Design and Performance Evaluation of an Improved Mobile IP Protocol

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Abstract—**Mobile IP is one of the dominating protocols that provide the mobility support in the Internet. However, even with some proposed optimization techniques, there is still space for improving the performance. In this paper, we present a novel mailbox-based scheme to further improve the performance. In this scheme, each mobile node migrating to a foreign network is associated with a mailbox. A sender sends packets to the receiver's mailbox, which will in turn forward them to the destination. During handoff, a mobile node can decide whether to move its mailbox and report the handoff to the home agent, or simply to report the handoff to the mailbox. In this way, the scheme is adaptive and can be made to reduce the workload on the home agent and minimize the total cost of message delivery and mobility management. To evaluate the performance of the proposed scheme, we develop a performance model considering two walk models for mobile nodes, based on which the cost function is derived. We also propose an iterative algorithm for deriving an optimal point where the cost function reaches its minimum. The results show that our new scheme can outperform Mobile IP route optimization with smooth handoff extension, no matter how many packets are to be received during each migration.**

Keywords- system design, simulations, statistics

I. Introduction

The tremendous growth of wireless communications technology and the advancement of laptop and notebook computers induce a growing demand for mobile and nomadic computing. Unlike stationary nodes in a wired network, mobile nodes can move from one location to another while maintaining continuous network connections. A challenge is to manage location information in such a way that provides seamless network access for mobile nodes while retaining connectivity with the wired network.

Researchers have investigated the Internet Protocol (IP) for mobile internetworking, leading to the development of a proposed standard for IP mobility support called Mobile IP [1]. In Mobile IP, each mobile node is assigned a long-term IP address called *home address* in its home network. While being away from the home network, the location of the mobile node is captured by a *care-of address* provided by a *foreign agent* in the foreign network. A *home agent* in the home network maintains a *mobility binding* between the home address and the care-of address in a *binding cache*. All packets destined to the mobile node are first routed with regular IP routing to its home network where they are captured by the home agent. The home agent then tunnels these packets to the foreign agent which, in turn, forwards them to the final destination.

However, Mobile IP suffers from the well known triangle routing problem. Therefore, Mobile IP route optimization [2] has been proposed to alleviate this problem. Any node that is willing to communicate with a mobile node maintains a binding cache. When the home agent intercepts a packet for the mobile node outside the home network, it may send a *binding update* message to the sender, informing it of the mobile node's current care-of address. The sender then updates its binding cache and tunnels any ensuing packets for the mobile node directly to its care-of address. An extension to the registration process, called *smooth handoff*, enables foreign agents to also make use of binding updates to reduce packet loss during a handoff. The mobile node may ask the new foreign agent to send a *Previous Foreign Agent Notification* message, which includes a binding update, to the previous foreign agent. The previous foreign agent then updates its binding cache and re-tunnels any packets for the mobile node to its new care-of address.

Although Mobile IP and route optimization provide general mechanisms for mobility support in the Internet, there are still several performance problems that need to be addressed.

First, both Mobile IP and route optimization require that a mobile node's home agent be notified of every location change. The route optimization further requires that every new location be registered with hosts that are actively communicating with the mobile node. Should the smooth handoff extension be implemented, an extra update message would be sent to the previous foreign agent. All these signaling messages for location management waste a lot of bandwidth.

Second, Mobile IP suffers from slow handoffs since the home agent has to handle all handoffs, even though it may be far away from the current location of the mobile node. The network delay adds to slow handoffs. This causes more packet loss since these packets are routed based on outdated location information, which is especially harmful to real-time applications such as voice over IP and video streaming. Although Route Optimization with smooth handoff extension [2] can, to some extent, reduce packet loss, tunneled packets

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that arrive at the previous foreign agent before the Previous Foreign Agent Notification are still lost since the previous foreign agent is not yet aware of the migration of the mobile node. It will then rely on upper layer protocols such as TCP to retransmit such lost packets from the possibly distant source. This will incur the latency of communication. TCP-based connections will also suffer from throughput reduction since the lost packets may be mistakenly treated as congestion and result in TCP's slow start mechanism.

Third, since all handoffs are handled by the home agent, they cause lots of signaling traffic between the mobile node and the home agent. In high speed LANs this is not an issue, but when low speed WANs are involved and lots of mobile nodes are performing simultaneous handoffs, network congestion may occur.

In this paper, we present a novel mailbox-based scheme to alleviate the performance problems stated above. Each mobile node migrating to a foreign network is associated with a *mailbox*. A sender sends packets to the receiver's mailbox which will in turn forward them to the destination. During each handoff, a choice can be made whether to report this handoff to the home agent or simply to the mailbox. In this way, the workload on the home agent as well as the registration delay can be reduced. Separating the mailbox from its owner also allows us to achieve adaptive location management that enables dynamic tradeoff between the packet delivery cost and the registration cost so as to minimize the total cost. Since the mailbox is located somewhere in the network close to the receiver, the packet retransmission cost could also be reduced.

To evaluate the performance of the proposed scheme, we develop a performance model including two walk models (namely, random walk and directional walk) of mobile nodes, based on which the cost function is derived. We also propose an iterative algorithm for deriving an optimal point where the cost function reaches its minimum. Mobile IP route optimization with smooth handoff extension is used as a benchmark in our performance comparison. The performance results show that our new scheme can outperform the benchmark, no matter how many packets are to be received during each migration.

The remaining of this paper is organized as follows. Section 2 describes our mailbox-based scheme. Section 3 presents the performance evaluation model. In Section 4, based on the performance model, we compare the performance of the proposed scheme with that of the benchmark scheme. Section 5 presents a review of related works. The final section provides the concluding remarks.

II. MAILBOX-BASED SCHEME

Throughout this paper, both home agent and foreign agent will be called *mobility agent* [1, 2]. In our scheme, all the modifications are done at mobility agent without any changes to the existing operating system of a mobile node.

In our mailbox-based scheme, every mobile node is associated with a mailbox, which is a data structure residing at a mobility agent. As shown in Fig. 1, if a sender wants to send a packet to a mobile node, it simply sends the packet to the receiver's mailbox (step 1). Later, the receiver receives the packet from its mailbox (step 2). (There is only one exception that a packet will not be sent to the mailbox but delivered directly to the receiver. This happens when the mobile node resides in its home network and the sender does not maintain the mobility binding for the receiver. Unless otherwise stated, the following discussions will preclude this condition.)

