Mobile Agent Modeling

Seong Hwan Kim and Thomas G. Robertazzi
Department of Electrical and Computer Engr.
University at Stony Brook,
Stony Brook, NY 11794
e-mail:
shkim@ece.sunysb.edu, tom@ece.sunysb.edu

Abstract — **Mobile agents have been proposed for collecting and processing network management information in the Internet or other networks and for delegating network control. This paper presents canonical stochastic models of mobile agent behavior. This includes modeling of agent dwell time, agent lifespan based on cloning scenarios, interreport processes, report interarrival processes and the minimum number of mobile agents guaranteeing Quality of Service levels.**

I. Introduction

Software mobility allows self-executable programs to move around a network, and collect information on the network [12]. Specifically, such mobile agents are useful for network status monitoring, network traffic balancing and distributed control for network management purposes. However, the analytical modeling and analysis of mobile agent behavior is in its infancy. A recent *DARPA* call for proposals on this topic is evidence of the necessity for such research. This paper develops canonical stochastic models to fill this need.

Mobile agents can be used for collecting (i.e. data mining [12]) and processing network management [6] [13][14] information as well as delegating network control in the Internet or intranet. Mobile agents can travel around a network based on a specific routing plan [10], and transport mobile agents' state, codes and data [2] to perform the functions listed above.

While a mobile agent travels around the network, it may report network status or process results. The information reporting mechanism is an important factor to decide the performance of mobile agents as well as networks. In [14], network status monitoring frequency by mobile agents is divided into a demand and a continuous case. However, in our study, the reporting mechanism depends on the mobile agent functions. Hence, we can provide plausible discrete time event models to analyze the mobilities.

This paper presents several statistical and mathematical models of mobile agent, and categorizes mobile agent functions. Included in these statistical models are dwell time in hosts, average life span, cloning, the interreporting process, the reports arrival process, and the minimum number of mobile agents guaranteeing a quality of service level. An understanding of these issues is necessary for designing optimal mobile agents codes, and network parameters (such as host speed and network capacity). Life span modeling using several distributions is also considered. In [10][17], only the time to complete a task is considered for life span. Here we consider the detailed processing states and find the expectation value of an agent's life span. This paper also examines killing mobile agents [4] and the optimal (minimum) number of mobile agents guaranteeing Quality of Service levels.

This paper is organized as follows. Section II describes mobile agent functions. Section III describes dwell time distributions. Section IV discusses the life spans of mobile agents and section V examines the interreport process of a mobile agent. Section VI describes the report arrival processes and section VII discusses an optimization problem involving the number of mobile agents relating to QoS and presents a plausible example with negative exponential service times. The conclusion is presented in section VIII.

II. Mobile Agent Functions

This paper categorizes mobile agent function into three major groups which are a secretary function [2], a network management function [12] and a maintenance function [15]. A secretary function (user level) allows a user/customer to command a mobile agent that does a specific job within a given time and with the best result or performance. A network management function (network level) lets a mobile agent travel around the network to collect network information, or allows a mobile agent to be delegated responsibility by the network controller. Finally, a maintenance function (connection level) helps to maintain connection/call and data transport.

As mentioned before, the information reporting mechanism is an important factor in deciding the performance of mobile agents as well as the networks. The reporting characteristics (i.e. interreporting) analysis of mobile agents can be divided into two categories depending on the number of reports to a central node or control node. The two categories are persistent reporting and intermittent reporting. Persistent reporting means that a mobile agent reports from every node it visits. Examples of persistent reporting include the network management function and the maintenance function. For the case of the network management function, a mobile agent travels around the network, collects information and reports the network's current state successively. The maintenance function has to track an object's movement (assumed agile mobility) involving a cellular communication customer or data files, thus causing many reports to be generated. In intermittent reporting, a mobile agent reports from some of the nodes it visits. The secretary function is an example of intermittent reporting. The secretary function may reside in a host or a market place which is composed of many hosts, and a mobile agent reports when it achieves its goal. Thus, the number of reports for the network management function and the maintenance function is generally larger than for the secretary function. Fig. 1 depicts the difference between three mobile agent function levels. The details of network, connection and user level are explained in [21].

