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Seong-Hwan Kim and Thomas G. Robertazzi

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Seong-Hwan Kim and Thomas G. Robertazzi,

Department of Electrical and Computer Engineering,

University at Stony Brook,

Stony Brook, NY 11794

Phone : 631-632-8400

FAX : 631-632-8494

Email : shkim@ece.sunysb.edu, tom@ece.sunysb.edu

**Abstract**

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

**Keywords**

Mobile agents, Dwell time, Life span, Interreporting time, Report interarrival process, Quality of Service.

## I. Introduction

Software mobility allows self-executable programs to move around the network, and collect information on the network [13]. Simply, 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 travel around a network, and transport a mobile agents' state, codes and data [3]. For a mobile agent, routing planning has been studied in [11]. For network management [7][14][15], mobile agents are used for "data mining" [13]. In [15], 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.

In this paper, several statistical and mathematical models of mobile agents are developed and mobile agent functions are categorized. 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 considered. In [11][18], only the time to complete a task is considered for life span. Here we consider the detailed processing states and find the expectated value of an agent's life span. This paper also examines killing mobile agents [5] and the optimal (minimum) number of mobile agents.

This paper is organized as follows. Section II describes mobile agents and their 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. The conclusion is presented in section VIII. An example of negative exponential service times is presented in the Appendix.

## II. Mobile Agent Functions

Mobile agent functions can be divided into three major groups which are a secretary function [3], a network management function [13] and a maintenance function [16]. A secretary function (user level) allows a customer to order a mobile agent (MA) to do some job within a given time with the best result or performance. A network management function (network level) lets a MA move around the network to collect network information, or allow a MA to be delegated responsibility by the network controller. Finally, a maintenance function (call level) helps to maintain calls and data transport.

For interreporting process analysis, the reporting characteristics of mobile agents can be divided into two categories depending on the number of reports to a central 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 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 such as 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 some goal. Thus, the number of reports for the network management function and the maintenance function is generally larger

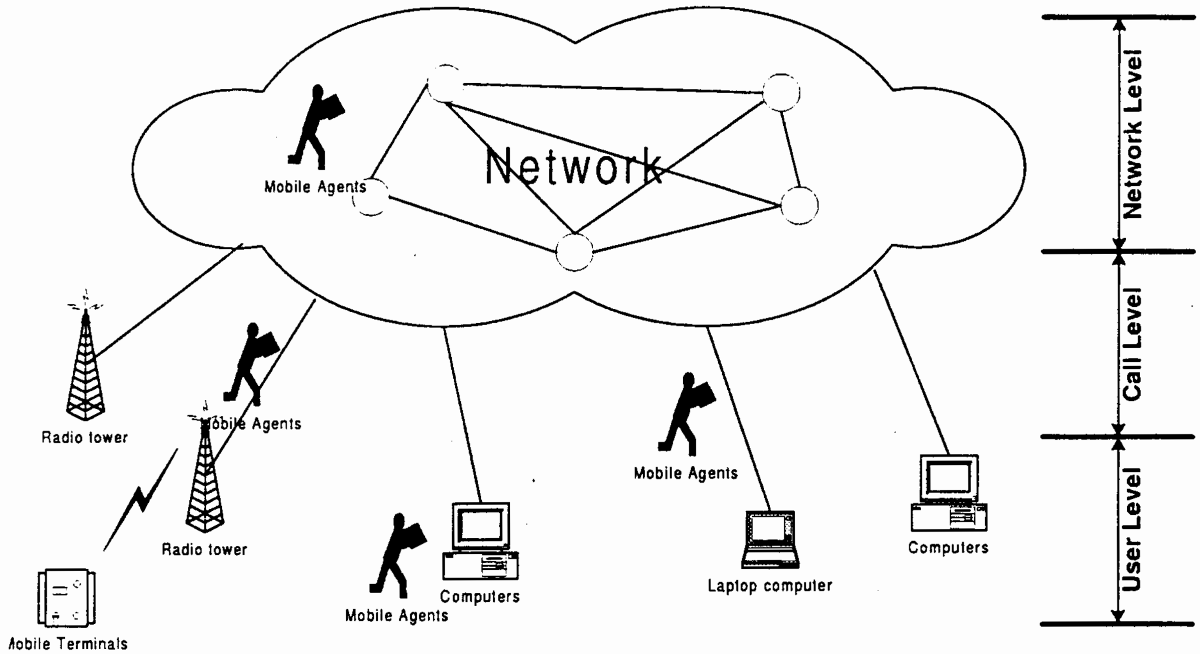


Fig. 1. Three different mobile agent function levels

than for the secretary function. Fig. 1 depicts the difference between three mobile agent function levels. The details of network, call, and user level are explained in [22].

## III. Dwell Time Distribution

One or more mobile agents are inserted into a network from a central host for management purposes. In Aglets [3], inserting mobile agents into a network is called "dispatch." These mobile agents will travel from host to host, making measurements and reporting 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 queueing. The processor in a host is assumed to be preemptive.

The dwell (or residing) time of a mobile agent in a host (see Fig. 2), $D$ is,

$$D = \text{Execution time} + \text{Reporting time} \tag{1}$$

One cycle time, $C$ is,

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

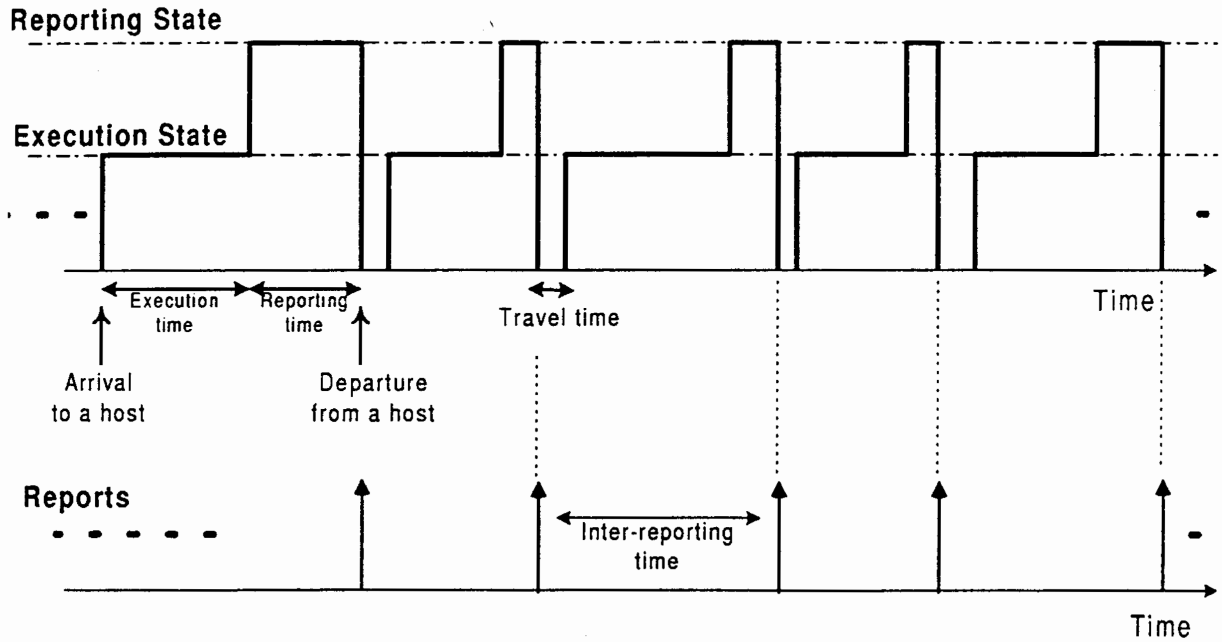


Fig. 2. Mobile agent state transition diagram

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 [3], report generation to the source and report propagation delay and an acknowledgment delay from the source. The report round trip propagation delay maybe relatively larger than the mobile agent travel 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 $r(t)$.

$$d(t) = e(t) * r(t) \tag{3}$$

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

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

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

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

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

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

Here,

$$\begin{aligned} E^*(s) &\equiv \int_0^\infty e(t) e^{-st} dt \\ R^*(s) &\equiv \int_0^\infty r(t) e^{-st} dt \\ V^*(s) &\equiv \int_0^\infty v(t) e^{-st} dt \end{aligned} \tag{7}$$

## IV. Life span of a Mobile Agent

In killing (or discarding) mobile agents, there are two situations. One is that the source can discard returning mobile agents, the other 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** For the secretary function, 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. [11]

Each scenario may also include reuse of mobile agents. That is, after finishing a job (e.g. collecting network information, secretary function), 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 when a mobile agent doesn't report successively (intermittent reporting case). In other words, a mobile agent reports with independent probability of $\gamma$ at each host and doesn't report with probability $1-\gamma$. That is,

$$\begin{aligned} P_n(k) &= \Pr[k\text{-th report occurs in } n\text{-th hop}] \\ &= \Pr[k\text{-th report in } n\text{-th hop} \mid k\text{-1 reports in } (n\text{-}1) \text{ hops}] \\ &= \Pr[\underbrace{(k-1) \text{ reports in } (n-1) \text{ hops}}_{Event1}, \underbrace{\text{another report in } n\text{-th hop}}_{Event2}] \\ &= \begin{pmatrix} n-1 \\ k-1 \end{pmatrix} \gamma^k (1-\gamma)^{n-k}, \quad \text{where } n = k, k+1, \cdots \end{aligned} \tag{8}$$

Here, event 1 and event 2 are independent of each other. This probability distribution is called the Pascal distribution [4] or the negative binomial distribution [2]. The mean and the variance of $P_n(k)$ are,

$$E[N] = \frac{k}{\gamma}, \quad VAR[N] = \frac{k(1-\gamma)}{\gamma^2} \tag{9}$$

There are two different cases for mobile agent life span due to mobile agents' cloning ability. A mobile agent may clone itself [1][3]. Agents may experience task overload and capacity overload [19][20], thus Agent cloning is useful for resolving agent overload. There is a cloning case and a no cloning case (one can call this the sterile agent case). Intuitively, the no cloning case has a shorter life span than the cloning case lifespan for a mobile agent family which is generated by mobile agent clonings.

