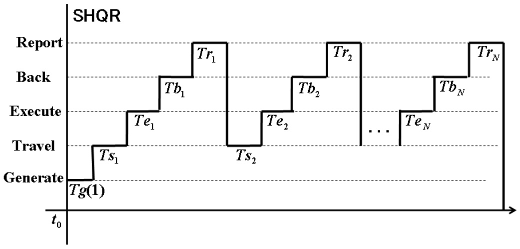

Fig. 4. The execution process of the SHQR approach

$$T_{SHQR} = Tg(1) + \sum_{i=1}^{N}(Ts_i + Te_i + Tb_i + Tr_i). \quad (7)$$

Let $SHQR^*$ be the Laplace transform of $t(1)$ or T_{SHQR}, based on the analytical method in V-A, the distribution of the round trip time of the agent/the SHQR approach satisfies

$$SHQR^*(s) = G^*(s) \cdot [S^*(s) \cdot E^*(s) \cdot B^*(s) \cdot R^*(s)]^N. \quad (8)$$

Thus, the distribution of the round trip time of agents in the SHQR approach can be gained by a reverse Laplace transform. The mean and the variance of can be given from (4), respectively.

D. SQR

The execution process of the SQR approach is plotted in Fig. 5 from which it can be seen that similar to the PQR approach, there are N agents being generated. The round trip time of an agent can be expressed as

$$t(k) = \sum_{i=1}^{k}[Tg(i) + Ts_i + Te_i] + Tb_k + Tr_k \quad (9)$$

and the round trip time of the SQR approach can be expressed as

$$T_{SQR} = \sum_{i=1}^{N}[Tg(i) + Ts_i + Te_i] + Tb_N + Tr_N. \quad (10)$$

Let $\delta_i = Tg(i) + Ts_i + Te_i$ and $\delta(t)$ be the pdf of δ_i. Since $Tg(i)$, Ts_i, and Te_i are independent variables, the pdf of δ_i, $\delta(t)$, can be expressed as the convolution of $g(t)$, $s(t)$, and $e(t)$, i.e.,

$$\delta(t) = g(t) * s(t) * e(t). \quad (11)$$

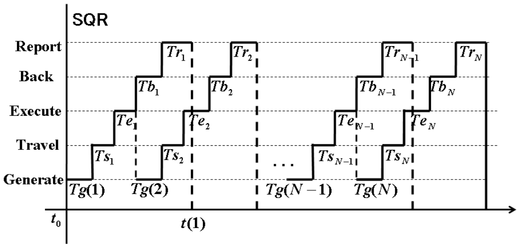

Fig. 5. The execution process of the SQR approach

Let $\Delta_k = \sum_{i=1}^{k} \delta_i$, then similar to the PQR approach, the Laplace transform of Δ_k, Δ^*, satisfies

$$\begin{aligned}
\Delta^*(s) &= E\left(e^{-s\Delta_k}\right) = E\left(e^{-s\sum_{i=1}^{k}\delta_i}\right) \\
&= \sum_{\ell=1}^{N} E\left[e^{-s\sum_i^k \delta_i | k=\ell}\right] P(k=\ell) \\
&= \sum_{\ell=1}^{N} E\left[e^{-s\sum_i^\ell (Tg(i)+Ts_i+Te_i)}\right] P(k=\ell) \\
&= \sum_{\ell=1}^{N} [G^*(s) \cdot S^*(s) \cdot E^*(s)]^\ell P(k=\ell) \\
&= \sum_{\ell=1}^{N} (L^*(s))^\ell p(k=\ell)
\end{aligned}$$

where $L^*(s) = G^*(s) \cdot S^*(s) \cdot E^*(s)$ is the Laplace transform of δ_i and N is the number of visited places/nodes for the user task. Based on the discussion in Section V-B, $p(k=\ell) = \rho(1-\rho)^{\ell-1}$ for $1 \le \ell \le N$ where ρ is the probability that the agent is the ℓ-th generated. Consequently, we have

$$\begin{aligned}
\Delta^*(s) &= \sum_{\ell=1}^{N} \rho(1-\rho)^{\ell-1} (L^*(s))^\ell \\
&= \rho L^*(s) \cdot \frac{1 - [(1-\rho)L^*(s)]^N}{1 + \rho L^*(s) - L^*(s)}.
\end{aligned}$$

Let SQR^* be the Laplace transform of $t(k)$, the distribution of the round trip time of an agent in the SQR approach satisfies

$$SQR^*(s) = \Delta^*(s) \cdot B^*(s) \cdot R^*(s).$$

Thus, the distribution of the round trip time of agents in the SQR approach can be gained by a reverse Laplace transform. The mean and the variance of can be given from (4), respectively.