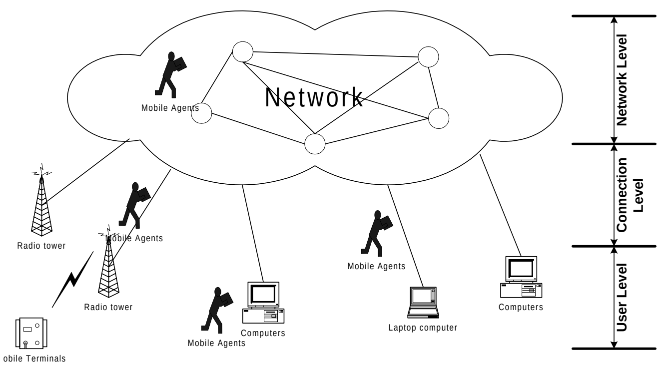

Figure 1: Different mobile agent levels of functions.

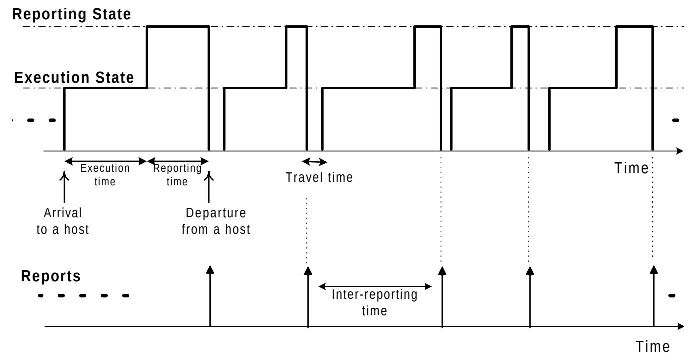

Figure 2: Mobile agent state transition diagram.

III. Dwell Time Distribution

One or more mobile agents are inserted into a network from a central host for management purpose and each resides in a host for a period of the time. The dwell time in a host is an important parameter that decides information reporting behavior. During the residence of mobile agents that travel from host to host, mobile agents make measurements and report results back to the central host. If a mobile agent arrives at a host, it is assumed that there is no queueing delay because every mobile agent has the highest priority and it will be served without delay. The processor in a host is assumed to be preemptive for mobile agents.

The dwell (or residing) time of a mobile agent in a host, D is,

$$D = \text{Execution time} + \text{Reporting time} \quad (1)$$

One cycle time, C is,

$$C = D + \text{Travel (or Propagation) time to next host} \quad (2)$$

Fig. 2 illustrates the cycle of execution time, reporting time and travel (or propagation) time to an adjacent host. Dwell (or residing) time depends on the network host status, specifically, congestion, job load in a host and processor speed, etc. Here, the time periods are assumed to be independent of each other.

Reporting time contains such latency as execution suspension, data serialization, encoding [2], report generation to the source and report propagation delay and an acknowledgment delay from the source. The report round trip propagation delay may be relatively longer than the mobile agent travel (or hop) time since a mobile agent may travel far from the source. That is, the distance between adjacent hosts is shorter than the distance between a mobile agent and the source (or center). The execution time probability density function (pdf) is given by *e(t),* the reporting time pdf is given by $r(t)$, the travel time pdf is given by $v(t)$ and the dwell time pdf is given by *d(t)*. The sum of two independent random variables from Eq. (1) results in a convolution of the two probability density function (pdf) *e(t)* and *r(t)*.

$$d(t) = e(t) * r(t) \quad (3)$$

After taking the Laplace transform of dwell time $d(t)$,

$$\begin{aligned} D^*(s) &= E[e^{-st}] \\ &= E^*(s) \cdot R^*(s) \quad (4) \end{aligned}$$

While, the cycle time pdf, $c(t)$, is,

$$\begin{aligned} c(t) &= d(t) * v(t) \\ &= e(t) * r(t) * v(t) \quad (5) \end{aligned}$$

Also, the Laplace transform of $c(t)$ is,

$$\begin{aligned} C^*(s) &= D^*(s) \cdot V^*(s) \\ &= E^*(s) \cdot R^*(s) \cdot V^*(s) \quad (6) \end{aligned}$$

IV. Life span of a Mobile Agent

There are two situations in killing (or discarding) mobile agents. One situation is that the source can discard returning mobile agents, the other situation is that an arbitrary host can discard mobile agents. These two rules can be used in the same network. Several mobile agent discarding scenarios are proposed in the following.

Scenario 1 A host discards outdated mobile agents and it reports this to the source.