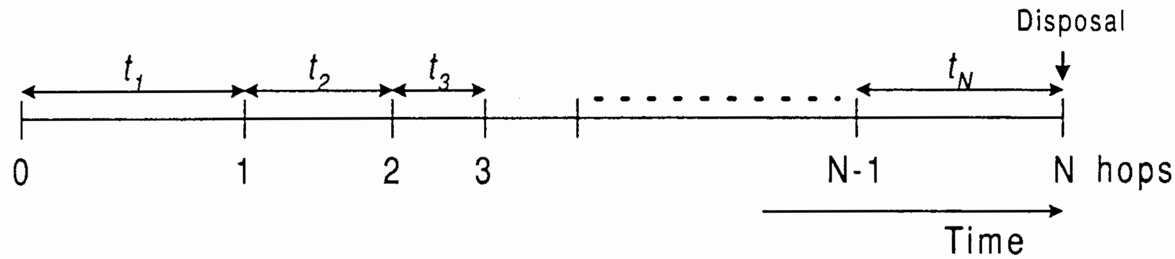


Fig. 3. Total life span of a mobile agent

### 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:

$$\begin{aligned} T_L &= t_1 + t_2 + t_3 + \cdots\cdots + t_N \\ &= \sum_{k=1}^{N} t_k \qquad \text{where, N} \geq 1 \end{aligned} \tag{10}$$

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

$$\begin{aligned} E[T_L] &= E[\sum_{k=1}^{N} t_k] \\ &= E[E[T_L|N]] \\ &= E[N]E[T_L] \end{aligned} \tag{11}$$

Here, $N$ and $T_L$ are independent of each other. In order to obtain the distribution of the life span, let $L^*(s)$ be the Laplace transform of the life span $T_L$.

$$\begin{aligned} L^*(s) &= E[e^{-sT_L}] \\ &= E[e^{-s(t_1+t_2+t_3+\cdots+t_N)}] \\ &= \sum_{n=1}^{\infty} E[e^{-sT_L}|N=n] \Pr[N=n] \\ &= \sum_{n=1}^{\infty} (C^*(s))^{n-1} D^*(s) \Pr[N=n] \end{aligned} \tag{12}$$

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 $p$,

$$\text{Pr[Disposal of a mobile agent]}=p \tag{13}$$

then the distribution of a mobile agent is discarded after $n$-th host visiting and processing (including execution and report time) is,

$$\text{Pr[Mobile agent keeps traveling for n-1 hops, then disposal]}=(1-p)^{n-1}p \tag{14}$$

which becomes a geometric distribution. Then

$$\begin{aligned} L^*(s) &= \sum_{n=1}^{\infty} (C^*(s))^{n-1} D^*(s)(1-p)^{n-1}p \\ &= \frac{pD^*(s)}{(1-(1-p)C^*(s))} \end{aligned} \tag{15}$$

*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 as the mother mobile agent which is $E[T_L]$ from Eq. (11) 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 Cloned mobile agents which do not clone case

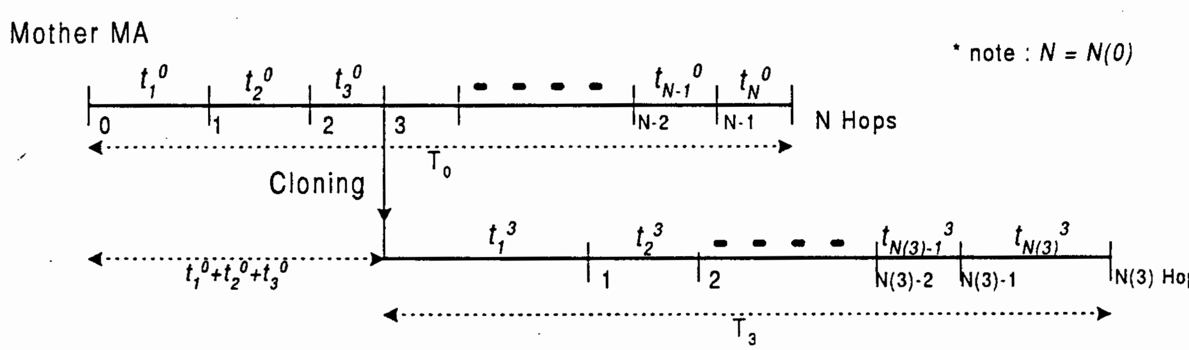


Fig. 4. One possible case of one time cloning from a mother mobile agent

It is assumed that a mother mobile agent may clone at each of $N$ hosts it visits during its lifespan. The independent probability a clone is produced at each host is $\beta$. The life span of a family of mobile agents is defined as the longest life span of a mobile agent which is generated from either a source or a mother 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 mother mobile agent which clones mobile agents, $E[T_C]$, is

$$E[T_C] = \sum_{k=1}^{N} E[T_C^k] \cdot \Pr[k \text{ times cloning at arbitrary hosts in } N \text{ hops}] \tag{16}$$

where $k$ indicates the number of clones. Here "$k$ times cloning" means a mother mobile agent produce exactly $k$ clones during its lifespan. The life span of $k$ cloned mobile agents and mother mobile agent, $T_C^k$, is obtained by (see Fig. 4 and 5)

$$T_C^k = \max(T_0, \sum_{i=1}^{n_1} t_i^0 + T_{n_1}, \cdots\cdots, \sum_{i=1}^{n_k} t_i^0 + T_{n_k}) \tag{17}$$

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. Also $t_i^j$ is the cycle time of a mobile agent which is cloned at the $j$-th visited host by a mother mobile agent and $i$ indicates the $i$-th host visited by a mobile agent. Here, $T_i$ and $t_i^0$ for all $i$ are random variables with expectation values of $E[T_L]$ from Eq. (11) and $E[t]$ (expected value of the 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 MA can clone until she is discarded. If a mother MA runs up to $N$ hops, then the probability of cloning, $P_k$, is

$$\Pr[k \text{ times cloning at arbitrary hosts in } N \text{ hops}] = \begin{pmatrix} N \\ k \end{pmatrix} (1-\beta)^{N-k}\beta^k \tag{18}$$

where, Pr[cloning at an arbitrary host]$=\beta$.