E. HQR

Similar to the PQR approach and the SQR approach, there are N agents dispatched to the network for the user task. Different from the previous two approaches, the HQR approach utilizes mobile agents' self-clone characteristic. The execution process of the HQR approach is plotted in Fig. 6.

For a clear view on the working mechanism of the HQR approach, the generation process of the HQR approach was

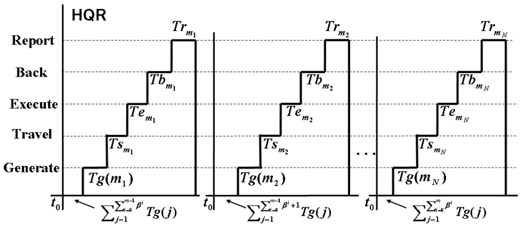

Fig. 6. The execution process of the HQR approach

plotted in a tree structure as shown in Fig. 7. This tree structure is called the generation tree.

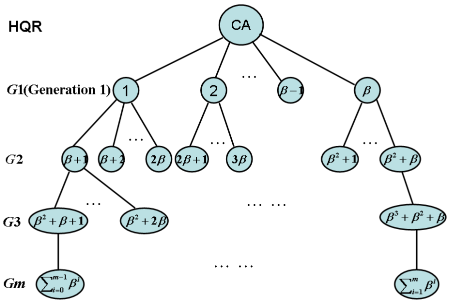

Fig. 7. The generation tree of the HQR approach

From Fig. 7, it can be seen that if there are $N = \beta^m$ agents to be dispatched to $N = \beta^m$ places/nodes to complete the user request, the the total number of generated agents in the HQR approach, including the clone agents and the work agents, satisfies

$$\begin{aligned}&\beta(\text{the 1st generation}) + \beta\cdot\beta(\text{the 2nd generation})\\&\qquad\qquad + \cdots + \beta^m(\text{the } m\text{-th generation})\\&= \sum_{i=1}^{m}\beta^i = \frac{\beta}{\beta-1}\cdot(N-1)\end{aligned} \tag{12}$$

Before the first dispatched agent is generated, the number of generated clone agents is $\sum_{i=1}^{m-1}\beta^i$ and the time for generating all the clone agents is the sum of the generation time of all these agents, i.e., $\sum_{j=1}^{\sum_{i=1}^{m-1}\beta^i} Tg(j)$. Similarly, the time for generating all agents, denoted by D_{HQR}, should includes the generating time of both clone agents and work agents:

$$D_{HQR} = \sum_{j=1}^{\sum_{i=1}^{m}\beta^i} Tg(j). \tag{13}$$

After a first work agent is generated, it sets off immediately to complete the assigned task (as shown in Fig. 6), the round trip time of the first generated work agent satisfies

$$t(1) = \sum_{j=1}^{\sum_{i=1}^{m-1}\beta^i+1} Tg(j) + Ts_1 + Te_1 + Tb_1 + Tr_1. \tag{14}$$

Similarly, the round trip time of the k-th generated work agent satisfies

$$t(k) = \sum_{j=1}^{\sum_{i=1}^{m-1}\beta^i+k} Tg(j) + Ts_k + Te_k + Tb_k + Tr_k. \tag{15}$$

