Analysis of Mobile Agents' Fault-Tolerant Behavior

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1 Introduction

The dramatic popularity of the Internet has created numerous opportunities, such as distance learning, electronic commerce, and multimedia communication. At the same time, a number of challenges come into being, such as in organizing information and facilitating its efficient retrieval. From the network perspective, there will be additional challenges and problems in meeting bandwidth requirements and network management. The promising of reduced network load (or decreased network latency) makes mobile agent technology an attractive focus for system design.

As defined in [3], mobile agents are software entities that can migrate across the network (hence mobile) representing users in various tasks (hence agents). The kernel of this technology is to move the computation to the data rather than the data to the computation [2]. When a large amount of data are stored at remote hosts, mobile agents allow users to package their requests, dispatch it to a destination host where interactions take place locally, and return with a comparatively small result. Furthermore, mobile agents can sense their execution environment and react autonomously to changes. These merits often motivates programmers to use mobile agent technology in distributed system design. Successful examples of mobile agent systems include Aglets, Voyager, Agent Tcl, Tacoma, Knowbots, and Telescript.

As mobile agents are the medium for implementing various executions, their behaviors are paramount for the network performance. Clearly, one of the pivotal tasks ahead, if mobile agents are to have significant impact, is to explore quantitative studies on the behaviors of mobile agents, which can reveal the inherence of the mobile agent approach and ultimately guide future researches. This issue, unlike that of system design using mobile agents, has not yet been adequately addressed so far.

In this paper, we propose a fault-tolerant model for mobile agents executing in large distributed networks and analyze the life expectancy of mobile agents in our model. The key idea is the use of stochastic regularities of mobile agents' behavior – all the mobile agents in the network as a whole can be stochastically characterized though a single mobile agent may act randomly. In effect, our analytical results reveal new theoretical insights into the statistical behaviors of mobile agents and provide useful tools for effectively managing mobile agents in large networks.

2 The Fault-Tolerant Execution Model

Our execution model is built on a mobile agent-based network as stated in the previous section. For a large network with a large number of nodes, suppose that agents can be generated from every node on networks, and each node on networks provide mobile agents an execution environment. Initially, there are a pile of tasks generated in the network. Then a pile of agents, whose number is equal to that of the tasks, is generated. Each task is carried by an agent. Those agents wander among nodes in the network to search for their destinations. At each node, agents have local information about the error rate of each adjoin link, but they do not have global knowledge on the state of the network. The sequence of nodes visited by the agent compose the agent's itinerary. Agents'

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0-7695-2101-0/04 $ 20.00 IEEE

itineraries can be either static or dynamic. A static itinerary is entirely defined at the source and does not change during the agent travelling; whereas a dynamic itinerary is subject to modifications by the agent during its execution [4].

Since mobile agents are capable of sensing the execution environment and reacting autonomously to changes [2], a dynamic itinerary is adopted in this context, i.e., an agent decides its itinerary on the fly. Let h_i denote the ith host in the itinerary and $NB(i)$ denote the set consisted by the neighbor hosts of h_i. The number of neighbor hosts in set $NB(i)$ is denoted by d_i, i.e., the connectivity degree of host h_i. Once an agent reaches a node, say h_i, it executes locally. After completed its execution, the agent selects a node from $NB(i)$ to move to. Suppose that there is an error rate for each candidate direction, mobile agents will prefer a route with a low error rate to shun failures. The selected node in $NB(i)$ is denoted by h_{i+1}^1. In case that a failure takes place on h_{i+1}^1, the agent is blocked and has to return to the previous host h_i. Then, it will reselect another neighbor host from $NB(i)$ and move to. The jth selected host in $NB(i)$ is denoted by h_{i+1}^j. An agent is supposed will not jump to the same neighbor host twice since in a general way a failure host will not recover in a very short time. This process will continue until the agent successfully enters a host and completes its execution there. The final visited host in $NB(i)$ is denoted by h_{i+1}. In case that all the d_i neighbor hosts are out of work, the agent dies. In this context, we say a host is down if it is out of work; otherwise, it is up. Furthermore, if host h_i subjects to a failure when the agent moves to a down host in $NB(i)$, the agent is also lost.

3 Life Expectancy

In an asynchronous distributed system, e.g., the Internet, there are no bounds on transmission delays of messages or no relative process speeds. Therefore, when a mobile agent is blocked by reason of a failure in an asynchronous distributed system, the agent owner cannot correctly determine whether the agent has failed or is merely slow [1]. Therefore, the reliability of agents' execution is paramount for measuring the network performance. We treat this problem as a probability problem using the behavior of mobile agents to build a probability estimation on the number of hosts an agent can visit. Let v_i denote the number of hosts selected by an agent in set $NB(i)$ and X_i^j be a 0 or 1 valued random variable with probability $p = P(X_i^j = 1)$ for $i = 1, 2, \cdots$ and $j = 1, 2, \cdots, d_i$. The event $\{X_i^j = 1\}$ indicates that the agent can not enter the host h_i^j in set $NB(i)$, then the parameter p measures the incidence of failure in the network.