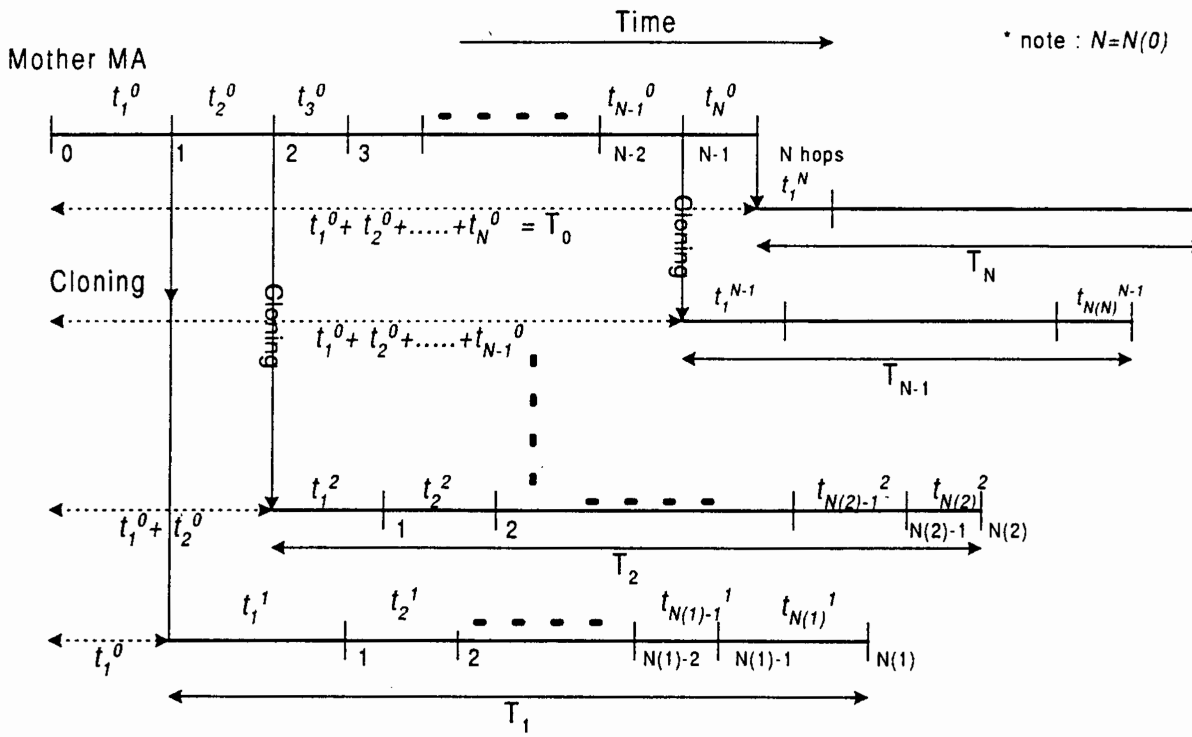


Fig. 5. Mobile agents' life spans with $N$-time clones

First of all, the average life span (LS) of the one time cloning case (see Fig. 4), $E[T_C^1]$,

$$
\begin{aligned}
E[T_C^1] &= \sum_{i=1}^{N} \max(T_0, \sum_{j=1}^{i} t_j^0 + T_i) \Pr[\text{clone at host } i] \\
&= \max(T_0, t_1^0 + T_1) \Pr[\text{clone at host } 1] \\
&\quad + \max(T_0, t_1^0 + t_2^0 + T_2) \Pr[\text{clone at host } 2] + \\
&\quad \cdots + \max(T_0, \sum_{j=1}^{N} t_j^0 + T_N) \Pr[\text{clone at host } N]
\end{aligned} \tag{19}
$$

As mentioned before, the probability of cloning at an arbitrary host is uniformly distributed. If the mother mobile agent produces one clone during its life span, $E[T_C^1]$ is,

$$E[T_C^1] = \frac{1}{\binom{N}{1}} \sum_{i=1}^{N} \max(T_0, \sum_{j=1}^{i} t_j^0 + T_i) \tag{20}$$

If the mother mobile agent produces exactly two agents during its life span, then $E[T_C^2]$

is,

$$\begin{aligned} E[T_C^2] &= \sum_{i=2}^{N} \max(T_0, t_1^0 + T_1, \sum_{j=1}^{i} t_j^0 + T_i) \Pr[\text{clones at host 1 and host } i] \\ &+ \sum_{i=3}^{N} \max(T_0, t_1^0 + t_2^0 + T_2, \sum_{j=1}^{i} t_j^0 + T_i) \Pr[\text{clones at host 2 and host } i] + \\ &\cdots + \max(T_0, \sum_{j=1}^{N-1} t_j^0 + T_{N-1}, \sum_{j=1}^{N} t_j^0 + T_N) \Pr[\text{clones at host } N\text{-}1 \text{ and host } N] \end{aligned} \tag{21}$$

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

$$E[T_C^k] = \frac{1}{\begin{pmatrix} N \\ k \end{pmatrix}} \sum\sum\cdots\sum \max \underbrace{(T_0, \cdots, \sum_{j}^{k'} t_j^0 + T_{k'})}_{(k+1) terms}$$

For $N$ times cloning (see Fig. 5),

$$E[T_C^N] = \frac{1}{\begin{pmatrix} N \\ N \end{pmatrix}} \max(T_0, t_1^0 + T_1, t_1^0 + t_2^0 + T_2, \cdots, \sum_{j=1}^{N} t_j^0 + T_N) \tag{22}$$

Then, the expectation value of life span of cloning, $E[T_C]$, is

$$E[T_C] = \sum_{k=1}^{N} E[T_C^k] \cdot \Pr[k \text{ times cloning at arbitrary hosts in } N \text{ hops}] \tag{23}$$

With some specific mathematical assumptions, one can find the expected life span of the averaged mobile agents' life spans, $E_A[T_C]$. That is using the Bernoulli model of cloning:

$$E_A[T_C] = \sum_{k=1}^{N} \begin{pmatrix} N \\ k \end{pmatrix} (1-\beta)^{N-k} \beta^k \cdot E_A[T_C^k] \tag{24}$$

First, the expected life span of the averaged one time cloned mobile agent case is,

$$\begin{aligned} E_A[T_C^1] &= \frac{1}{\begin{pmatrix} N \\ 1 \end{pmatrix}} \cdot \frac{1}{2}\{T_0 + (t_1^0 + T_1)\} + \frac{1}{\begin{pmatrix} N \\ 1 \end{pmatrix}} \cdot \frac{1}{2}\{T_0 + (t_1^0 + t_2^0 + T_2)\} \\ &+ \cdots + \frac{1}{\begin{pmatrix} N \\ 1 \end{pmatrix}} \cdot \frac{1}{2}\{T_0 + (\sum_{j=1}^{N} t_j^0 + T_N)\} \end{aligned} \tag{25}$$

The first term in $E_A[T_C^1]$ is an average life span of the mother mobile agent and the cloned mobile agent which is cloned at the first host, and this average is weighted by the amount of $1/N$, as the probability of one time cloning at host $i$ is $1/N$ (uniformly distributed). The life span of the cloned mobile agent at host 1 is the sum of the mother MA's dwell time at host 1, $t_1^0$, and the cloned MA's life span. From the assumption, a cloned mobile agent also lives with the same life span expectancy as a mother MA's $E[T_L]$. Eq. (25) can be simplified as,

$$\begin{aligned} E_A[T_C^1] &= \frac{1}{2N}\left\{N \cdot T_0 + \sum_{i=1}^{N}\sum_{j=1}^{i} t_j^0 + \sum_{i=1}^{N} T_i\right\} \\ &= \frac{1}{2N}\left\{N \cdot T_0 + \sum_{i=1}^{N}\left(\sum_{j=1}^{i} t_j^0 + T_i\right)\right\} \end{aligned} \tag{26}$$

For 2 times cloning, $E_A[T_C^2]$, after some simplifications, is,

$$\begin{aligned} E_A[T_C^2] &= \frac{1}{\binom{N}{2}}\frac{1}{3}\left\{\frac{N(N-1)}{2}T_0 + \sum_{i=1}^{N-1}(N-i)\left(\sum_{j=1}^{i} t_j^0 + T_i\right)\right. \\ &\left. + \sum_{i=2}^{N}(i-1)\left(\sum_{j=1}^{i} t_j^0 + T_i\right)\right\} \end{aligned} \tag{27}$$

After the two times cloning, it is algebraically difficult to formulate $E_A[T_C^i]$. However, an upper bound on the expected life span of averaged life spans can be obtained by using the $N$ times cloning case, because the $N$ times cloning case will produce the longest averaged life span. The $E_A[T_C^N]$ can be obtained by summing every cloned MA's life span and the mother MA's life span, then dividing by $(N+1)$ which is the total number of events.

$$\begin{aligned} E_A[T_C^N] &= \frac{1}{N+1}\left(T_0 + (t_1^0 + T_1) + (t_1^0 + t_2^0 + T_2) + \cdots + (\sum_{j=1}^{N} t_j^0 + T_N)\right) \\ &= \frac{1}{N+1}\left(T_0 + \sum_{i=1}^{N}\left(\sum_{j=1}^{i} t_j^0 + T_i\right)\right) \end{aligned} \tag{28}$$

Then, one can obtain the upper bound of the average life span over time,

$$E_A[T_C] = \binom{N}{1}(1-\beta)^{N-1}\beta^1 E_A[T_C^1] + \cdots + \binom{N}{N}(1-\beta)^0\beta^N E_A[T_C^N]$$