Since in this approach, each agent will visit only one node/work place and then return back to the client agent, we simplify the expression of the round trip time of an agent by a notation Λ_i such that $\Lambda_i = Ts_i + Te_i + Tb_i + Tr_i$. Let $\lambda(t)$ be the pdf of Λ_i and Λ^* be the Laplace transform of Λ_i. Since Ts_i, Te_i, Tb_i, and Tb_i are independent variables, the pdf of Λ_i, $\lambda(t)$, can be expressed as the convolution of the pdf of Ts_i, Te_i, Tb_i, and Tr_i, i.e., $\lambda(t) = s(t) * e(t) * b(t) * r(t)$ and the Laplace transform of Λ_i, Λ^*, satisfies $\Lambda^*(s) = S^*(s)\cdot E^*(s)\cdot B^*(s)\cdot R^*(s)$. Thus, the round trip time of the k-th generated work agent can be simplified as

$$\begin{aligned}t(k) &= \sum_{j=1}^{\sum_{i=1}^{m-1}\beta^i+k} Tg(j) + \Lambda_i\\&= D_{HQR} + \sum_{j=1}^{k} Tg\left(\sum_{i=1}^{m-1}\beta^i + j\right) + \Lambda_i.\end{aligned} \tag{16}$$

Consequently, the round trip time of the HQR approach, denoted by T_{HQR}, satisfies

$$T_{HQR} = \max_{1\le k\le \beta^m}\{t(k)\}. \tag{17}$$

Utilizing the analysis on $\Omega^*(s)$ in Section V-A and $\Phi^*(s)$ in Section V-B, we have

$$\begin{aligned}D^*_{HQR} &= E\left(e^{-s\sum_{j=1}^{\sum_{i=1}^{m-1}\beta^i} Tg(j)}\right)\\&= [G^*(s)]^{\sum_{j=1}^{\sum_{i=1}^{m-1}\beta^i}} = [G^*(s)]^{\frac{\beta^m-\beta}{\beta-1}};\\E&\left(e^{-s\sum_{l=1}^{k} Tg\left(\sum_{i=1}^{m-1}\beta^i+l\right)}\right)\\&= \Phi^*(s) = \rho G^*(s)\cdot\frac{1-[(1-\rho)G^*(s)]^N}{1-(1-\rho)G^*(s)}\end{aligned}$$

due to the fact that the distribution of $Tg\left(\sum_{i=1}^{m-1}\beta^i + l\right)$ is the same as $Tg(l)$. Therefore, let HQR^* be the Laplace transform of $t(k)$, the distribution of the round trip time of agents in the HQR approach satisfies

$$HQR^*(s) = E(e^{-st(k)}) = D^*_{HQR}(s)\cdot\Phi^*(s)\cdot\Lambda^*(s) \tag{18}$$

F. EHQR

Firstly, we plot the generation tree of the EHQR approach for a better understanding of the generation process of the EHQR approach. From Fig. 8 we can see that there are $N = \beta^m$ agents generated in total and each of the generated agents, including the clone agents, will be dispatched to a node/workplace for completing the user task. The time for generating all $N = \beta^m$ agents is $\sum_{i=1}^{N} Tg(i)$. Specially, the generation of the k-th generated agent, denoted by $x(k)$, can be calculated by $x(k) = \lceil\log_\beta k\rceil$. The sequence number of

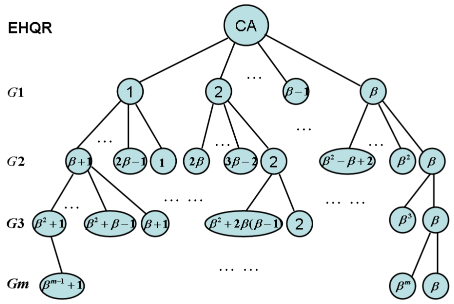

Fig. 8. The generation tree of the EHQR approach

the k-th generated agent on the $x(k)$-th generation, denoted by $y(k)$, satisfies

$$y(k)=\begin{cases} k & 1\le k\le \beta; \\ k-\beta^{x(k)-1} & \beta<k\le\beta^m. \end{cases}$$

That is, the k-the generated agent is the $y(k)$-th generated on the $x(k)$-th generation. Then, the exact site of the k-th agent on the $x(k)$-th generation satisfies

$$Y(k)=\begin{cases} k & x(k)=1; \\ y(k)+\left\lfloor \frac{k-\beta^{x(k)-1}}{\beta-1}\right\rfloor & x(k)>1. \end{cases}$$