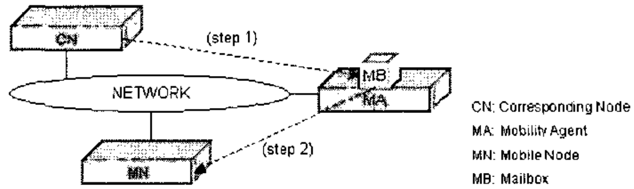

Figure 1. Mailbox-based scheme

Initially, the mailbox is residing on the same network as its owner. The mobile node realizes that it has entered a new foreign network when it receives an *Agent Advertisement* [4] message from a new foreign agent. It then sends registration message to the old foreign agent where its mailbox resides. The old foreign agent then decides whether to move the mailbox to the new foreign agent with the consideration of two factors: the distance to the new foreign agent and the communication traffic of the mobile node. Here the communication traffic is defined as the number of packets expected to receive during the residence time at the new foreign agent. If the mobile node is expected to receive many packets while the distance is long, it will be costly to forward all these packets to the new address and better to move the mailbox closer to the mobile node so as to achieve a more optimal route. On the other hand, if the mobile node seldom receives packets or the distance is quite short, it is economical to leave the mailbox at where it was in order to reduce the registration overhead, should a mailbox migrates. The distance may be obtained from the routing table of the old foreign agent if it uses link state routing protocols such as OSPF [5]. The communication traffic is easy to obtain since the mailbox acts as a relay and buffer station of the mobile node.

In this work, we use a pair of thresholds (d, n) to determine the mailbox's migration. If either the distance exceeds d or the communication traffic exceeds n, the mailbox will migrate to the new foreign agent. Otherwise, the mailbox stays at the old foreign agent. We differentiate two kinds of handoff, i.e., handoff without mailbox and handoff with mailbox, and we refer them as *local handoff* and *home handoff*, respectively. Upon each home handoff, a new threshold pair is calculated based on the current circumstances, which will be discussed in Section 3.

Besides mailbox, another new data structure called *address table* is defined in each mobility agent. Each entry in the address table has six attributes: the *home address* of the mobile node, the *mailbox's address*, a *valid tag*, the *threshold pair*, a *pointer to the mailbox*, and the *care-of address* of the mobile node. The valid tag is used to indicate whether the mailbox's address is outdated or not. Table I gives an example of address table where the first entry shows a remote mailbox in another mobility agent and the second entry shows a local mailbox.

The scheme also defines operations for two processes, *Migrating* and *Packet-Forwarding*, which are presented in the following two subsections.

TABLE I. AN EXAMPLE OF ADDRESS TABLE

Home Addr	Mailbox's Addr	Valid Tag	Threshold Pair	Pointer to Mailbox	Care-of Addr
Addr A	Remote Address	*true*	Null	Null	Null
Addr B	Local Address	*true*	$(d; n)$	A Pointer	Addr C

A. Migrating

Upon receiving the advertisement from a new mobility agent MA_a, the mobile node (*MN*) determines that it has crossed the boundary of the old network and roamed to a new one. It then initiates the registration process. It first uses gratuitous ARP [3] to update the ARP caches of the nodes in the foreign network so that they associate *MN*'s link layer address with its home address. Then it sends a "REGISTRATION" message to MA_a. The key information contained in the "REGISTRATION" message is the address of the mobility agent MA_m where the mailbox, *MB*, currently resides. Fig. 2 illustrates the message exchanging in the registration process.

Upon receiving the "REGISTRATION" message, MA_a extracts the address of MA_m from the message, and sends a "MB_REGISTRATION" message to MA_m.

Upon receiving the "MB_REGISTRATION" message, MA_m decides whether to move *MB* to MA_a according to the threshold pair in the address table. In the case when *MB* does not migrate, MA_m simply updates the care-of address of *MN* to MA_a. Otherwise, it will act as follows:

- setting the valid tag of the corresponding entry to *false* meaning that this mailbox will no longer be used; and
- sending a "CREATE" message to MA_a to request it to create a new mailbox *MB'* for *MN*.

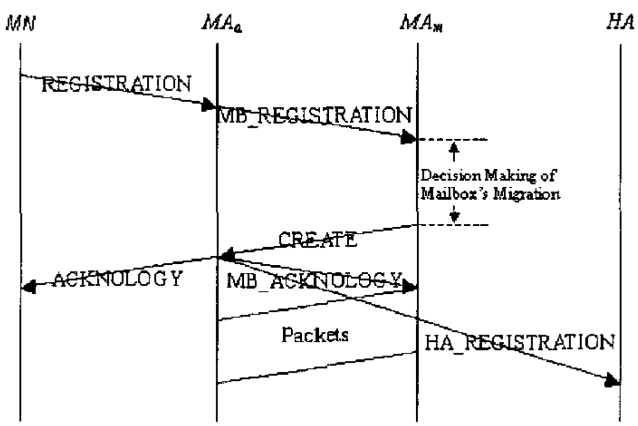

Figure 2. Message exchanging in registration

Upon receiving the "CREATE" message, MA_a creates *MB'* and adds an entry to its address table recording this newly created *MB'*. Based on the current circumstances, it calculates a new threshold pair for the mobile node. It also sends three messages:

- an "ACKNOLOGY" message to *MN* informing it of the new address of its mailbox *MB'*,
- an "MB_ACKNOLOGY" message to MA_m telling it the creation of *MB'*, and
- an "HA_REGISTRATION" message to home agent (*HA*) registering the new address of the mailbox.

After receiving the "MB_ACKNOLOGY" message, MA_m perform the following actions:

- updating the address of the mailbox in the address table to that of *MB'*;
- setting the valid tag to *true*;
- streaming every packet buffered in *MB* to *MB'*;
- informing the new address of the mailbox to the senders of the buffered packets in *MB* by sending "UPDATE" messages; and
- after all the packets have been streamed out, deconstructing the mailbox and setting null to the last three attributes in the address table, i.e., the threshold pair, the pointer to the mailbox and the care-of address.

After receiving the "HA_REGISTRATION" message, the *HA* updates the address of the mailbox in its address table accordingly.

B. Packet-forwarding

If a correspondent node (*CN*) wants to send a packet to an *MN*, it first checks its binding cache to see whether or not the address of *MN* has been cached locally. If yes, it tunnels the packet to the cached address. Otherwise, it sends the packet with regular IP routing to the *MN*'s home address. Once the packet arrives at the home network, the *HA* will intercept the packet since it acts as a proxy ARP server for *MN*.

