Explicit Proactive Handoff with Motion Prediction for Mobile IP

Fang Feng, and Douglas S. Reeves
Departments of Electrical and Computer Engineering and Computer Science
North Carolina State University
Raleigh, NC 27695
Tel: (919)513-7309, Email: {ffeng, reeves}@eos.ncsu.edu

***Abstract*— Mobile IP has been widely accepted, but lacks a fast handoff mechanism. In this paper, we introduce an explicit proactive handoff scheme with motion prediction. Since each user has patterns of movement, a mobile node predicts its future motion and explicitly notifies its old foreign agent which subnet it is likely to handoff to. During a handoff, the old foreign agent duplicates and forwards packets to the predicted subnets. With our scheme, network-layer handoff latency can be reduced to the level of link-layer handoff latency, and the number of packets lost during handoffs is also minimized. With a real network activity trace, we demonstrate that this scheme is able to predict motion accurately, with only a small overhead in bandwidth consumption and computation.**

I. Introduction

Wireless local area networks (WLANs) have become extremely popular in these years. Link-layer mechanisms provide support for link-layer handoff, which is used to switch a mobile node (MN) from the radio link of one access point (AP) to that of another access point. For WLANs connected by an IP backbone, Mobile IP [1] is the protocol for location management and network-layer handoff. This updates the routing information for the MN, to reflect movement from one subnet to another subnet.

Mobile IP, however, still has problems. First, it uses IP packets to transfer mobility management information. The latency of network-layer handoff is in the order of 0.1 to 1 second, 10 times larger than link-layer handoff latency. This cannot meet the requirement of delay-sensitive or real-time traffic. The second problem is handoff disruption. Mobile IP doesn't buffer packets sent to an MN during handoffs. Therefore, these packets may be lost and need to be retransmitted. The third problem is that the two types of handoffs are coupled. Because of the latency gap between them, packet loss will occur even after the completion of link-layer handoff.

In most circumstances, an MN is carried by an individual. As a result, it will be moved according to hourly, daily or weekly patterns corresponding to a person's regular activities. Packet arrival patterns also depend on the services and applications the person uses. Significant changes to these patterns are likely to be infrequent. Studies of wireless networks by Tang [2] [3] and Kotz [4] confirm this observation. An MN's patterns can be utilized to predict its future behavior and assist handoff. With prediction, it is possible to prepare network-layer handoff before link-layer handoff to reduce latency and packet loss. The MN's optimal handoff strategy should also be adjusted dynamically according to the prediction to minimize handoff cost. Handoff decisions based on movement prediction eliminates the need to wait for beacon signals from other subnets, and assists the discovery of handoff target in an environment of overlapping coverage areas and changing wireless channel conditions.

Based on these observations, we propose an explicit proactive handoff scheme with motion prediction for Mobile IPv4. It adopts a proactive approach to prepare network-layer handoff before link-layer handoff. Each MN records its movement patterns and predicts its future subnets. Before link-layer handoff, the MN explicitly notifies its current foreign agent (FA) of the predicted subnets. The current FA then duplicates packets sent to this MN, and forwards them to these predicted subnets. Network-layer handoff latency is close to that of link-layer handoff, and packet loss is reduced by buffering forwarded packets at FAs. This scheme is fully distributed because the network-layer handoff is controlled by the MN, and FAs are notified only if the MN recommends packet forwarding. The extra bandwidth consumption introduced is much less than that of other proactive handoff schemes.

The rest of this paper is organized as follows. We first review some of the related work in Section II. In Section III, the proposed scheme is described. We evaluate its performance with simulation results in Section IV, and Section V is the conclusion and future work.

II. Related Work

A number of schemes have been proposed to solve the problems of Mobile IP mentioned above. Here we focus on dedicated fast handoff schemes, which can be categorized as reactive, proactive, or a combination of the two according to whether the packets sent to the MN start to arrive at the new subnet after or before the link-layer handoff.

A. Reactive Handoff

In simultaneous 802.11 and MIPv4 handoff [5], when an MN associates with a new AP, it sends MIPv4 registration information to the new FA. This information is contained within 802.11 frames, and initiates MIPv4 location registration process. This scheme reduces handoff latency, but doesn't solve the problems caused by the latency gap between link-layer handoff and network-layer handoff.

[6] utilizes a filtering database and a MAC bridge connecting WLANs. When an MN associates with a new WLAN, its MAC address is broadcast locally by the new AP. It is received by the MAC bridge and stored in the filtering database, along with the corresponding port. Before the MN completes network-layer handoff, the MAC bridge relays MAC frames for the MN from the old WLAN to the new WLAN. Scalability and reliability may be problems for this scheme, due to its dependence on a centralized bridge mechanism.

B. Proactive Handoff

The Daedalus project [7] uses IP multicast and buffering to reduce packet loss. Each base station and its neighboring base stations form a multicast group. When an MN connects to a base station, it registers a corresponding multicast address at the home agent (HA). Using this address, packets are multicast to and buffered at the base stations of this multicast group. If an MN switches to a neighboring base station, it can receive packets before performing a network-layer handoff to register a new multicast address.