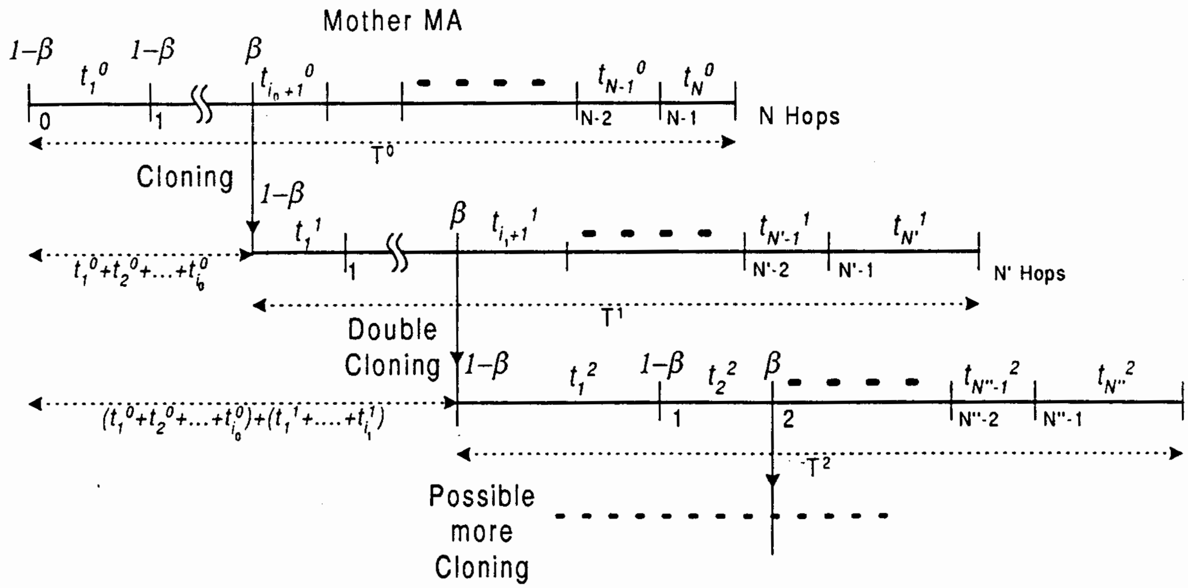


Fig. 6. The case of cloning of the cloned mobile agent

$$
\begin{aligned}
&= \sum_{k=0}^{N} \binom{N}{k} (1-\beta)^{N-k}\beta^{k} E_A[T_C^k] - \binom{N}{0} (1-\beta)^{N}\beta^{0} E_A[T_C^0] \\
&\leq \sum_{k=0}^{N} \binom{N}{k} (1-\beta)^{N-k}\beta^{k} E_A[T_C^N] - \binom{N}{0} (1-\beta)^{N}\beta^{0} E_A[T_C^0] \\
&= E_A[T_C^N] \sum_{k=0}^{N} \binom{N}{k} (1-\beta)^{N-k}\beta^{k} - (1-\beta)^{N}\beta^{0} E[T_L] \\
&= E_A[T_C^N] - (1-\beta)^{N} E[T_L] \qquad (29)
\end{aligned}
$$

Here $E_A[T_C^0]$ is the expected life span for no cloning, that is equal to $E[T_L]$. Thus, the upper bound of the expected value of the averaged life span is,

$$
\begin{aligned}
E_A[T_C] &\leq E_A[T_C^N] - (1-\beta)^{N} E[T_L] \\
&= \frac{1}{N+1}\left(T_0 + \sum_{i=1}^{N}\left(\sum_{j=1}^{i} t_j^0 + T_i\right)\right) - (1-\beta)^{N} E[T_L] \qquad (30)
\end{aligned}
$$

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

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

$$T^1_{CC} = t^0_1 + t^0_2 + \cdots + t^0_{i_0} + T^1 \tag{31}$$

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

$$T^2_{CC} = (t^0_1 + t^0_2 + \cdots + t^0_{i_0}) + (t^1_1 + t^1_2 + \cdots + t^1_{i_1}) + T^2 \tag{32}$$

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

$$T^n_{CC} = \sum_{k=0}^{n-1} \sum_{j=1}^{i_k} t^k_j + T^n \tag{33}$$

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,

$$\begin{aligned} E[T_{CC}] &= (1-\beta)^N \beta^0 T^0 + (1-\beta)^{i_0} \beta^1 T^1_{CC} + (1-\beta)^{i_0+i_1} \beta^2 T^2_{CC} \\ &\quad + \cdots + (1-\beta)^{i_0+i_1+\cdots+i_{n-1}} \beta^n T^n_{CC} \\ &= (1-\beta)^N \beta^0 T^0 + \sum_{k=0}^{n-1} (1-\beta)^{\sum_{m=0}^{k} i_m} \cdot \beta^{k+1} \left( \sum_{w=0}^{k} \sum_{j=1}^{i_w} t^w_j + T^{k+1} \right) \end{aligned} \tag{34}$$

where, Pr[clone at an arbitrary host]=$\beta$. There are several different scenarios of cloning. However, these are also time consuming to transcribe.

## V. Interreport process of a mobile agent

The interreport time is defined as the time between the reports which are generated from a mobile agent. It varies depending on their reporting behaviors which are persistent reporting, intermittent reporting and stationary agent reporting. The stationary reporting case is not considered in this paper, because it stays in one host instead of moving around 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 function. The network management function may require an agent to report in every hop (persistent reporting).

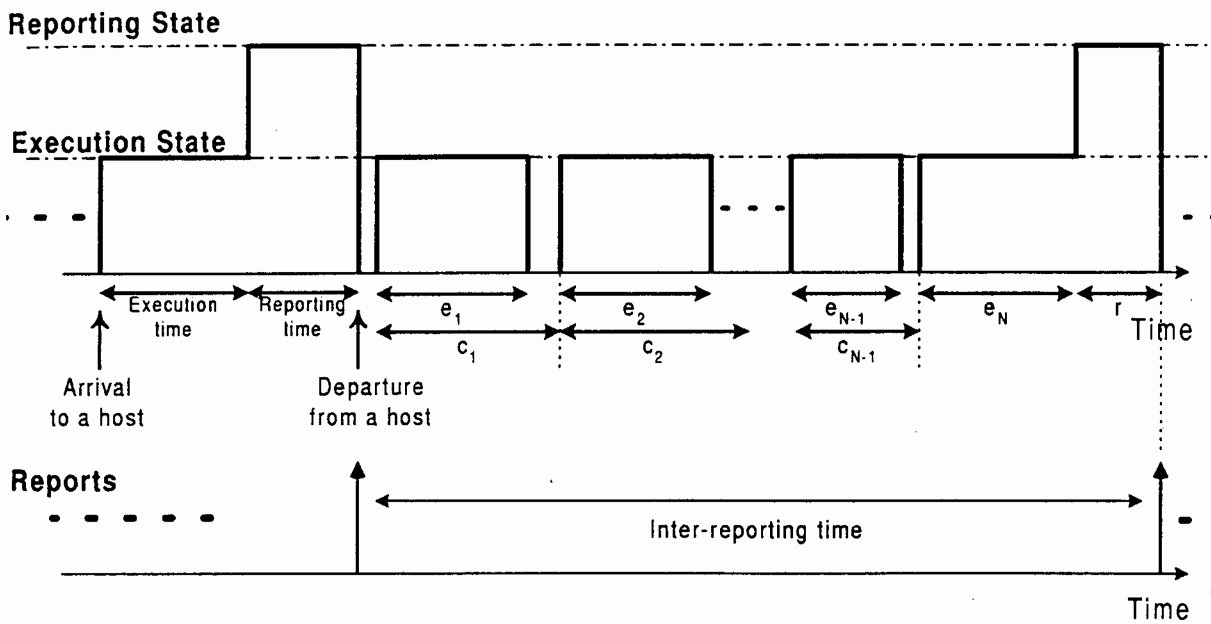


Fig. 7. Interreporting time with intermittent reporting

The maintenance function may or may not require a report every hop and the secretary function doesn't report in every hop (intermittent reporting). So, the interreporting times from a group of inhomogeneous mobile agents to the source may be complex.

### *A. Persistent Reporting*

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

$$E[\text{Interreporting time with persistent reporting}] = E[\text{One cycle time}] \tag{35}$$

### *B. Intermittent Reporting*

The intermittent interreporting time is longer than the persistent interreporting time because a 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.

$$\begin{aligned}
& E[\text{interreporting time}] \\
= \; & E[\text{time between the previous report and the next report}] \\
= \; & E[\text{cycle time 1} + \text{cycle time 2} + \cdots + \text{execution time N} + \text{reporting time}] \\
= \; & E[c_1 + c_2 + \cdots + c_{N-1} + e_N + r] 
\end{aligned} \tag{36}$$

Here the intermittent interreporting time is,

$$I = c_1 + c_2 + \cdots + c_{N-1} + e_N + r \tag{37}$$

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 as,

$$\Pr[report] = \gamma \tag{38}$$

then,

$$\Pr[\text{report occurs in } N\text{-hop after } N-1 \text{ hops without reporting}] = (1-\gamma)^{N-1}\gamma \tag{39}$$

The intermittent interreport distribution with probability of $\gamma$ is

$$\begin{aligned} I^*(s) &= \sum_{n=1}^{\infty} E[e^{-sI}|N=n] \cdot \Pr[N=n] \\ &= \sum_{n=1}^{\infty} (C^*(s))^{n-1} (E^*(s) \cdot R^*(s)) (1-\gamma)^{n-1}\gamma \\ &= \frac{\gamma \cdot E^*(s)R^*(s)}{1-(1-\gamma)C^*(s)} \end{aligned} \tag{40}$$

## VI. Report arrival process at source

If the reporting processes follow the interreporting process mentioned in the previous section, then the report arrival processes from a group of mobile agents to a source can be obtained. In this section, a statistical analysis of the reports arrival processes is presented.