When a mobility agent receives a packet destined to *MN*, it will perform actions according to the decision tree below.

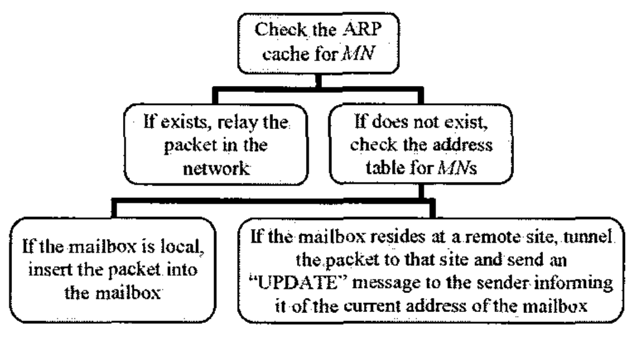

Figure 3. Decision tree when receiving a packet

For a packet in *MB* to be forwarded to *MN*, the agent MA_m first checks the valid tag. If it is *false*, i.e., the mailbox is migrating to the new foreign agent (*FA*), the packet forwarding will be suspended and will rely on the migrating process to stream the packet to the new mailbox. If the valid tag is *true*, it tunnels the packet to the care-of address of *MN*.

III. Performance Modeling

In this section, we develop a performance model to be used for evaluating the proposed scheme (to be described in Section 4). We first present a system model for a mobile network and two walk models (such as random walk and directional walk) for a mobile node, which are adopted in many existing studies such as [9] and [10]. Based on these models, we develop the cost functions for our scheme as well as the benchmark scheme. The cost function includes both the signaling transmission cost and the packet delivery cost.

A. System Model

The model assumes that the coverage area of the mobile network is partitioned into *cells*. A cell is defined as the coverage area of a mobility agent that has the capability of exchanging packets with mobile nodes directly through the air interface. A mobility agent serves only one cell and cells do not overlap with each other.

A movement occurs when a mobile node moves from the residing cell to one of its neighboring cells. The distance between any two cells in the network is measured by the minimum number of cell boundary crossings required for a mobile node to travel from one cell to another. If we assume that a mobility agent is a router in a cell that can communicate directly through wired line with other mobility agents in the neighboring cells, the distance between two mobility agents can also be defined as the distance between their cells.

We consider a grid configuration for the mobile network composed of equal-sized, non-overlapping, rectangular cells. In this grid configuration as shown in Fig. 4, each cell has four neighbors. The distance between two cells with coordinates (x_1,y_1) and (x_2,y_2) is $|x_2-x_1|+|y_2-y_1|$.

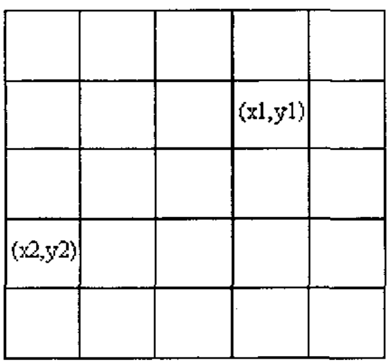

Figure 4. Grid configuration of the mobile network

B. Walk Models

The cost function of our scheme depends on the walk model of a mobile node. Two walk models are considered here, namely *random walk model* and *directional walk model*. In the random walk model, a mobile node moves to one of its four neighbors with equal probability of 1/4 as shown in Fig. 5.

The random walk model may be appropriate for pedestrian mobile users. For mobile vehicle users, a directional walk model is more suitable. We assume that a mobile node moves towards only one direction in our analysis period. It moves to the next cell on the moving direction with a probability of 1 as shown in Fig. 6.

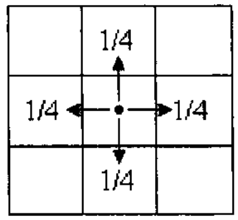

Figure 5. Random walk model

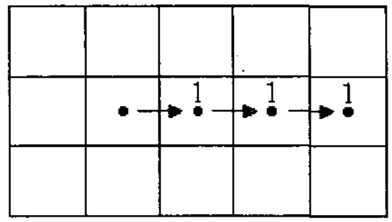

Figure 6. Directional walk model.

In general, the cost function could be expressed as follows irrespective of what scheme is used.

$$Cost_{total} = Cost_{signaling}/ExpNum + Cost_{packet} \tag{1}$$

where $ExpNum$ denotes the expected number of packets to be received within the residence time at a cell. We divide $Cost_{signaling}$ by $ExpNum$ because we want the signaling cost of a handoff to be undertaken by all the packets within the residence time after the handoff. Table II lists all the parameters used for the performance modeling.

C. Cost Function for Our Scheme under Random Walk Model

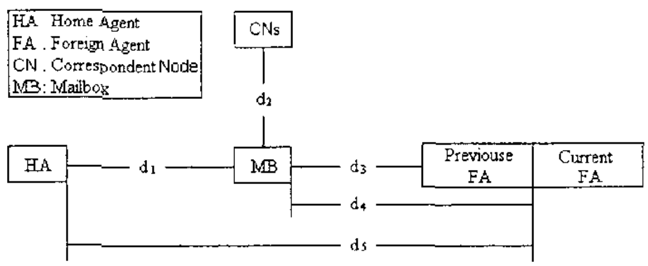

Figure 7. Network scenario about mobile node's migration in our scheme

Fig. 7 depicts the network scenario about mobile node's migration in our scheme. The Current FA is the foreign agent after the mobile node's migration from the Previous FA. So the two foreign agents must be adjacent to each other, i.e., $d_4 = d_3 \pm 1$ where the $\pm$ sign depends on whether the mobile node migrates close to or far away from the mailbox. In case of the home handoff, the Current FA will become the new residing place for the mailbox. Here d_2 is the average distance to all the correspondent nodes.