E. Shim et al. used neighborcasting [8] to achieve low latency handoff. An MN can transfer its old FA information to the new FA, which then constructs a neighbor table. Before link-layer handoff, the MN notifies the old FA to forward duplicated packets to all neighboring FAs. Network-layer handoff latency can be reduced significantly in this scheme.

R. Hsieh et al. proposed a seamless handoff architecture for Mobile IP [9]. A decision engine is added to the architecture of hierarchical Mobile IPv6. A handoff is initiated by an MN when it receives beacon signals from neighboring access routers (ARs). And the decision engine uses location tracking information of the MN and load information of these ARs to determine handoff time and target. Packets sent to the MN are initially forwarded to the new AR by the old AR, and simulcasted to both ARs after the old AR requests simulcast. This scheme successfully reduces network-layer handoff latency and packet loss, but it is centralized, requires extra signaling and imposes a bound on the speed of MNs.

C. Combined Handoff

Low latency handoff [10] [11] utilizes the L2 trigger mechanism (described in section III-B). In pre-registration handoff, an MN performs network-layer handoff before the link-layer handoff, based on information from the L2 trigger. In post-registration handoff, an MN first completes link-layer handoff. It continues using the old FA and care-of address (CoA) through a bi-directional tunnel between the old FA and the new FA. The combined handoff method first tries a pre-registration handoff. If it fails, post-registration handoff is used.

Simultaneous Binding [1] [13] aims at decoupling network-layer handoff from link-layer handoff, by enabling an MN to bind to multiple subnets simultaneously. An MN can retrieve the FA/CoA information from the beacon signals of APs, and register multiple CoAs with the HA before or after the link-layer handoff. The HA or correspondent node (CN) forwards duplicated packets to these CoAs simultaneously until the MN completes network-layer handoff.

Y. Gwon et al. introduced Mobile Initiated Tunneling Handoff [14]. Before disconnecting from the old AP, an MN can initiate a handoff by sending the old FA a handoff request containing the new FA's information got from the mobile pre-trigger. Or it can initiate the handoff process after connecting to the new AP and receiving a link-up trigger, and send the new FA a handoff request containing the old FA's information. A bi-directional tunnel is set up between these two FAs for the MN until it completes Mobile IP registration. This scheme achieved low latency and low loss handoffs with less requirements on L2 triggers and access networks than other fast handoff schemes.

Generally the proactive approach provides better performance, since packets are forwarded to the new subnet in advance. But these proactive schemes can cause unnecessary handoff preparations and forward too many duplicated packets. Neighborcasting forwards duplicated packets to all neighbor FAs without considering the MN's moving direction. With simultaneous binding, an MN binds to any subnet from which it can receive a beacon signal, although in fact it may not directly move to all these subnets. As argued in the shadow cluster concept [12], a MN has influence near its current location and along its anticipated path, and resource reservation should be made for the MN based on the predicted demands. This idea can be applied to improve the performance of proactive handoff, and is one of the major motivations of our proposal.

III. Proactive Handoff with Motion Prediction

A. Motivations

We wish to minimize the effort and optimize the performance of network-layer handoff when an MN is moving among WLANs connected by an IP backbone. Each MN predicts its future movement based on the recorded movement patterns, and use this to prepare network-layer handoff to reduce handoff latency and packet loss.

Handoff decision based on movement patterns eliminates the need for the MN to wait for beacon signals from neighboring subnets, which typically takes hundreds of milliseconds. Handoff target discovery only based on received signal strength can be a problem when the MN is in the overlapping coverage areas of multiple subnets and wireless channel conditions have great fluctuation. Movement patterns can provide another criterion to find the most possible handoff target in such a case.

Movement pattern and motion prediction are only concerned with network-layer movement, i.e., the logical movement between subnets. Physical or geographic location is of no importance to our scheme. We speculate that network-layer movement is simpler and more predictable than geographic movement, and is more meaningful for our purposes. For example, since subnets are of different shapes and sizes, an MN's geographic movement parameters may not directly correspond to its regular activities, which on the other hand can be inferred by its network-layer movement.

It is also desirable to impose as few modifications to Mobile IPv4 as possible, and to require the minimum amount of additional capabilities from the link layer. After describing the method, we will return to these stated motivations.

B. System Overview

The system is assumed to have multiple WLANs connected by a wired IP backbone. Mobile IPv4 is used for location management among subnets. The proposed proactive handoff scheme is used to reduce the latency and packet loss of network-layer handoff. Authentication and authorization of users are issues that must be handled by separate protocols.

The proposed scheme utilizes the L2 (layer 2) "trigger" mechanism[1]. The "Mobile Trigger" notifies the MN about an impending link-layer handoff, and the "Link-Up Trigger" informs the FA that an MN has connected to the radio link of its subnet. Beacon signals (link-layer frames) periodically transmitted by each AP contain information for both link-layer and network-layer handoffs, such as the ID of the AP, the AP's frequency hopping or direct sequence parameters, the subnet ID and the IP address of the FA in that subnet, etc. Therefore an MN does not need to wait for an FA advertisement to initiate location registration when it connects to the radio link of an AP in another subnet.