### A. *Persistent Reporting*

The persistent reporting case is considered (see Fig. 2). In Fig. 8, $t$ is the report interarrival time to a source and $t_i$ is the interreporting time of each 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 using:

$$t = \min(t_1, t_2, t_3, \cdots\cdots, t_n) \tag{41}$$

Then, if each mobile agent has the same interreport time distribution (i.e. i.i.d.), the reports interarrival time cumulative distribution function (cdf) can be obtained using $c(x)$

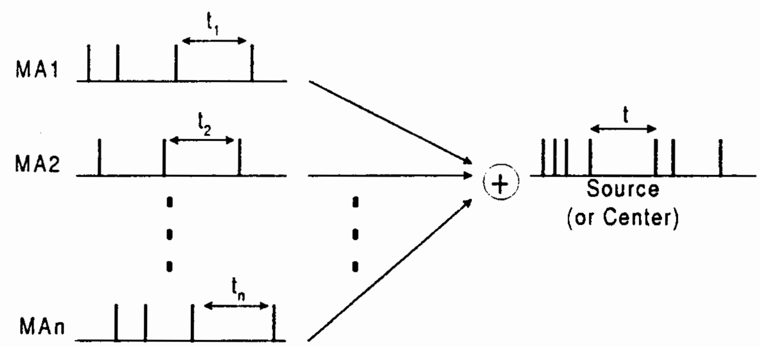


Fig. 8. Reports arriving to the source from each mobile agent

which is the one cycle time,

$$\begin{aligned}\Pr[t > x] &= \Pr[t_1 > x, t_2 > x, t_3 > x, \cdots\cdots, t_n > x] \\ &= (1 - \int_0^x c(t_1)dt_1)(1 - \int_0^x c(t_2)dt_2)\cdots\cdots(1 - \int_0^x c(t_n)dt_n) \\ &= (1 - C(x))^n \qquad (42)\end{aligned}$$

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

### *B. Intermittent Reporting*

The reports arrival process is same as the peristent case except for the probability of reporting (see example for the difference)

## 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. In the previous section, the report interarrival process is defined. Each cumulative distribution function of persistent and intermittent reporting cases is a function of the number of mobile agents, $n$, and report interarrival time $x$. Now it's 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, $x_{\max} \leq R$. In achieving this inequality, a source can guarantee some level of QoS. Here, the minimum number of mobile agents, $n_{\min}$, is found satisfying $x_{\max} \leq R$. As the number of mobile agents, $n$, increases, the report interarrival times become smaller (i.e. the distribution becomes shaper, see Fig. 11).

*A. Persistent reporting*

$F(x_{\max}) \approx L$ (for $L \to 1, L \neq 1$) is found as a function of $n$ which is the number of mobile agents. When $L \to 1$, the report interarrival time $x$ will reach the maximum and 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. (42) and the cumulative distribution function $F_p(x)$,

$$\begin{aligned} F_p(x) &= 1 - \Pr[t > x] \\ &= 1 - \Pr[t_1 > x, t_2 > x, t_3 > x, \cdots\cdots, t_n > x] \\ &= 1 - (1 - C(x))^n \end{aligned} \tag{43}$$

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

$$1 - (1 - C(x_{\max}))^n = L$$

$$\Leftrightarrow \quad n = \left\lceil \frac{\ln(1 - L)}{\ln(1 - C(x_{\max}))} \right\rceil \tag{44}$$

$$\Leftrightarrow \quad n_{\min} = \lim_{L \to 1, L \neq 1} \left\lceil \frac{\ln(1 - L)}{\ln(1 - C(R))} \right\rceil \tag{45}$$

*B. Intermittent Reporting*

The intermittent reporting case also is the same as the persistent reporting case except for the inclusion of $\gamma$, which is the probability of reporting.

## VIII. Conclusion

Different categories of mobile agent are modeled in terms of dwell time, life span, inter-reporting time distribution, report interarrival time distribution to a source and 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.

## Appendix

### *(Example: Negative Exponential Assumption)*

*A. Dwell Time*

For some concrete analysis, $e(t)$, $r(t)$, and $v(t)$ are assumed to be negative exponentially distributed with different service rates resulting in an overall 3-stage hypoexponential distribution. The negative exponential model is a potentially good mathematical mobility model [21] as 1) it is plausible for some types of actual data, and 2) the resulting model is tractable. For illustrative purpose, the travel time is assumed to be negligible at certain points below (such as interreporting process, report arrival process). Also, the service rate of the execution time is assumed to be larger than the reporting time service rate and a Markovian type model is assumed. Then $e(t)$, $r(t)$ and $v(t)$ can be written as,

$$\begin{aligned} e(t) &= \mu_1 e^{-\mu_1 t}, \quad t \geq 0 \\ r(t) &= \mu_2 e^{-\mu_2 t}, \quad t \geq 0 \\ v(t) &= \mu_3 e^{-\mu_3 t}, \quad t \geq 0 \end{aligned} \tag{46}$$

where, $\mu_1 \neq \mu_2 \neq \mu_3$. The Laplace transform results are,

$$E^*(s) = \frac{\mu_1}{s+\mu_1}, \quad R^*(s) = \frac{\mu_2}{s+\mu_2}, \quad V^*(s) = \frac{\mu_3}{s+\mu_3} \tag{47}$$

The Laplace transform of the dwell time distribution is,

$$D^*(s) = \frac{\mu_1\mu_2}{(s+\mu_1)(s+\mu_2)} \tag{48}$$

The Laplace transform of the cycle time distribution is,

$$C^*(s) = D^*(s) \cdot V^*(s) \tag{49}$$

$$= \frac{\mu_1\mu_2\mu_3}{(s+\mu_1)(s+\mu_2)(s+\mu_3)} \tag{50}$$

The inverse Laplace transform of Eq. (48), probability density function (pdf), is:

$$d(t) = \frac{\mu_1\mu_2}{-\mu_1+\mu_2}(e^{-\mu_1 t} - e^{-\mu_2 t}), \qquad t \geq 0 \tag{51}$$

Eq. (51) is plotted in Fig. 9.