TABLE II. PARAMETERS FOR PERFORMANCE MODELING

Parameter	Explanation
$f_m(t)$	(exponential) probability distribution function of the packet's inter-arrival time
λ	mean packet arrival rate, i.e., $f_m(t) = \lambda e^{-\lambda t}$
$f_r(t)$	(exponential) probability distribution function of the mobile node's residence time at a cell
$1/\mu$	mean residence time at a cell, i.e., $f_r(t) = \mu e^{-\mu t}$
$Cost_{homehandoff}(X)$	signaling cost of the home handoff, given that it occurs at the mobile node's Xth migration
$Cost_{localhandoff}(i,X)$	signaling cost of the ith local handoff, given that the home handoff occurs at the mobile node's Xth migration
$Cost_{update}$	signaling cost of bind updates to the correspondent nodes
$Cost_{normal}(i,X)$	normal packet delivery cost during the period of the mobile node's (i-1)th and ith migration, given that the home handoff occurs at the mobile node's Xth migration
$Cost_{retransmission}(i,X)$	abnormal packet delivery cost due to packet loss and retransmission during the period of the mobile node's (i-1)th and ith migration, given that the home handoff occurs at the mobile node's Xth migration
$T_{normal}(i,X)$	time period that the mailbox has the correct care-of address about the mobile node during the period of the mobile node's (i-1)th and ith migration, given that the home handoff occurs at the mobile node's Xth migration
$T_{retransmission}(i,X)$	time period that the mailbox has the incorrect care-of address about the mobile node during the period of the mobile node's (i-1)th and ith migration, given that the home handoff occurs at the mobile node's Xth migration
$T(i,X)$	sum of $T_{normal}(i,X)$ and $T_{retransmission}(i,X)$, which is equal to $1/\mu$ on average
$ExpMig$	expected number of migrations that might trigger a home handoff
N	number of correspondent nodes
m	proportionality constant between the transmission cost (the transmission time) of the wireless link and that of the wired link
δ_{C_s}	proportionality constant between the signaling transmission cost and the transmission distance
δ_{C_p}	proportionality constant between the packet delivery cost and the transmission distance
δ_{T_s}	proportionality constant between the signaling transmission time and the transmission distance
$p(X)$	probability that the home handoff occurs at the mobile node's Xth migration
$p_d(X)$	probability that the home handoff occurs at the mobile node's Xth migration due to the threshold d
$p_n(X)$	the probability that the home handoff occurs at the mobile node's Xth migration due to the threshold n
$p_d^t(x)$	probability that the distance to the mailbox is t after the mobile node's xth migration, given that the distance threshold is d; as a special case, $p_d^d(x)$ means the probability that the distance to the mailbox, after the mobile node's xth migration, meets the threshold d which triggers the home handoff.
$f_X(x),\ 0 \le x \le X$	average distance to the mailbox after the mobile node's xth migration, given that the home handoff occurs at the mobile node's Xth migration

Derivation of $Cost_{signaling}$

Suppose the mailbox migrates at the mobile node's Xth migration, it is for sure that there are $X-1$ local handoffs and one home handoff. Thus the $Cost_{signaling}$ is expressed as

$$Cost_{signaling} = \sum_{X=1}^{\infty} p(X) \frac{Cost_{homehandoff}(X) + \sum_{i=1}^{X-1} Cost_{localhandoff}(i,X) + Cost_{update}}{X} \quad (2)$$

where we can express $Cost_{homehandoff}(X)$, $Cost_{localhandoff}(i,X)$ and $Cost_{update}(X)$ as follows (refer to Fig. 2 for details).

$$Cost_{homehandoff}(X) = (2m + 3d_4 + d_5)\delta_{C_s} = (2m + 3f_X(X) + d_5)\delta_{C_s} \quad (3)$$

$$Cost_{localhandoff}(i,X) = (m + d_4)\delta_{C_s} = (m + f_X(i))\delta_{C_s} \quad (4)$$

$$Cost_{update} = N \times d_5 \times \delta_{C_s} \quad (5)$$

Derivation of *ExpNum*

Since we assume a random packet incoming rate λ and a random migration rate μ, we have

$$ExpNum = \int_{t_r=0}^{\infty} \lambda t_r \times \mu e^{-\mu t_r} dt_r = \lambda/\mu \quad (6)$$

$Cost_{packet}$

Similar to the $Cost_{signaling}$, the $Cost_{packet}$ is expressed as follows.

$$Cost_{packet} = \sum_{X=1}^{\infty} p(X) \frac{\sum_{i=1}^{X}\left(Cost_{normal}(i,X)\frac{T_{normal}(i,X)}{T(i,X)} + Cost_{retransmission}(i,X)\frac{T_{retransmission}(i,X)}{T(i,X)} \right)}{X} \quad (7)$$

where the $Cost_{normal}(i,X)$ and $Cost_{retransmission}(i,X)$ are

$$Cost_{normal}(i,X) = (d_2 + d_3 + m)\delta_{C_p} = (d_2 + f_X(i-1) + m)\delta_{C_p} \quad (8)$$

$$\begin{aligned} Cost_{retransmission}(i,X) &= (d_2 + d_3 + m + d_4 + m)\delta_{C_p} \\ &= (d_2 + f_X(i-1) + m + f_X(i) + m)\delta_{C_p} \end{aligned} \quad (9)$$

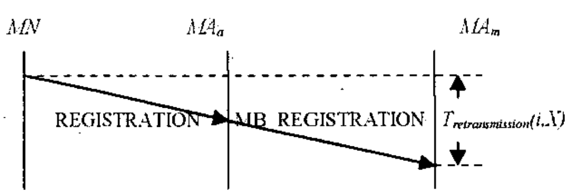

Figure 8. Retransmission time

According to the Fig. 8, $T_{retransmission}(i,X)$ is the time period after the ith migration of the mobile node and before the "MB_REGISTRATION" message arrives at MA_m. So we have

$$T_{retransmission}(i,X) = (m + d_4)\delta_{T_s} = (m + f_X(i))\delta_{T_s} \quad (10)$$

Derivation of *p(X)*

It is a little bit difficult and tricky to derive $p(X)$. Firstly, we use the following diagram to model the migration pattern of a mobile node.

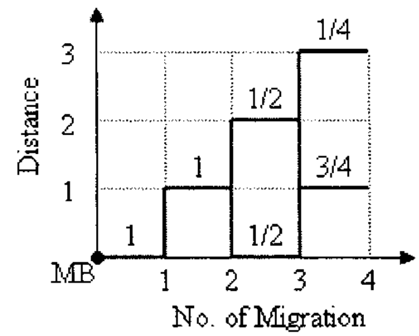

Figure 9. Model of migration pattern

Initially, the mailbox and the mobile node are co-located. Therefore, when the x-axis is 0, the y-axis is also 0. After the first migration, the distance to the mailbox becomes 1 with a 100% probability. Thus we see a value of 1 above the red stripe between 1 and 2 migrations. Next, after the second migration, the distance could be either 2 or 0, each with a probability of 1/2. This probability distribution could be derived by using the following trick of extending the y-axis to negative. We define 1 to represent a movement to either up or right neighboring cell and -1 to represent a movement to either down or left cell as shown in Fig. 10.