That is, the k-th agent is the $Y(k)$-th agent on the $x(k)$-th generation and it will be the $(Y(k)\cdot\beta)$-th agent on the $(x(k)+1)$-th generation. Finally, the k-th agent will appears as the $\left(Y(k)\cdot\beta^{m-x(k)}\right)$-th agent on the m-th generation, i.e., the last generation of the generation tree and all agents will departure from the service server after generation of finish their generating task. Since in each β agents, there will be one agent came from an upper generation which needn't any generating time, the departure sequence number of the k-th agent on the final generation is

$$N_{seq}(k)=Y(k)\beta^{m-x(k)}-\text{int}\left(\frac{Y(k)\beta^{m-x(k)}}{\beta}\right). \tag{19}$$

Therefore, the dispatched time of the k-th generated agent, $t_{disp}(k)$, satisfies

$$\begin{aligned} t_{disp}(k) &= \sum_{i=1}^{\beta^{m-1}+N_{seq}(k)} Tg(i) \\ &= \sum_{i=1}^{\beta^{m-1}} Tg(i)+\sum_{i=1}^{N_{seq}(k)} Tg\left(\beta^{m-1}+j\right). \end{aligned}$$

Consequently, from the execution process of the EHQR approach (see Fig. 9), it is easy to see that the round trip time of the k-th generated agent satisfies

$$t(k)=t_{disp}(k)+\Lambda_k \tag{20}$$

where $\Lambda_i=Ts_i+Te_i+Tb_i+Tr_i$. The round trip time of EHQR, denoted by T_{EHQR}, satisfies

$$T_{EHQR}=\max_{1\le k\le N} t(k). \tag{21}$$

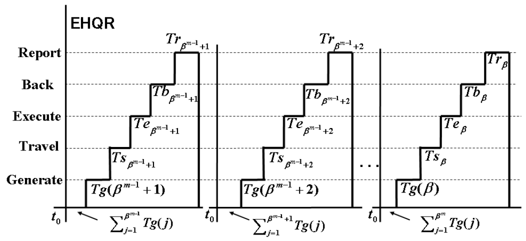

Fig. 9. The execution process of the EHQR approach

Similar to the analysis in Section V-E, the Laplace transform of $t(k)$, denoted by $EHQR^*$, satisfies

$$EHQR^*(s)=\left[G^*(s)\right]^{N/\beta}\cdot\Phi^*(s)\cdot\Lambda^*(s) \tag{22}$$

VI. CONCLUSION

For a better understanding to the existing approaches of mobile agent-based information retrieval and further improvement of these approaches, we extended the study in [14] and [22] and provided the exact distribution of the round trip time of several existing approaches. In our study, the process of mobile agents to execute an user query is divided into a number of stages according to the different characteristics and requirements of each stage. This division enables our analysis on the round trip time of an agent and of an approach. Based on our analytical results, the round trip time is decided by the time consumption of each stage, and the time consumption of each stage is mainly decided by the user task, the network connecting statement, the bandwidth and transmission delay, the size of mobile agents, and the dispatching approach of mobile agents. Fig. 10 and Fig. 11 show the comparison results on the round trip times of analyzed approaches in a randomly generated network topology with 5000 nodes where β is set to be 4. Our results reveal the insight of mobile agent-based information retrieval approaches and our analytical method provides a useful tool for further research to information retrieval.

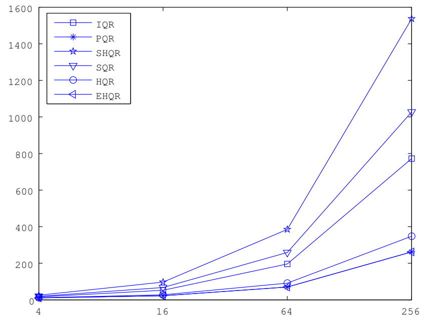

Fig. 10. Comparison of the round trip time as a function on the number of destination servers when the size of a sub-task/report is 50KB.

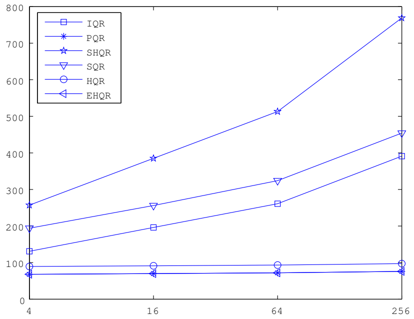

Fig. 11. Comparison of the round trip time as a function on the size of a sub-task/report when the number of destination servers is set to be 64.

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