Scenario 2 Once a mobile agent completes its job, it will be discarded.

Scenario 3 After k reports, a mobile agent will be discarded. In other words, it is an aging process. [10]

Each scenario may also include reuse of mobile agents. That is, after finishing a job, a mobile agent may be reused after updating mobile agent code. For scenario 3, one can calculate the probability of the k-th report at the n-th hop, $P_n(k)$, when a mobile agent reports intermittently. Assume that a mobile agent reports with independent probability of γ at each host and doesn't report with probability $1-\gamma$. That is,

$$\begin{aligned} P_n(k) &= \Pr[k\text{-th report occurs in } n\text{-th hop}] \\ &= \Pr[k\text{-th report in } n\text{-th hop} \mid \\ &\qquad k\text{-1 reports in } (n\text{-1}) \text{ hops}] \\ &= \Pr[\underbrace{(k-1) \text{ reports in } (n-1) \text{ hops}}_{Event1}, \\ &\qquad \underbrace{\text{another report in } n\text{-th hop}}_{Event2}] \\ &= \binom{n-1}{k-1} \gamma^k (1-\gamma)^{n-k} \qquad n = k, k+1, \cdots \quad (7) \end{aligned}$$

This probability distribution is called the Pascal distribution or the negative binomial distribution.

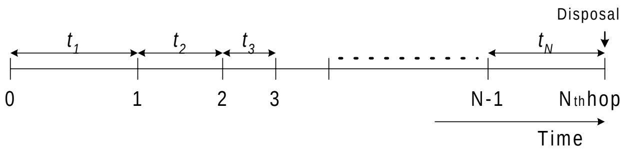

Figure 3: Total life span of a mobile agent.

A mobile agent may clone itself [1][2] when agents experience task overload and capacity overload [18][19]. The life span of mobile agent can vary due to this mobile agent's cloning ability. The analysis of mobile agent life span is divided into two different cases. One is a cloning case and the other is a no cloning case (one can call this a sterile agent case). Intuitively, the no-cloning case has a shorter life span than the cloning case. A mobile agent can generate a mobile agent family that is a group of mobile agents by cloning.

a. Without Cloning (Sterile Case)

The total life span (LS), or life span of a mobile agent, T_L (see Fig. 3) , without cloning is:

$$\begin{aligned} T_L &= t_1 + t_2 + t_3 + \cdots\cdots + t_N \\ &= \sum_{k=1}^{N} t_k \qquad \text{where, N} \geq 1 \end{aligned} \tag{8}$$

Here N is the total number of hosts visited by a mobile agent and t_k indicates one cycle time which consists of the dwell time in the k-th host (i.e. execution time + reporting time) and the travel time of a mobile agent. t_N is different from the other t_k since t_N does not contain travel time due to the mobile agent discard at N-th host. The average life span of a mobile agent is,

$$\begin{aligned} E[T_L] &= E[\sum_{k=1}^{N} t_k] \\ &= E[E[t_k|k=N]] - E[Travel \quad Time] \\ &= E[N]E[t_k] - E[Travel \quad Time] \end{aligned} \tag{9}$$

Here, N and t_k are independent of each other, and t_k represents one cycle time. Let $L^*(s)$ be the Laplace transform of the life span T_L to obtain the distribution of the life span.

$$\begin{aligned} L^*(s) &= E[e^{-sT_L}] \\ &= E[e^{-s(t_1+t_2+t_3+\cdots+t_N)}] \\ &= \sum_{n=1}^{\infty} E[e^{-sT_L}|N=n]\Pr[N=n] \\ &= \sum_{n=1}^{\infty} C^*(s)^{n-1}D^*(s)\Pr[N=n] \end{aligned} \tag{10}$$

Here $C^*(s)$ is the Laplace transform of one cycle time distribution $c(t)$ and $D^*(s)$ is the Laplace transform of dwell time distribution, $d(t)$. If the mobile agent disposal (or discard) probability is p, then the distribution of a mobile agent that is discarded after n-th host visiting and processing (including execution and report time) is,

$$\Pr[\text{Mobile agent keeps traveling for n-1 hops, then disposal}] = (1-p)^{n-1}p \tag{11}$$