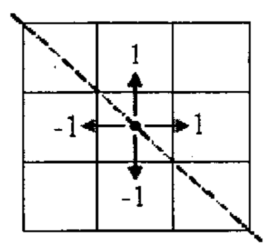

Figure 10. Extending the y-axis to negative

With this new configuration, we can redraw Fig. 9 as Fig. 11 where Fig. 9 could be viewed as the absolute of Fig. 11.

So a mobile node's migration could be represented as a string of 1 and -1. To achieve a distance of t after the xth migration, we must have $(x+t)/2$ times of 1 and $(x-t)/2$ times of -1. This is a simple binomial distribution problem and we could express this probability distribution as the following equation.

$$Prob^t(x) = C_x^{\frac{x+t}{2}} / 2^x, \quad t \in R \quad (11)$$

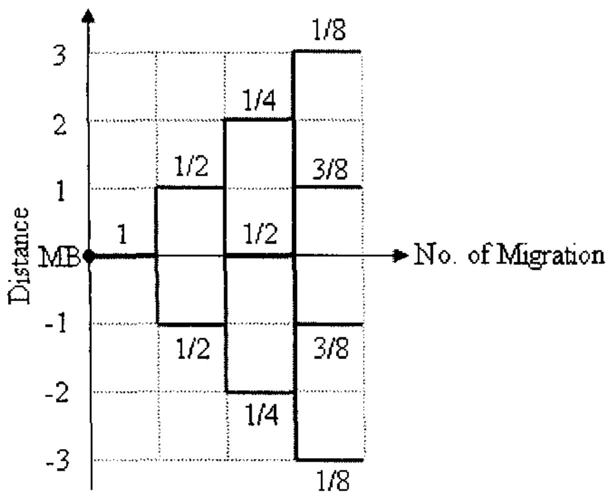

Figure 11. Model of migration pattern with the new configuration

Now we could easily represent the probability distribution as shown in Fig. 9 as follows:

$$p^t(x) = \begin{cases} Prob^t(x) + Prob^{-t}(x) = 2C_x^{\frac{x+t}{2}}/2^x, & t > 0 \\ Prob^0(x) = C_x^{\frac{x}{2}}/2^x, & t = 0 \end{cases} \quad (12)$$

The following two probability distribution functions are also useful in the derivation of $p(X)$. They are same as expressions (11) and (12) expect for the initial y-axis which starts at r. Fig. 12 graphically shows the two distributions with $r = 1$.

$$Prob^{t,r}(x) = Prob^{t-r}(x), \quad t, r \in R \quad (13)$$

$$p^{t,r}(x) = \begin{cases} Prob^{t,r}(x) + Prob^{-t,r}(x) = Prob^{t-r}(x) + Prob^{-t-r}(x), & t > 0 \\ Prob^{0,r}(x) = Prob^{0-r}(x), & t = 0 \end{cases} \quad (14)$$

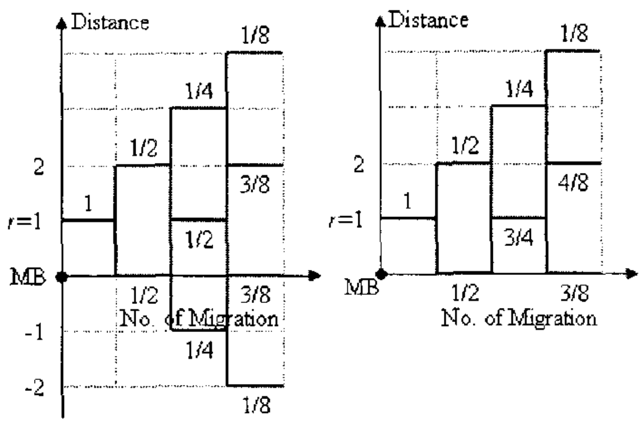

Figure 12. Graphical representation of (13) and (14)

Next let us find out $p_d^d(x)$. Obviously, when x < d, we have $p_d^d(x) = 0$ and when x = d, we obtain $p_d^d(x) = p^d(X) = 1/2^{d-1}$.

When x = d+2k+1 (for k = 0, 1, ...), $p_d^d(x)$ is also equal to 0 as shown in Fig. 13. However, when x = d+2k (where k = 0, 1, ...), $p_d^d(x)$ will not be easy to derive since once the threshold d is met, the probability overflow will take place.

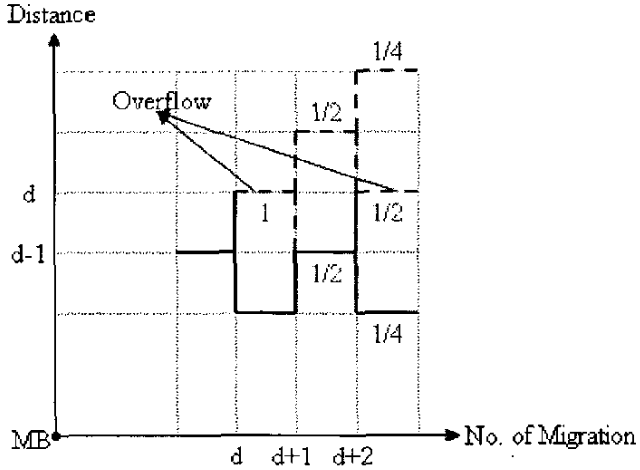

Figure 13. The probability distribution of $p_d^d(x)$

If there is no overflow at the dth migration, we will have $p_d^d(d+2) = p^d(d+2)$. But now there is overflow, therefore, $p_d^d(d+2)$ is equal to $p^d(d+2)$ minus the part that the overflow $p_d^d(d)$ should contribute as shown in the red dash line in Fig. 13, i.e., $p_d^d(d+2) = p^d(d+2) - p_d^d(d)/2$. In general, we could express $p_d^d(x)$ as

$$p_d^d(x) = \begin{cases} 0, & x < d \text{ or } x = d + 2k + 1 \\ p^d(x), & x = d \\ p^d(x) - \sum_{i=0}^{\frac{x-d}{2}-1} p_d^d(d+2i)\, p^{d,d}(x-d-2i), & x = d + 2k \end{cases} \quad (15)$$

Similarly, $p_d^t(x)$ could be derived as $p^t(x)$ minus the part contributed by the overflows. So,

$$p_d^t(x) = \begin{cases} p^t(x), & x < 2d - t \\ 0, & x = 2d - t + 2k + 1 \\ p^t(x) - \sum_{i=0}^{\frac{x-2d+t}{2}} p_d^d(d+2i)\, p^{t,d}(x-d-2i), & x = 2d - t + 2k \end{cases} \quad (16)$$

where $0 \le t \le d$.