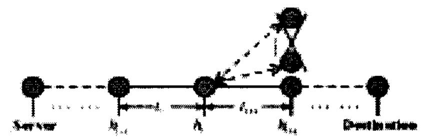

Figure 1: Life expectancy of a Mobile Agent

Theorem 1 *The probability that the agent will enter the jth selected host in $NB(i)$, denoted by $P\{v_i = j\}$, satisfies,*

$$P\{v_i = j\} = x^{j-1}(1-p) \qquad (1)$$

where $x = p(1-p)$.

Proof Since the event $\{v_i = j\}$ is equivalent to the event $\{X_i^1 = 1, X_i^0 = 0, X_i^2 = 1, \cdots, X_i^0 = 0, X_i^j = 0\}$, where $\{X_i^1 = 0\}$ indicates the event that the host h_i is up, the probability $P\{v_i = j\}$ can be evaluated as follows

$$\begin{aligned} P\{v_i = j\} &= P\{\{X_i^1 = 1, X_i^0 = 0, X_i^2 = 1, \\ &\qquad \cdots, X_i^0 = 0, X_i^j = 0\}\} \\ &= P\{X_i^1 = 1\}P\{X_i^0 = 0\}P\{X_i^2 = 1\} \\ &\qquad \cdots P\{X_i^0 = 0\}P\{X_i^j = 0\} \end{aligned}$$

due to the fact that whether a machine will fail or not is an independent even to other machines in the network. Thus, it is easy to see that

$$P\{v_i = j\} = [p(1-p)]^{j-1}(1-p)$$

since $P\{x_i^k = 1\} = p$ for $k = 1, 2, \cdots, d_i$. Hence, the theorem is proven.

From theorem 1, the probability that the agent will enter one of the hosts in $NB(i)$ equals to $\sum_{j=1}^{d_i} P\{v_i = j\} = p(1 - x^{d_i})/(1-x)$. It is easy to see that the success probability of each step (an agent can successfully enter another host from the current host) is decided by two parameters: the error rate of each host and

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the number of neighbor hosts of the current host. It is in direct proportion to the error rate increase and in inverse proportion to the number of neighbor hosts increase, which is coincident with intuition. Regarding the average number of selected hosts in set $NB(i)$, we have the following theorem.

Theorem 2 *The average number of selected hosts in set $NB(i)$, denoted by $E[v_i]$, satisfies*

$$E[v_i] = \frac{1 - x^{d_i}}{1 - x}$$

where $x = p(1 - p)$.

Proof For $j = 1, \cdots, d_i - 1$, the probability that the agent will enter the jth selected host is $[p(1 - p)]^{j-1}(1 - p)$ and the probability that the agent will die then is $[p(1 - p)]^{j-1}p^2$ since both the jth selected host and host h_i are down. Thus, the total probability that an agent will select exactly j hosts in the set $NB(i)$ is $[p(1 - p)]^{j-1}[1 - p(1 - p)]$, the sum of these two probabilities. When $j = d_i$, the probability that the agent will enter the last selected host is $[p(1 - p)]^{d_i-1}(1 - p)$. If the agent can not enter the d_ith selected host, it will die no matter the host h_i is up or down, i.e., the corresponding probability that the agent will die is $[p(1-p)]^{j-1}p$. Similarly, the probability that an agent will select all the d_i hosts in set $NB(i)$ equals to $[p(1 - p)]^{d_i-1}$. Therefore, denoted $p(1 - p)$ by x, the average number of hosts the agent will selected can be expressed as

$$\begin{aligned} E[v_i] &= \sum_{j=1}^{d_i-1} j(1-x)x^{j-1} + d_i x^{d_i-1} \\ &= \frac{1 - x^{d_i} - d_i x^{d_i-1}(1-x)}{1-x} + d_i x^{d_i-1} \\ &= \frac{1 - x^{d_i}}{1 - x} \end{aligned}$$

Hence, the theorem is proven. □ □

From Figure 2, it is easy to see that the average number of hosts an agent will selected in a neighbor host set is an increase function on both error rate p and the number of neighboring hosts d_i. Furthermore, if the time cost for passing a link approximates to a constant c, we have the following theorem to estimate the average time consumption for mobile agents entering a host in set $NB(i)$.