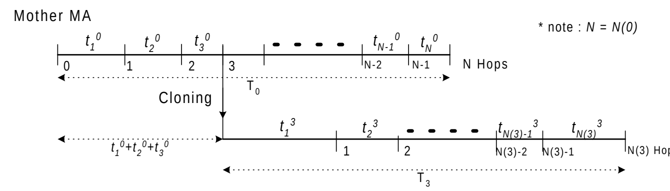

Figure 4: A possible case of one time cloning from a mother mobile agent.

which becomes a geometric distribution. Then

$$L^*(s) = \frac{pD^*(s)}{(1-(1-p)C^*(s))} \tag{12}$$

b. With Cloning

There are two possible cases involving cloning. One is that cloned mobile agents can not clone themselves and the other is that cloned mobile agents can clone. It is assumed that once a mobile agent is cloned, it also travels (or lives) with the same life span expectancy which is $E[T_L]$ from Eq. (9) as the mother mobile agent, and a mobile agent may clone one mobile agent at a time. Here a mother mobile agent is a mobile agent which clones a child mobile agent. First, cloned mobile agents which do not clone themselves are considered.

b.1 No-Cloning of Cloned Mobile Agents Case

It is assumed that a mother mobile agent may clone at each of N-th host it visits during its lifespan. The independent probability of cloning at each host is β. The life span of a mobile agent family is defined as the longest life span of a mobile agent which is generated from a mother/source mobile agent. In other words, the last discarded mobile agent's life span plus the time between the birth of a mother mobile agent and the birth of the latest discarded mobile agent is the life span of a mobile agent family. The expected life span of all cloned mobile agents and a mother mobile agent, $E[T_C]$, is

$$E[T_C] = \sum_{k=1}^{N} E[T_C^k] \cdot P_N(k) \tag{13}$$

where k indicates the total numbers of cloning by the mother mobile agent during its lifespan and $P_N(k)$ is the probability of k times cloning by the mother mobile agent at arbitrary hosts during total N hops.

The life span of all k cloned mobile agents and mother mobile agent, T_C^k, is obtained by (see Fig. 5):

$$T_C^k = \max(T_0, \sum_{i=1}^{n_1} t_i^0 + T_{n_1}, \cdots\cdots, \sum_{i=1}^{n_k} t_i^0 + T_{n_k}) \tag{14}$$

Inside of the maximum parenthesis, there are $k+1$ mobile agents' life spans including that of a mother mobile agent and cloned agents. Here T_i is the life span of a cloned mobile agent which is cloned at the i-th visited host by a mother mobile agent, and T_0 is the life span of the mother mobile agent. The t_i^j is a cycle time of a mobile agent which is cloned at the j-th visited host by a mother mobile agent and i-th visited host by a cloned mobile agent. Here, T_i and t_i^0 for all i are random variables with expectation values of $E[T_L]$ from Eq.

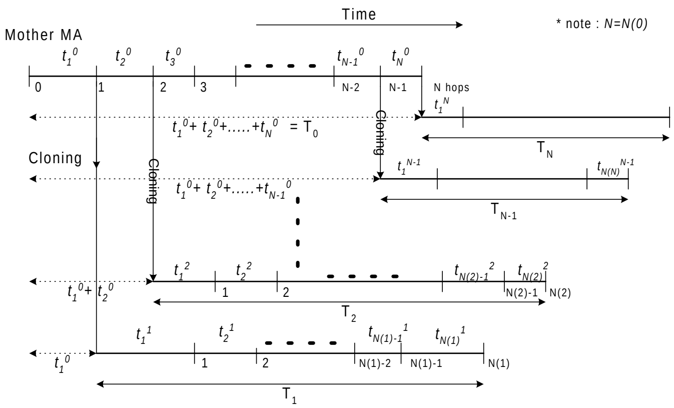

Figure 5: Mobile agents' life spans with N-time clones.

(9) and $E[t]$ (expected value of a cycle time) respectively. The probability of k times cloning is assumed to follow a Bernoulli random distribution and the time process is assumed to be stationary and ergodic.

Fig. 4 depicts the one time cloning case for a mother mobile agent traveling around the network. In Fig. 5, a mother agent life span is the first line and the N times cloned mobile agents' life spans are represented by the other lines. A mother mobile agent can clone until she is discarded. If a mother mobile agent runs up to N hops, then the probability of cloning, P_k, is

$$\begin{aligned} & \Pr[k \text{ times cloning at arbitrary hosts during } N \text{ hops}] \\ = & \begin{pmatrix} N \\ k \end{pmatrix} (1-\beta)^{N-k}\beta^k \end{aligned} \tag{15}$$

where, β=Pr[cloning at an arbitrary host].