Now we could finally derive $p(X)$. If the threshold $d = 1$, it is for sure that the home handoff takes place each time the mobile node migrates. So we have

$$p(X) = \begin{cases} 1, & X = 1 \\ 0, & X > 1 \end{cases} \tag{17}$$

When $d > 1$, the home handoff may not take place at each mobile node's handoff. Suppose the home handoff occurs at the mobile node's Xth handoff, there will be no home handoff at any of the previous X-1 handoffs. So

$$p(X) = (1 - \sum_{i=1}^{X-1} p(i))(1-(1-p_d(X))(1-p_n(X))) \tag{18}$$

where $p_d(X)$ and $p_n(X)$ are expressed as follows.

$$p_d(X) = \frac{p_d^d(X)}{\sum_{i=0}^{d} p_d^i(X)} \tag{19}$$

$$\begin{aligned} p_n(X) &= Prob(expected\ no.\ of\ packets\ \geq\ n) \\ &= 1 - Prob(expected\ no.\ of\ packets\ <\ n) \\ &= 1 - \sum_{i=0}^{n-1} Prob(expected\ no.\ of\ packets\ =\ i) \\ &= 1 - \sum_{i=0}^{n-1}\left[\int_{t_r=0}^{\infty}\left(\frac{(\lambda t_r)^i}{i!}e^{-\lambda t_r}\right)\mu e^{-\mu t_r}dt_r\right] \\ &= \left(\frac{\lambda}{\lambda+\mu}\right)^n \end{aligned} \tag{20}$$

With the help of $p(X)$, we obtain the expected number of migrations that might trigger a mailbox's migration.

$$ExpMig = \sum_{X=1}^{\infty} X \times p(X) \tag{21}$$

Derivation of $f_X(x)$

Suppose the mailbox will migrate at the mobile node's Xth migration. So when $x < X$, $p_d^d(x)$ must be 0. So

$$f_X(x) = \sum_{i=0}^{d-1} \frac{p_d^i(x)}{\sum_{i=0}^{d-1} p_d^i(x)} \times i, \qquad x < X \tag{22}$$

When $x = X$, a home handoff takes place. As mentioned earlier, this could happen either because of d or n. If it is because of d, it is for sure that $f_X(x) = d$. If it is because of n, then $f_X(x)$ is the same as when $x < X$. So

$$f_X(x) = \frac{p_d(x)}{1-(1-p_d(x))(1-p_n(x))} \times d + \frac{p_n(x) - p_d(x)p_n(x)}{1-(1-p_d(x))(1-p_n(x))} \times \sum_{i=0}^{d-1}\left(\frac{p_d^i(x)}{\sum_{i=0}^{d-1} p_d^i(x)} \times i\right), \quad x = X \tag{23}$$

D. Cost Function for Our scheme under Directional Walk Model

In the directional walk model, since the mobile node handoffs to its next cell along its moving direction, the number of migrations before a home handoff takes place is bounded by the distance threshold, d. Therefore, we should rewrite (2), (7) and (21) as follows.

$$Cost_{signaling} = \sum_{X=1}^{d} p(X) \frac{Cost_{homehandoff}(X) + \sum_{i=1}^{X-1} Cost_{localhandoff}(i,X) + Cost_{update}}{X} \tag{24}$$

$$Cost_{packet} = \sum_{X=1}^{d} p(X) \frac{\sum_{i=1}^{X}\left(Cost_{normal}(i,X)\frac{T_{normal}(i,X)}{T(i,X)} + Cost_{retransmission}(i,X)\frac{T_{retransmission}(i,X)}{T(i,X)}\right)}{X} \tag{25}$$

$$ExpMig = \sum_{X=1}^{d} X \times p(X) \tag{26}$$

where all the terms but $p(X)$ and $f_X(x)$ remain the same.

For $p(X)$, only $p_d(X)$ requires modification as:

$$p_d(X) = \begin{cases} 0, & X < d \\ 1, & X = d \end{cases} \tag{27}$$

For $f_X(x)$, since the distance to the mailbox increases by 1 each time a migration takes place, we thus have

$$f_X(x) = x \tag{28}$$

E. An Iterative Algorithm for Calculating the Optimal Threshold Pair

The cost function of our scheme highly depends on the chosen threshold pair (d; n). Therefore, it is important to have a method to derive the optimal threshold pair to minimize the cost function. Since d and n can only be discrete values, the cost function is not a continuous function of d and n. Thus it is not appropriate to take derivatives with respect to d and n of the cost function to get at the minimum. We use an iterative algorithm similar to the one proposed in [11] although it may result in a local minimum. If we assume that the cost function follows a convex characteristic, this algorithm must produce the global minimum. Starting with $d = 1$ and $n = 1$, we iteratively increase d by 1 until the cost difference between the systems with the current and previous threshold pairs starts to be positive, i.e., d has reached its optimal value. We apply the same technique to find out the optimal value of n. The only difference is that we use $k \times ExpNum$ as the increment of n since n could be very large depending on $ExpNum$. A scale k is used to control the accuracy of n. A smaller value of k implies greater accuracy but requires more iteration. In our experiment, we choose k = 0.2. The mathematical presentation of the algorithm is presented below.

- Define the cost difference function:

$$\Delta(d,n,d',n') = Cost_{total}(d,n) - Cost_{total}(d',n')$$

where (d; n) and (d'; n') represents the current and previous threshold pairs, respectively.

- Initialization:

$d = 1; n = 1;$

- Step 1:

$$\begin{aligned} &while\ \Delta(d+1,n,d,n) < 0 \\ &\quad d = d+1; \\ &d_{optimal} = d; \end{aligned}$$

- Step 2:

$$\begin{aligned} &while\ \Delta(d_{optimal}, n + k \times ExpNum, d_{optimal}, n) < 0 \\ &\quad n = n + k \times ExpNum; \\ &n_{optimal} = n; \end{aligned}$$

F. Cost Function for Mobile IP Route Optimization with Smooth Handoff Extension

Let us first define some new parameters.