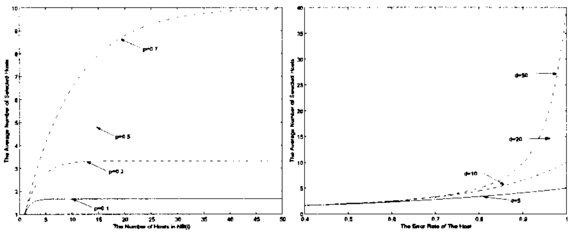

Figure 2: The Changes of $E[v_i]$ over p and d_i

Theorem 3 *The average time consumption for an agent entering a host in $NB(i)$, denoted by $E[t_i]$, satisfies*

$$E[t_i] = c(1 + p)\frac{1 - x^{d_i}}{1 - x}$$

Proof By the assumption that the time consumption for an agent passing a link is c, the time consumption of the period that an agent moves to a down host and returns to the previous host equals to $2c$. As a result, the time consumption that the agent enters the jth selected host is $2(j - 1)c$ and the time consumption that the agent dies then is $2jc$. Consider about the corresponding probabilities analyzed in the proof of Theorem 4, the average time consumption for an agent successfully enters a host in set $NB(i)$ equals to

$$\begin{aligned} E[t_i] &= \sum_{j=1}^{d_i-1} (2j-1)c[p(1-p)]^{j-1}(1-p) \\ &\quad + \sum_{j=1}^{d_i-1} 2jc[p(1-p)]^{j-1}p^2 \\ &\quad + (2d_i - 1)c[p(1-p)]^{d_i-1}(1-p) \\ &\quad + 2d_i c[p(1-p)]^{j-1}p \\ &= \sum_{j=1}^{d_i-1} 2jcx^{j-1}(1-x) \\ &\quad - \sum_{j=1}^{d_i} c(1-p)x^{j-1} + 2cd_i x^{d_i-1} \\ &= c(1+p)\frac{1 - x^{d_i}}{1 - x} \end{aligned}$$

Hence, the theorem is proven. □

Especially, the average time consumption is $E[t_i] = (1 + p)c$ when $d_i = 1$, and it is $E[t_i] = (1 + 2p - p^3)c$.

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From theorem 3, the probability that an agent will blocked in host h_i equals to $1 - [p(1 - x^{d_i})/(1 - x)]$. Therefore, denoted $(1 - x^{d_i})/(1 - x)$ by y_i, the probability that an agent will visit exactly k hosts along its itinerary including the server equals to $P\{v = k\} = (1 - py_i)\prod_{i=1}^{k-1} py_i$, and the average number of hosts visited by the agent equals to $E[v] = \sum_{k=1}^{\infty} k(1 - py_i)\prod_{i=1}^{k-1} py_i$. In particular,when the average connectivity of the network, denoted by d, is available, y_i equals to $(1 - x^d)/(1 - x)$ and the average number of hosts visited by the agent satisfies the following equation

$$E[v] = \frac{1 - x}{1 - x - p(1 - x^d)}$$

where v denotes the number of hosts visited. It is easy to see that the average number of hosts visited by the host is decided by the parameters p and d, i.e., the error rate and the connectivity of the network, which is coincide to intuition. Similarly, the average time consumption for an agent enters a host in set $NB(i)$ is

$$E[t] = c(1 + p)\frac{1 - x^d}{1 - x}$$

Thus, the following theorem comes into existence.

Theorem 4 *Agents' life expectancy satisfies*

$$E[L] = \frac{c(1 + p)y}{1 - py}$$

where p is the error rate, x equals to $p(1 - p)$, and y equals to $(1 - x^d)/(1 - x)$.

Proof Due to the fact $L = \sum_{i=1}^{v} t_i$ (see Figure 2), we have

$$\begin{aligned} E[L] &= E\left[\sum_{i=1}^{v} t_i\right] = E\left[E\left(\sum_{i=1}^{v} t_i \middle| v\right)\right] \\ &= E(v)E(t) \end{aligned}$$

Then, from the results of $E(v)$ and $E(t_i)$ respectively, we have

$$\begin{aligned} E[L] &= \frac{1 - x}{1 - x - p(1 - x^d)} \cdot \frac{1 - x^d}{1 - x} c(1 + p) \\ &= c(1 + p)\frac{1 - x^d}{1 - x - p(1 - x^d)} \end{aligned}$$

Hence, the theorem is proven. □

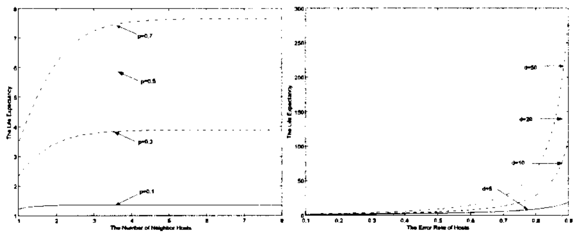

Figure 3: The Changes of $E[L]$ over p and d

Figure 3 shows the changes of agents' average life expectancy. It is easy to see that the average life expectancy is an increase function on both the error rate and the network connectivity. In particular, it is a convex function on the parameter d and a concave function on the parameter p.

4 Conclusion Remarks

In this paper, we proposed a fault-tolerant execution model of mobile agents and analyzed the life expectancy (including the average time consuming of mobile agents between two hosts, the average number of hosts agents will visit, and the agents' life expectancy). All the results show that the agents' behavior is influenced by hosts' error rate and network connectivity. Thus, the behavior of mobile agents can be effectively managed according to network characteristics.

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