The probability of cloning at an arbitrary host is uniformly distributed, then the average life span (LS) of the one time cloning case (see Fig. 4), $E[T_C^1]$,

$$E[T_C^1] = \frac{1}{\begin{pmatrix} N \\ 1 \end{pmatrix}} \sum_{i=1}^{N} \max(T_0, \sum_{j=1}^{i} t_j^0 + T_i) \tag{16}$$

For the k-th cloning case the detailed expression is omitted because of its complexity. For N times cloning,

$$E[T_C^N] = \frac{1}{\begin{pmatrix} N \\ N \end{pmatrix}} \max(T_0, t_1^0+T_1, t_1^0+t_2^0+T_2, \cdots, \sum_{j=1}^{N} t_j^0+T_N) \tag{17}$$

With a few mathematical assumptions, one can find the upper bound of the expected life span of the averaged mobile agents' life spans, $E_A[T_C]$, and the details are presented in [21]. The cloning of cloned mobile agents case also is presented in [21].

b.2 Cloning of cloned mobile agents

If a cloned mobile agent can clone, then the life span of a family of mobile agents will be different. In Fig. 6, a mother mobile agent clones a child mobile agent (level-1 cloning), then the child (or cloned) mobile agent clones a grandchild mobile agent (level-2 cloning). Mathematically it is assumed that

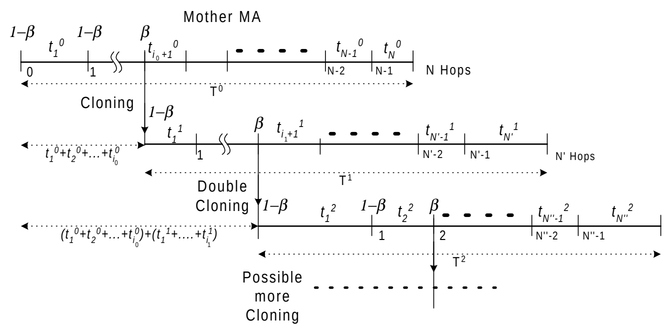

Figure 6: The case of cloning of the cloned mobile agent.

this process can continue up to an infinite number of times (level-∞ cloning).

At first, the life span of 1-th cloned mobile agent (level-1 cloning), T_{CC}^1 where $_{CC}$ indicates the cloning of a clone, is

$$T_{CC}^1 = t_1^0 + t_2^0 + \cdots + t_{i_0}^0 + T^1 \tag{18}$$

and, T_{CC}^2 (for level-2 cloning) is (see Fig. 6),

$$T_{CC}^2 = (t_1^0 + t_2^0 + \cdots + t_{i_0}^0) + (t_1^1 + t_2^1 + \cdots + t_{i_1}^1) + T^2 \tag{19}$$

Here i_k indicates the number of visited hosts by level-k mobile agent. Then, T_{CC}^n (for level-n cloning) is,

$$T_{CC}^n = \sum_{k=0}^{n-1}\sum_{j=1}^{i_k} t_j^k + T^n \tag{20}$$

The expected life span of a given line of descendants consisting of a mother mobile agent and cloned child, grandchild, etc. if there are n-time clones, is,

$$\begin{aligned} E[T_{CC}] &= (1-\beta)^N\beta^0T^0 + (1-\beta)^{i_0}\beta^1T_{CC}^1 + \\ & \quad (1-\beta)^{i_0+i_1}\beta^2T_{CC}^2 + \cdots \\ & \quad +(1-\beta)^{i_0+i_1+\cdots+i_{n-1}}\beta^nT_{CC}^n \\ &= (1-\beta)^N\beta^0T^0 + \sum_{k=0}^{n-1}(1-\beta)^{\sum_{m=0}^{k} i_m} \cdot \beta^{k+1} \\ & \times \left(\sum_{w=0}^{k}\sum_{j=1}^{i_w} t_j^w + T^{k+1} \right) \end{aligned} \tag{21}$$

where, Pr[clone at an arbitrary host]=β. There are several different scenarios of cloning, but further descriptions are omitted.