- $Cost_{HARegistration}$: the signaling cost of registering the home agent;
- $Cost_{retransmission}$: the abnormal packet delivery cost due to packet loss and retransmission; it is important to notice that the packet is retransmitted from the sender instead of the mailbox as in our scheme.

The following diagram depicts the network scenario about smooth handoff.

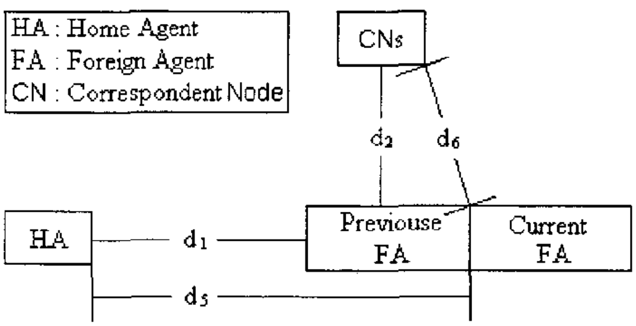

Figure 14. Network scenario about smooth handoff

During each handoff, the Current FA will send registration messages to both the home agent and the Previous FA. It also updates each correspondent node's binding cache. So

$$Cost_{signaling} = Cost_{HARegistration} + Cost_{update} \tag{29}$$

$$Cost_{HARegistration} = (m + 1 + d_5)\delta_{C_s} \tag{30}$$

The packet forwarding cost is somewhat similar to that in our scheme when the home handoff occurs at its first handoff. The only difference is the retransmission cost.

$$Cost_{packet} = Cost_{normal}(1,1) \times \frac{T_{normal}(1,1)}{T(1,1)} + Cost_{retransmission} \times \frac{T_{retransmission}(1,1)}{T(1,1)} \tag{31}$$

$$Cost_{retransmission} = (d2 + m + d6 + m)\delta_{C_s} \tag{32}$$

IV. PERFORMANCE EVALUATION

In this section, we compare the performance of our scheme under the two walk models with that of the benchmark scheme which is Mobile IP route optimization with smooth handoff extension. Note that the values of expressions (3) and (30) vary as d_5 varies. Also (32) changes as d_6 changes its value. To be more convincing, we compare our scheme under the worst case with the smooth handoff under the best case. Therefore, we take the upper bound value of (3) when d_5 is in its maximum $d_1 + f_X(X)$, and the lower bound value of (30) and (32) when d_5 and d_6 are in their minimum $d_1 - 1$ and $d_2 - 1$, respectively. Table III lists some of the parameters used in our performance evaluation. We set δ_{C_s}, the signaling transmission cost per hop, as a normalized value 1. The packet delivery cost per hop δ_{C_p} is twice as high as the signaling cost. δ_{T_s} could be viewed as the signaling processing time on a router and we set it 0.05 sec. We also assume the transmission cost (the transmission delay) in a wireless environment is twice as high (long) as that in the wired environment. Finally, there are five active correspondent nodes.

TABLE III. PARAMETERS USED FOR EVALUATION

δ_{C_s}	δ_{C_p}	δ_{T_s}	m	N
1	2	0.05 (sec)	2	5

Other parameters that might affect the cost function are $ExpNum$, d_1 and d_2. We choose $ExpNum$ as the x-axis and select two (d_1; d_2) pairs: (100; 0) and (0; 100). The first pair visualizes the scenario when the mobile node is far away from the home agent while close to its correspondent nodes and the second pair shows the scenario in a reverse condition.

Fig. 15 shows the changes of the optimal threshold d with different $ExpNum$. In general, d decreases as $ExpNum$ increases no matter which distance pair and walk model are used. This is because when $ExpNum$ gets bigger, that is to say, the mobile node is expected to receive more packets during its residence time in the new foreign network, it is thus not economical to leave the mailbox at its old place which will result in suboptimal route. By decreasing the value of d, it is more likely that this threshold is met and the home handoff occurs at an early time before the suboptimal route becomes severe. Under the same (d_1; d_2) pair, directional model has a little bit higher value of d. This is because, should the same d be used, the random walk model usually takes more local handoffs before a home handoff takes place than the directional walk model. Thus the directional walk model must not be in its optimum since the home handoff occurs so early that the cost saving due to local handoffs cannot make up the cost wasting due to the home handoff. With a larger d, the directional walk model can achieve a balance between cost saving and wasting so as to achieve the optimum.