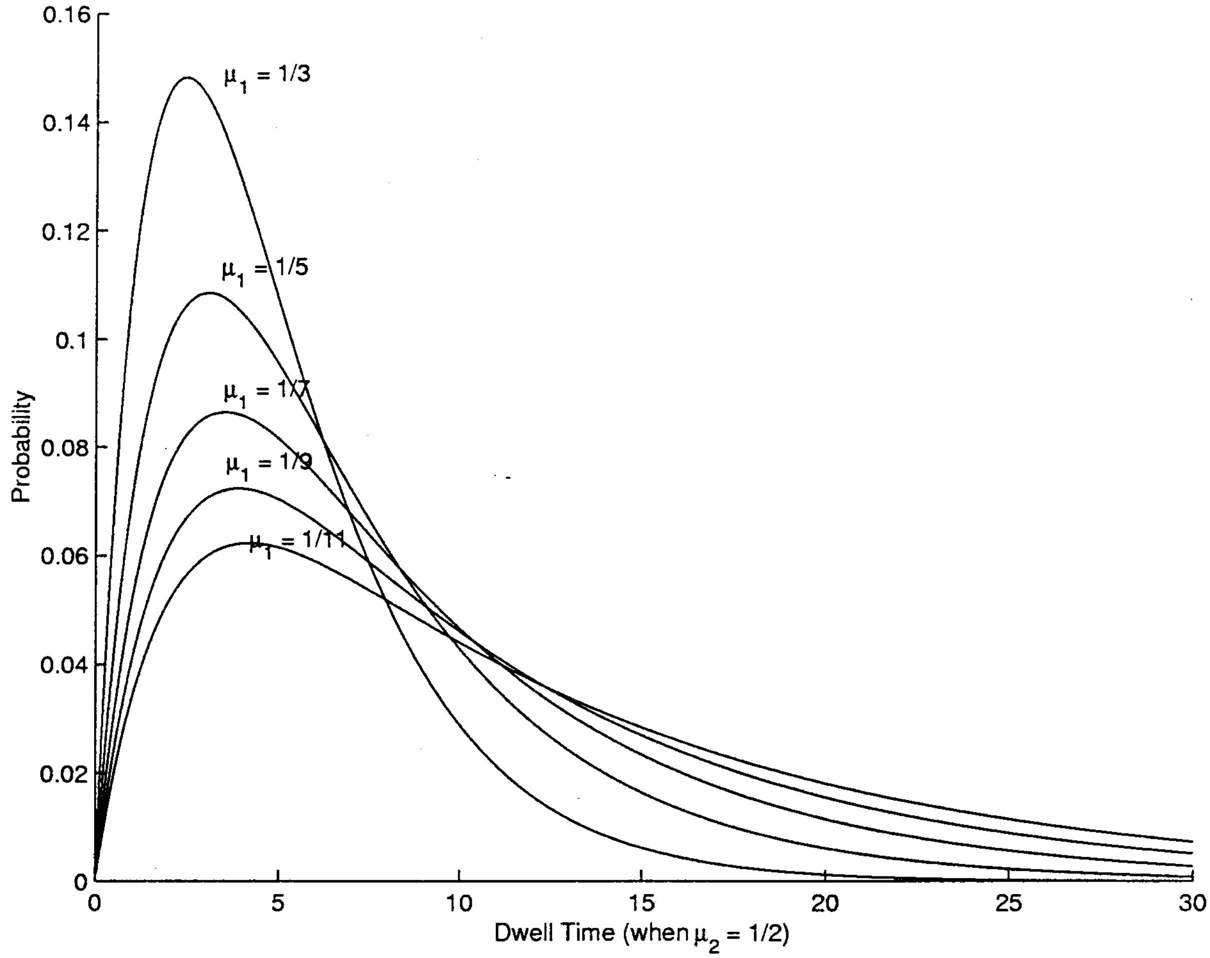


Fig. 9. Dwell time distribution

The mean of the dwell time distribution $f(t)$ of a mobile agent, $E_d[t]$, is,

$$E_d[t] = E_e[t] + E_r[t] = \frac{1}{\mu_1} + \frac{1}{\mu_2} \qquad (52)$$

where, $E_e[t]$ and $E_r[t]$ are the mean of execution time and reporting time respectively. The variance of *d(t)* is, from Eq. (48),

$$\sigma_t^2 = E_d[t^2] - (E_d[t])^2 = \frac{1}{\mu_1^2} + \frac{1}{\mu_2^2} \qquad (53)$$

The coefficient of variation, $c_v$, which is a measurement of the variation relative to the mean, also it is a measurement of the burstiness and the smoothness of a random variable.

$$c_v^2 = \frac{\sigma_t^2}{E^2[t]} = \frac{\mu_1^2 + {\mu_2}^2}{(\mu_1 + \mu_2)^2} \tag{54}$$

Here $c_v^2$ is less than 1, thus in this example the dwell time is not bursty.

*B. Life span of a Mobile Agent: Without Cloning (Sterile Case)*

Continuing the previous section example (negative exponential service time assumption), a mobile agent life span distribution, *l(t)*, can be obtained by the Laplace transform of *l(t)*, $L^*(s)$ which is

$$L^*(s) = \sum_{n=1}^{\infty} E[e^{-sT_L}|N = n] \Pr[N = n] = \frac{p\mu_1\mu_2(s + \mu_3)}{s^3 + (\mu_1 + \mu_2 + \mu_3)s^2 + (\mu_1\mu_2 + \mu_1\mu_3 + \mu_2\mu_3)s + p\mu_1\mu_2\mu_3} \tag{55}$$

Here Eq. (55) is from Eq. (12) and the life span of a mobile agent is the sum of individual dwell times and travel times. The average life span is,

$$E[T_L] = \frac{1}{p}\left(\frac{1}{\mu_1} + \frac{1}{\mu_2} + \frac{1}{\mu_3}\right) - \frac{1}{\mu_3} \tag{56}$$

Fig. 10 shows the sterile mobile agent's average life span with varying $\mu_1$, $\mu_2$ and $\mu_3$.

*C. Interreport process of a mobile agent: Intermittent reporting case*

The example of negative exponential times is again presented. However, the travel time is assumed to be relatively small because short distances between adjacent nodes. The intermittent interreporting time Laplace transform given a negative exponential distributions assumption is ,

$$I^*(s) = \sum_{n=1}^{\infty} E[e^{-sI}|N = n] \cdot \Pr[N = n] = \frac{\gamma\mu_1\mu_2}{(s + \gamma\mu_1)(s + \mu_2)} \tag{57}$$

If $\gamma = 1$, which is persistent reporting, this reduces to Eq. (48).

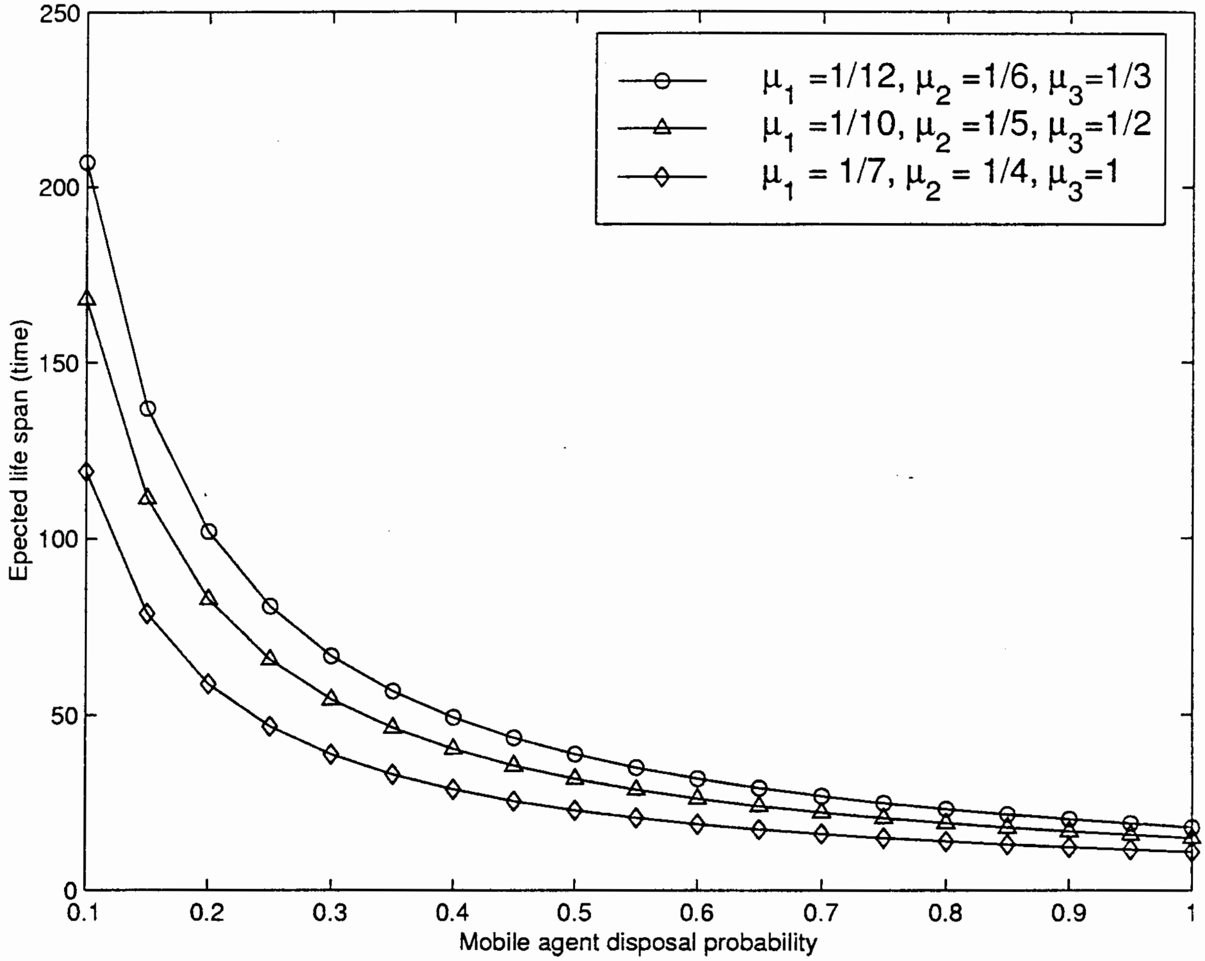


Fig. 10. Average life span of a mobile agent without cloning

The average interreporting time is,

$$\begin{aligned} E[t] &= -\frac{dI^*(s)}{ds}\bigg|_{s=0} \\ &= \frac{1}{\gamma\mu_1} + \frac{1}{\mu_2} \end{aligned} \quad (58)$$

*D. Report arrival process at source*

***Persistent Reporting***

Here it is assumed each host has the same negative exponential execution time distribution and the same reporting time distribution with means $\mu_1$ and $\mu_2$ respectively. The travel time is again ignored. Here, $p(t)$ is from Eq. (51) and it is also i.i.d.,

$$p(t) = \frac{\mu_1\mu_2}{-\mu_1 + \mu_2}(e^{-\mu_1 t} - e^{-\mu_2 t}), \quad t \geq 0$$

$$= \delta(e^{-\mu_1 t} - e^{-\mu_2 t}) \qquad where, \quad \delta = \frac{\mu_1\mu_2}{-\mu_1 + \mu_2} \tag{59}$$

then, one can obtain a CDF $F_p(x)$ of reports interarrival time to a source using $p(t)$ (for perisistent reporting),

$$\begin{aligned} F_p(x) &= \Pr[t \le x] \\ &= 1 - \Pr[t > x] \\ &= 1 - \left(\frac{\mu_2}{-\mu_1 + \mu_2} e^{-\mu_1 x} - \frac{\mu_1}{-\mu_1 + \mu_2} e^{-\mu_2 x}\right)^n \end{aligned} \tag{60}$$