V. Interreport process of a mobile agent

The interreport time is defined as the time between successive reports which are generated from a remote mobile agent to a source/center. It varies depending on their reporting behaviors which can be divided into persistent reporting, intermittent reporting and stationary agent reporting. The stationary reporting case is not considered in this paper, because an agent stays in one host instead of moving around (our major interest in this paper) the network. The difference between persistent and intermittent reporting is plotted in Fig. 2 and Fig. 7. This difference depends on the mobile agent's functions. The network management function may require an agent to report in every hop (persistent reporting).

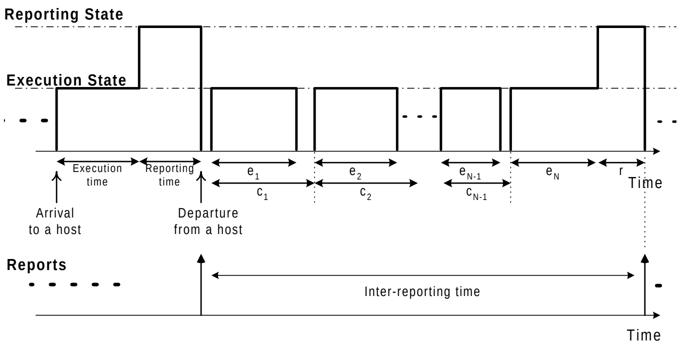

Figure 7: Interreporting time with intermittent reporting.

The maintenance function may or may not require a report in every hop and the secretary function doesn't report in every hop (intermittent reporting).

a. Persistent Reporting
In this case, the interreport time is equal to the one cycle time.

b. Intermittent Reporting
The intermittent interreporting time is longer than the persistent interreporting time because a remote mobile agent may not report in every hop (it may perform only the execution state). Thus, the idle period (i.e. no report period) has to be considered. The expectation value of interreporting time I is,

$$\begin{aligned} E[I] &= E[\text{interreporting time}] \\ &= E[\text{cycle time 1} + \text{cycle time 2} + \cdots + \\ &\quad (\text{execution time N} + \text{reporting time N})] \\ &= E[c_1 + c_2 + \cdots + c_{N-1} + e_N + r] \end{aligned} \tag{22}$$

Let the cycle time's Laplace transform be $C^*(s)$, the execution state's Laplace transform be $E^*(s)$, the reporting state's Laplace transform be $R^*(s)$ and N have an arbitrary distribution. If one sets a probability of report to γ, then the probability of a report occurring in N-th hop after $N-1$ hops without reporting is $(1-\gamma)^{N-1}\gamma$. The intermittent interreport distribution with probability of γ is:

$$\begin{aligned} I^*(s) &= \sum_{n=1}^{\infty} C^*(s)^{n-1} E^*(s) R^*(s) (1-\gamma)^{n-1}\gamma \\ &= \frac{\gamma \cdot E^*(s) R^*(s)}{1-(1-\gamma)C^*(s)} \end{aligned} \tag{23}$$

VI. Report arrival process at source

If the reporting process follows the interreporting process mentioned in the previous section, then the report arrival processes from a group of remote inhomogeneous mobile agents to a source can be obtained by a superposition process. Simply, this section is from the source/center perspective and the previous section is from the mobile agent perspective. In this section, a statistical analysis of the reports arrival processes is presented.

a. Persistent Reporting
The persistent reporting case (see Fig. 2) is considered in this section. The report interarrival time to a source is given by t and t_i is the interreporting time of i-th mobile agent, also the distribution of t_i is assumed as i.i.d.. The report interarrival time from a group of mobile agents to a source, t, can be obtained by:

$$t = \min(t_1, t_2, t_3, \cdots\cdots, t_n) \tag{24}$$

Since each mobile agent has an i.i.d. interreport time distribution, the reports interarrival time cumulative distribution function (cdf) can be obtained by $c(x)$ (which is the one cycle time),

$$\begin{aligned} \Pr[t > x] &= \Pr[t_1 > x, t_2 > x, t_3 > x, \cdots\cdots, t_n > x] \\ &= (1 - \int_0^x c(t_1)dt_1) \cdots\cdots (1 - \int_0^x c(t_n)dt_n) \\ &= (1 - C(x))^n \end{aligned} \tag{25}$$

where $C(x)$ is a cumulative distribution function of $c(x)$.

b. Intermittent Reporting
The reports arrival process is same as the persistent case except for the probability of reporting.