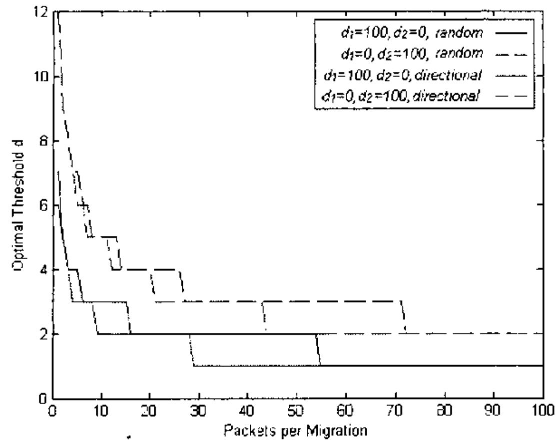

Figure 15. Optimal threshold *d*

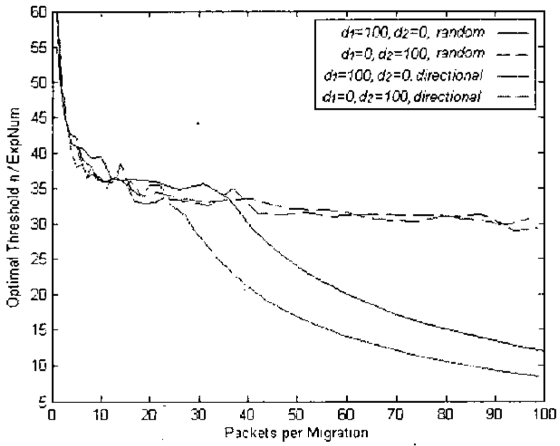

Figure 16. Optimal threshold *n/ExpNum*

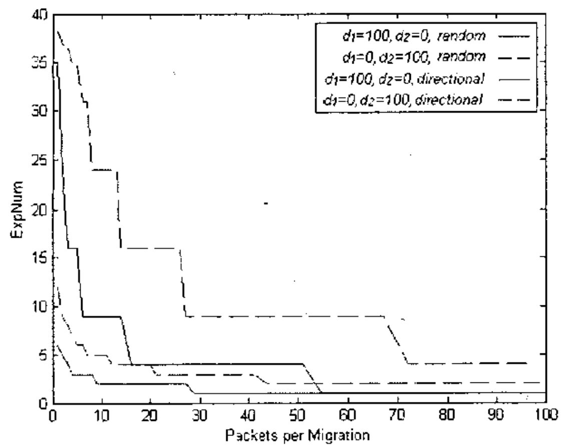

Figure 17. *ExpNum*

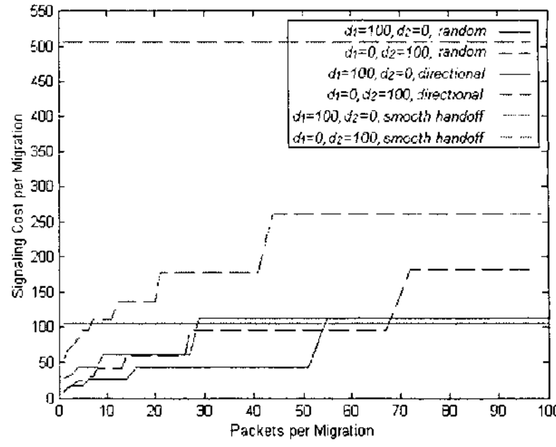

Figure 18. Signal cost per migration

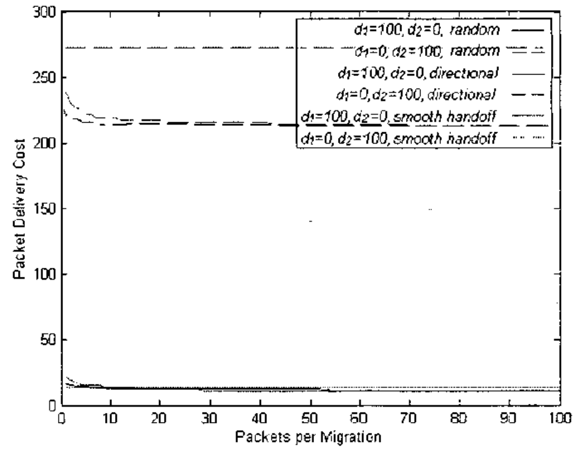

Figure 19. Packet forwarding cost

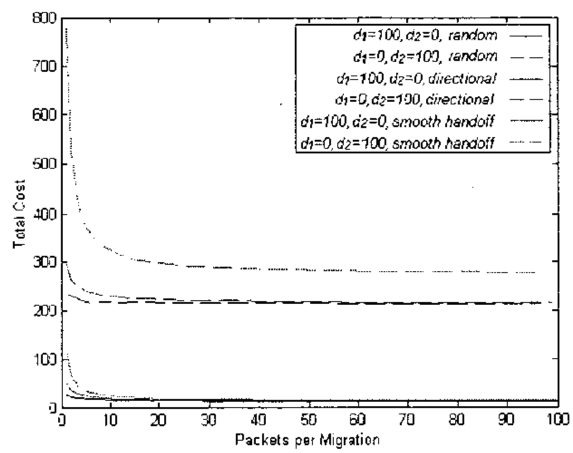

Figure 20. Total cost

Fig. 16 demonstrates the changes in the optimal threshold n with different *ExpNum* and we can make similar observations as in Fig. 15. However, we use "Optimal Threshold $n/ExpNum$" as y-axis instead of just n. This is because with the increase of *ExpNum*, n should also increase. But the increasing rate of n is not as fast as the increasing rate of *ExpNum* so as to make the home handoff more likely with larger *ExpNum*.

In Fig. 17, we can see that with increasing *ExpNum*, the expected number of local handoffs before a home handoff occurs drops due to the shrink of both d and n.

The last three figures show the signaling transmission cost, packet forwarding cost as well as the total cost, respectively. We observe that our scheme outperforms the smooth handoff scheme in all of the three costs, especially when *ExpNum* is small. This is because with small *ExpNum*, our scheme takes more advantages of the local handoffs and thus saves more cost. As *ExpNum* increases, the signaling cost of our scheme increases to approach that of the smooth handoff, which means that it is getting more and more likely that the home handoff occurs after the first handoff the mobile node just as the smooth handoff. The packet delivery cost is basically a decreasing curve due to the more optimal route. However, due to the large difference in retransmission cost, the packet delivery cost of our scheme will always outperform that of the smooth handoff provided that the correspondent nodes are not in the same network as the mobile node. The same reason applies to the total cost.

V. RELATED WORKS

In [6], a hierarchical mobility management scheme is proposed in which foreign agents are organized into hierarchy according to regional topology. Locality in user mobility is exploited to restrict handoff processing to the vicinity of a mobile node, which is quite similar to our idea of differentiating local handoff from home handoffs. It thus reduces handoff latency and the load on the inter-network. However, locality in this scheme depends on how the foreign agents are structured and once the hierarchy is built, it will not change. In our scheme, locality is a dynamic concept and can be changed adaptively by choosing a threshold set properly.

The reliability of [6] is enhanced in [7] by adding buffer to all the foreign agents so that the packet loss during the migration of a mobile node is eliminated. The buffer concept is quite like our mailbox. Actually, we can consider it as a special case of our mailbox with d = 1 or n = 0, i.e., the mailbox always stays with its owner. The efficiency of [6] is extended in [8] by introducing a new concept called "patron service". The patrons are the nodes from which the majority of traffic for the mobile node originated. So location updates can be limited to only those patrons.

VI. CONCLUSIONS

In this paper, we proposed a novel, mailbox-based scheme for improving Mobile IP's performance. The scheme has the following features: reduced work load on the home agent, reduced packet loss, fast handoff, per-user-based adaptive location management and dynamic tradeoff between the packet delivery cost and the registration cost. The performance evaluation conducted shows a very sound result that demonstrates the benefits of using mailbox, especially when the home agent is far away. Further study might deal with dynamic choice of the threshold pair (d; n) in order to achieve the best overall performance.

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