In order to obtain a probability density function of the report interarrival process, $f_p(t)$, first one has to simplify Eq. (60),

$$F_p(x) = 1 - \left(\frac{-\mu_1}{-\mu_1 + \mu_2}\right)^n \sum_{k=0}^{n} \binom{n}{k} (-\frac{\mu_2}{\mu_1})^k e^{-(\mu_1 k + \mu_2 (n-k))x} \tag{61}$$

then, pdf $f_p(x)$ will be,

$$f_p(x) = \left(\frac{\mu_1}{\mu_1 - \mu_2}\right)^n \sum_{k=0}^{n} \binom{n}{k} (-\frac{\mu_2}{\mu_1})^k (\mu_1 k + \mu_2(n-k)) e^{-(\mu_1 k + \mu_2(n-k))x} \tag{62}$$

The mean of this pdf $f_p(x)$ is,

$$\begin{aligned} E[x] &= \int_0^\infty x f_p(x) dx \\ &= \left(\frac{\mu_1}{\mu_1 - \mu_2}\right)^n \sum_{k=0}^{n} \binom{n}{k} \frac{\left(-\frac{\mu_2}{\mu_1}\right)^k}{\mu_1 k + \mu_2(n-k)} \end{aligned} \tag{63}$$

***Intermittent Reporting***

The result is the same as Eq. (63) except for the substitution $\mu_1$ with $\gamma\mu_1$. From the Eq. (57), the inverse Laplace transform of $I^*(s)$ is,

$$\begin{aligned} i(t) &= \mathcal{L}^{-1}(I^*(s)) \\ &= \frac{-\gamma\mu_1\mu_2}{\gamma\mu_1 - \mu_2}(e^{-\gamma\mu_1 t} - e^{-\mu_2 t}), \quad t \ge 0 \end{aligned} \tag{64}$$

and, the reports interarrival time under intermittent reporting is

$$t = \min(t_1, t_2, t_3, \cdots\cdots, t_n) \tag{65}$$

then, a CDF $F_i(x)$ of reports interarrival time to a source using $i(t)$ (for intermittent reporting)

$$\begin{aligned} F_i(x) &= 1 - \Pr[t > x] \\ &= 1 - \left( \frac{\mu_2}{-\gamma\mu_1 + \mu_2} e^{-\gamma\mu_1 x} - \frac{\gamma\mu_1}{-\gamma\mu_1 + \mu_2} e^{-\mu_2 x} \right)^n \end{aligned} \tag{66}$$

The probability density function is

$$f_i(x) = \left( \frac{\gamma\mu_1}{\gamma\mu_1 - \mu_2} \right)^n \sum_{k=0}^{n} \binom{n}{k} \left( -\frac{\mu_2}{\gamma\mu_1} \right)^k (\gamma\mu_1 k + \mu_2(n-k)) e^{-(\gamma\mu_1 k + \mu_2(n-k))x} \tag{67}$$

The expected value of $f_i(x)$,

$$\begin{aligned} E[x] &= \int_0^\infty x f_i(x) dx \\ &= \left( \frac{\gamma\mu_1}{\gamma\mu_1 - \mu_2} \right)^n \sum_{k=0}^{n} \binom{n}{k} \frac{\left( -\frac{\mu_2}{\gamma\mu_1} \right)^k}{\gamma\mu_1 k + \mu_2(n-k)} \end{aligned} \tag{68}$$

Apparently, the intermittent interreporting time distribution is wider than the persistent interreporting time distribution. Fig. 11 shows how the number of mobile agents, $n$, changes the distribution of the report interarrival process under two different situations, persistent reporting and intermittent reporting. The more mobile agents, the shorter the report interarrival time in both cases.

### *E. Minimum number of mobile agents*

***Persistent Reporting***

From Eq. (60),

$$\begin{aligned} F_p(x) &= 1 - \left( \frac{\mu_2}{-\mu_1 + \mu_2} e^{-\mu_1 x} - \frac{\mu_1}{-\mu_1 + \mu_2} e^{-\mu_2 x} \right)^n = L \\ &\Leftrightarrow \ n = \frac{\ln(1-L)}{\ln\left( \frac{\mu_2}{-\mu_1+\mu_2} e^{-\mu_1 x} - \frac{\mu_1}{-\mu_1+\mu_2} e^{-\mu_2 x} \right)} \end{aligned} \tag{69}$$

To find the minimum number of mobile agents, $n_{\min}$, satisfying the minimum interreporting time $R$ with probability $L$ (when the execution time and the reporting time of each host, $\mu_1$ and $\mu_2$, are given),

$$n_{min} = \lim_{L \to 1, L \neq 1} \left\lceil \frac{\ln(1-L)}{\ln\left( \frac{\mu_2}{-\mu_1+\mu_2} e^{-\mu_1 R} - \frac{\mu_1}{-\mu_1+\mu_2} e^{-\mu_2 R} \right)} \right\rceil \tag{70}$$

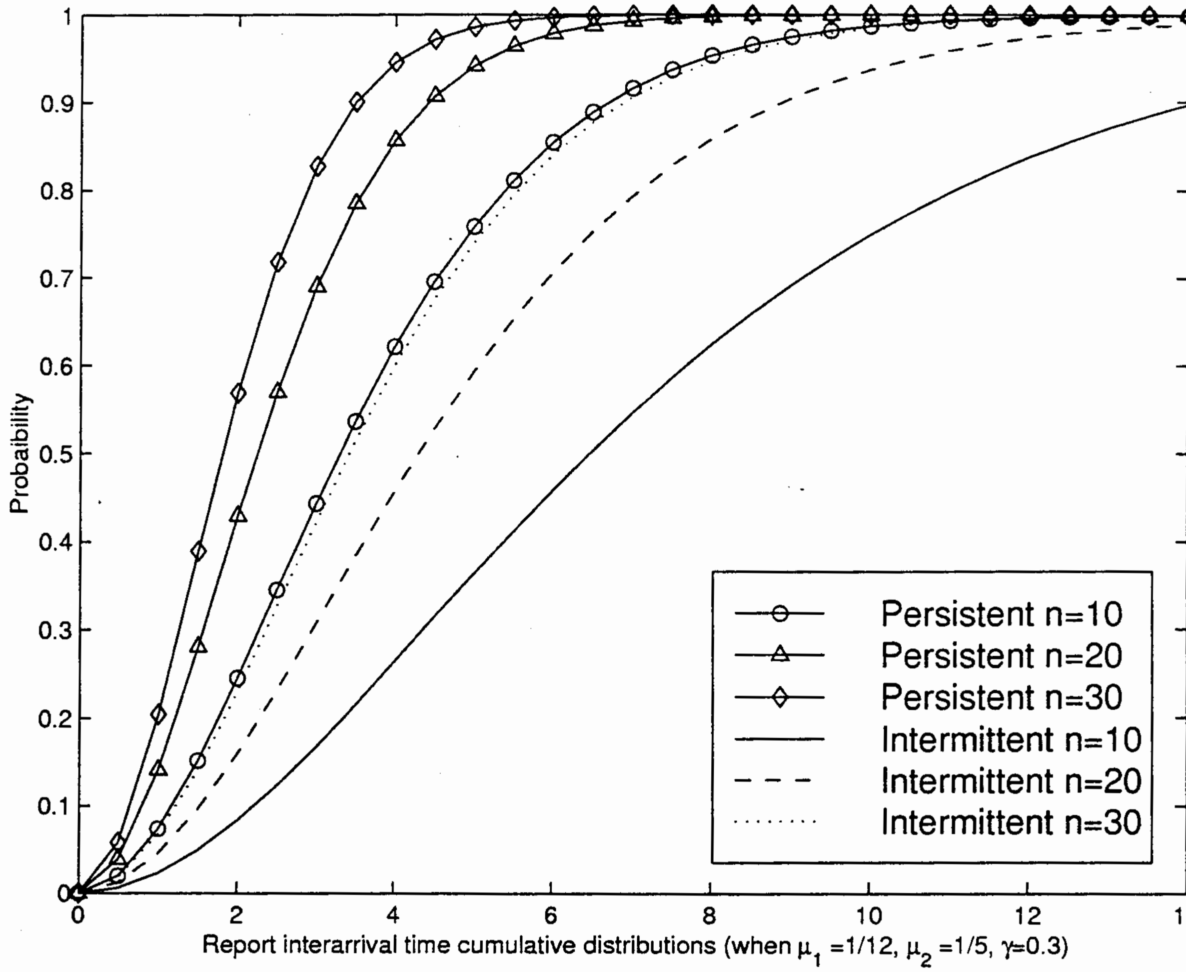


Fig. 11. Reports interarrival time cumulative distribution functions with different $n$ under persistent reporting and intermittent reporting

In order to increase the accuracy, one can increase $L$.