VII. Minimum number of mobile agents

Based on the probability distribution of the report arrival process, the minimum number of mobile agents guaranteeing a QoS (Quality of Service) level can be found using the report interarrival process.

Each cumulative distribution function of persistent and intermittent reporting case is a function of the number of mobile agents, n, and the report interarrival time x. Now it is desired to have the maximum length of x that meets the minimum required interreporting time of a source or a center, R. In other words, $x_{\max} \leq R$. To achieve this inequality, a source can guarantee some level of QoS. Here, the minimum number of mobile agents, $n_{\min}$, is found by satisfying $x_{\max} \leq R$. As the number of mobile agents, n, increases, the report interarrival times become shorter.

a. Persistent reporting
A report interarrival time cdf $F_p(x_{\max}) \approx L$ (for probability $L \to 1, L \neq 1$) can be found as a function of the number of mobile agents, n, using Eq. (25). If the probability $L \to 1$ and the report interarrival time x reaches the maximum interarrival time, then a minimum number of mobile agents can be obtained. For instance, if $L = 0.9999$, then 99.99% of the interarrival time $x_{\max}$ satisfies $x_{\max} \leq R$. To obtain a function of $x_{\max}$ and $n_{\min}$, one can use Eq. (25) and the cumulative distribution function $F_p(x)$,

$$F_p(x) = 1 - (1 - C(x))^n \tag{26}$$

then, the minimum number of mobile agents, $n_{\min}$, satisfying minimum requirement R with probability of L is (set $F(x_{\max}) \approx L$),

$$\begin{aligned} & 1 - (1 - C(x_{\max}))^n = L \\ \Leftrightarrow \quad & n_{\min} = \lim_{L \to 1, L \neq 1} \left\lceil \frac{\ln(1-L)}{\ln(1 - C(R))} \right\rceil \end{aligned} \tag{27}$$

b. Intermittent Reporting

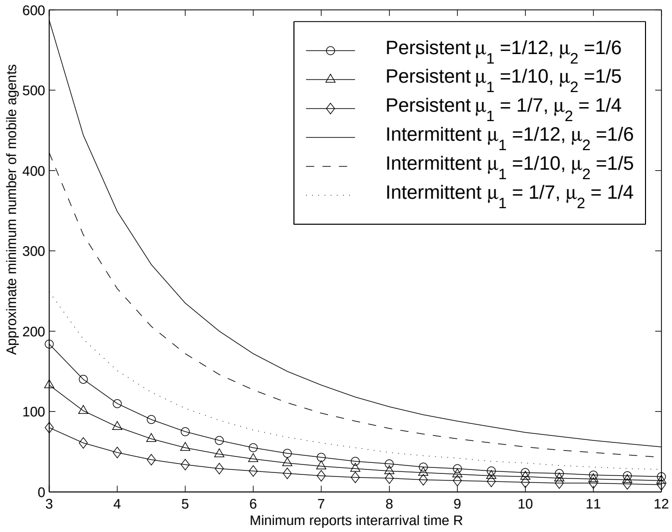

Figure 8: Minimum number of mobile agents satisfying required minimum reports interarrival time R under persistent reporting and intermittent reporting (when $\gamma = 0.3, L = 0.9999$).

The intermittent reporting case also is the same as the persistent reporting case except for the inclusion of the probability of reporting γ.

For the concrete analysis, $e(t)$, $r(t)$, and $v(t)$ are assumed to be negative exponentially distributed with different service rates, then the minimum number of mobile agents versus the required minimum interarrival time is plotted in Fig 8. A smaller R requires more mobile agents. Also, the intermittent reporting case requires more mobile agents than the persistent reporting case because their interreporting time is longer than the persistent case. In order to get a shorter report interarrival time (higher QoS), one needs a good deal of resources (e.g. mobile agents processing time and channel capacity, etc.). For instance, if a source wants to set up a path, it needs to know the most recent network status. In order to get the most recent network status, a selfish source may increase the number of mobile agents it dispatches. However, increasing the number of mobile agents causes network overload or congestion.

VIII. Conclusion

Different categories of mobile agent are modeled in terms of dwell time, life span, interreporting time distribution, report interarrival time distribution from a remote mobile agent to a source/center and the minimum number of mobile agents to guarantee a QoS. The stochastic modeling of mobile agents behavior is in its infancy. The study of mobile agents opens up a new application area rich in problems to researchers in stochastic modeling.

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