***Intermittent Reporting***

From Eq. (66),

$$F_i(R) = 1 - \left( \frac{\mu_2}{-\gamma\mu_1 + \mu_2} e^{-\gamma\mu_1 R} - \frac{\gamma\mu_1}{-\gamma\mu_1 + \mu_2} e^{-\mu_2 R} \right)^n \tag{71}$$

then, the minimum number of mobile agents, $n$, is,

$$n_{min} = \lim_{L \to 1, L \neq 1} \left\lceil \frac{\ln(1-L)}{\ln\left( \frac{\mu_2}{-\gamma\mu_1+\mu_2} e^{-\gamma\mu_1 R} - \frac{\gamma\mu_1}{-\gamma\mu_1+\mu_2} e^{-\mu_2 R} \right)} \right\rceil \tag{72}$$

The minimum number of mobile agents versus the required minimum interarrival time is plotted in Fig 12. A smaller $R$ requires more mobile agents. Also, the intermittent

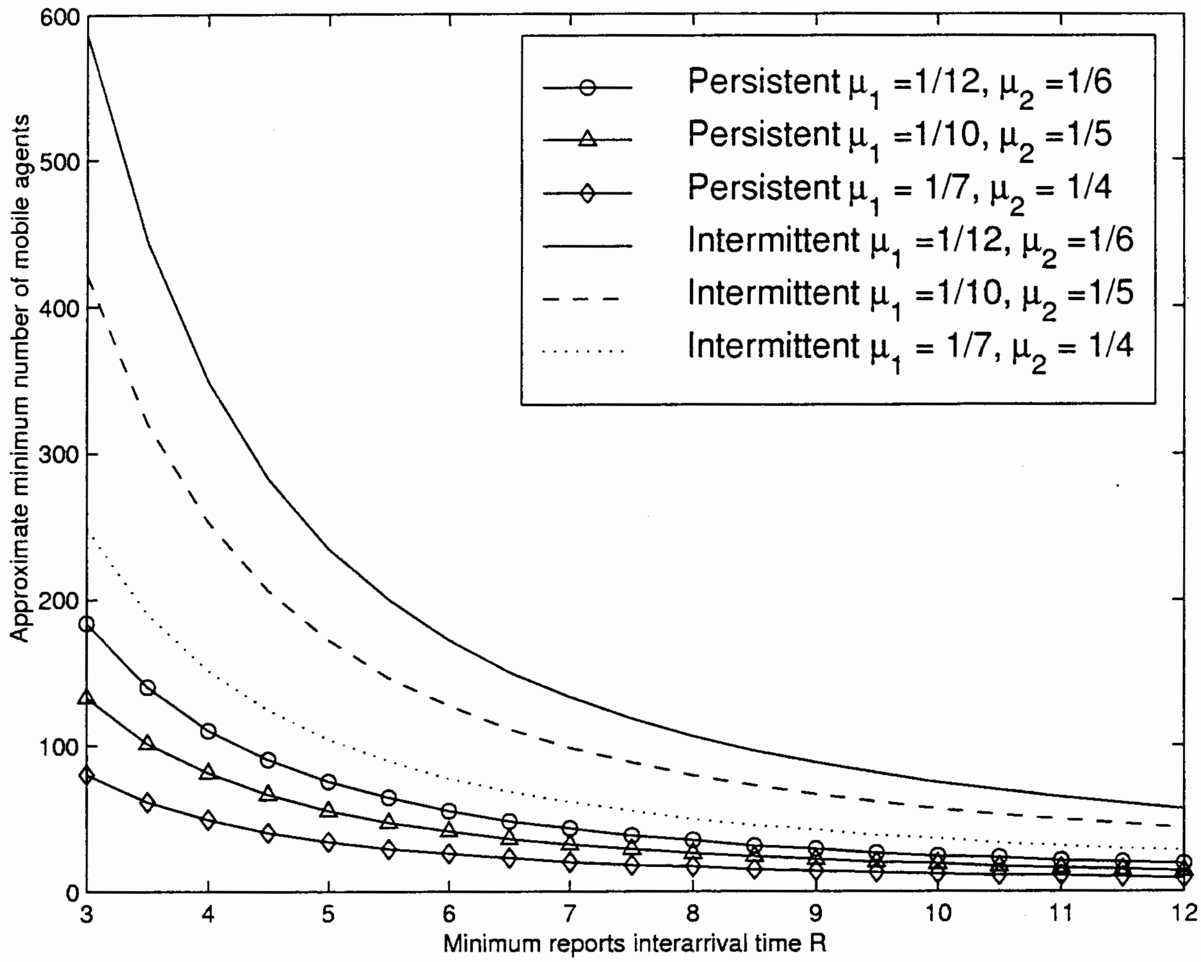


Fig. 12. Minimum number of mobile agents satisfying required minimum reports interarrival time $R$ under persistent reporting and intermittent reporting (when $\gamma = 0.3, L = 0.9999$)

reporting case requires more mobile agents than the persistent reporting case because their interreporting time is larger than the persistent case. In order to get a shorter report interarrival time (high 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 can increase the number of mobile agents it dispatches. However, increasing the number of mobile agents causes network overload or congestion.

## References


[1] W.T. Cockayne and M. Zyda, *Mobile Agent*, Manning, 1998.

[2] A. Leon-Garcia, *Probability and Random Processes for Electrical Engineering*, Addison Wesley, 2nd Ed., 1994.

[3] D. B. Lange and M. Oshima, *Programming and Deploying JAVA Mobile Agents with Aglets*, Addison Wesley, 1998.

[4] T.S. Rappaport, *Wireless Communications Principles and Practice*, Prentice Hall PTR, New Jersey, 1996.

[5] H. Tai and K. Kosaka, "The Aglets Project," *Communications of the ACM*, Vol.42, No.3, March 1999.

[6] R. Koblick, "Concordia," *Communications of the ACM*, Vol. 42, No. 3, March 1999.

[7] P. Bellavista, A. Corradi, C. Stefanelli, "An Integrated Management Environment for Network Resources and Services," *IEEE Journal on Selected Areas in Communications*, Vol.18, No.5, May 2000.

[8] J. Wong and A. Mikler, "Intelligent Mobile Agents in Large Distributed Autonomous Cooperative Systems," *Elsevier The Journal of Systems and Software*, 47(1999), pp. 75-87.

[9] D. Wong, N. Paciorek, and D. Moore, "Java-Based Mobile Agents," *Communications of the ACM*, Vol.42, No.3, March 1999.

[10] V. Pham and A. Karmouch, "Mobile Software Agents: An Overview," *IEEE Communications Magazine,* pp. 26-37, July, 1998.

[11] B. Brewington, R. Gray, and et al., "Mobile Agents for Distributed Information Retrieval," *Intelligent Information Agents: Agents-Based Information Discovery and Management on the Internet,* M. Klusch, ed., Springer-Verlag, Berlin, chapter 15, pp. 355-395, 1998.

[12] M. Greenberg, J. Byington, and D. Harper, "Mobile Agents and Security," *IEEE Communications Magazine*, pp. 76-86, July, 1998.

[13] A. Bieszczad, B. Pagurek and T. White, "Mobile Agents For Network Management," *IEEE Communications Surveys*, Vol. 1, No. 1, Forth quarter 1998.

[14] A. Karmouch, "Mobile Software Agents for Telecommunications," *IEEE Communications Guest Editorial 1*, July 1998.

[15] W. Caripe, G. Cyvenko, et al., "Network Awareness and Mobile agents Systems," *IEEE Communications Magazine*, July 1998.

[16] D. Kotz, G. Jiang, and R. Peterson, "Performance Analysis of Mobile Agents for Filtering Data Streams on Wireless Networks," *Computer Science Technical Report, Dartmouth College*, TR2000-366, May 2, 2000.

[17] D. B. Lange and M. Oshima, "Seven Good Reasons for Mobile Agents," *Communications of the ACM*, Vol. 42, No. 3, March 1999.

[18] C. Okino and G. Cybenko, "Modeling and Analysis of Active Messages in Volatile Networks," *Proceeding of the Allterton Conference on Comm., Control and Comp.,* Monticello, IL, 1991.

[19] O. Shehory, "Spawning Information Agents on the Web," *Intelligent Information Agents : Agents-Based Information Discovery and Management on the Internet,* chapter 17, pp. 412-430, 1998.

[20] O. Shehory, K. Sycara, et al., "Agent Cloning: An Approach to Agent Mobility and Resource Allocation," *IEEE Communications Magazine*, July 1998.

[21] Y. Fang, I. Chlamtac, "Teletraffic Analysis and Mobility Modeling of PCS Networks," *IEEE Transactions on Communications*, Vol. 47, No. 7, July 1999.

[22] Seong-Hwan Kim, T.G. Robertazzi, "Mobile Agent Modeling," *SUNY at Stony Brook Technical Report 786,* Nov. 28, 2000.