Two new messages are needed at the network layer. The first, the Forwarding Request message, is sent from an MN to the FA of its current subnet once the movement is predicted and the MN decides to handoff. This message contains the ID(s) and FA IP address(es) of the subnet(s) to which duplicated packets should be forwarded. The second, the Stop Forwarding message, is sent by the MN's HA to its previous FA once the MN completes location registration. This informs the previous FA to stop forwarding duplicated packets.

The MN is responsible for recording network-layer movements. From this movement history, the MN will predict its future motion using the path prediction algorithm. Each MN maintains a FIFO movement history cache. An entry in the movement history cache records the ID of a subnet to which the MN was previously attached, the start time of this attachment, and the IP address of the FA in that subnet. After the MN connects to the radio link of a new subnet, it creates a movement history cache entry of this connection, according to the beacon signal. It also has a pattern database to store movement patterns, which are sequences of movement history cache entries.

C. Handoff Process

Figure 1 shows the message diagram of a handoff. The handoff process is described as the following:

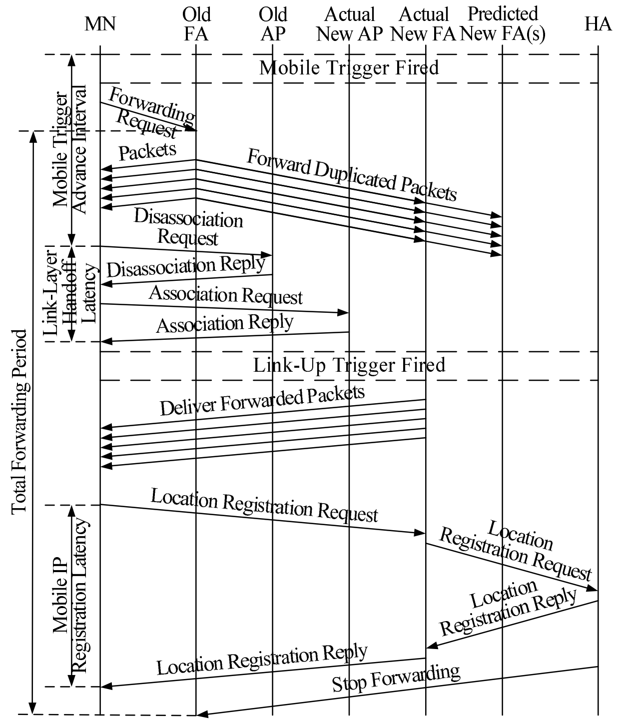

Fig. 1. Message Diagram during a Handoff

1) The MN moves to a subnet boundary. The Mobile Trigger informs the MN about an impending link-layer handoff when the received signal strength from the current AP falls below the threshold level.
2) The MN, with the information in its movement history cache and pattern database, uses the path prediction algorithm to predict the subnet or subnets to which it is likely to move. (If the history data is not sufficient to make a prediction, the MN will randomly choose one of the neighboring subnets as the predicted subnet. If it is first time that the MN associates with the current subnet, it will not do any proactive handoff, and the standard Mobile IPv4 mechanism will be used.) The number of predicted subnets can be pre-defined.
3) If there is a predicted subnet or subnets, the MN sends the ID(s) and FA IP address(es) of the predicted subnet(s) to the current FA. They are sent in a Forwarding Request message.
4) Data packets sent to the MN during the handoff are first tunneled to the current FA by the HA, or directly by the CN with route optimization. The current FA first decapsulates these packets, and then duplicates and forwards them to the FA(s) of the predicted subnet(s) using IP-within-IP encapsulation. The predicted FA(s) decapsulates and buffers these data packets in anticipation of the arrival of the MN.
5) If the MN continues moving, it eventually performs a link-layer handoff to connect to the radio link of an AP in the new subnet. A new entry for this movement is created in the movement history cache. The MN then compares the ID(s) of the predicted subnet(s) with the

[1]As specified in the Internet Draft "Supporting Optimized Handover for IP Mobility - Requirements for Underlying Systems"

ID from the beacon signal of the new AP.

6) If the prediction was not correct, the duplicated packets sent to the predicted FA will not reach the MN. These packets will eventually have to be retransmitted, as is normally the case without proactive handoff. Therefore the scheme falls back to the standard Mobile IPv4.
7) If the prediction was correct, the Link-up Trigger informs the FA of the new subnet to deliver its buffered data packets to the MN.
8) The MN registers its new care-of-address with the HA using Mobile IPv4 mechanisms.
9) The HA sends a Stop Forwarding message to the old FA to finish the handoff process.

Our scheme can also work in conjunction with other schemes to determine the handoff target. A separate mechanism can initially choose a certain subnet as the handoff target according to a variety of criteria such as the functionality of this subnet. Then our scheme will capture such a regular behavior and use it to predict the future network-layer movement of this MN.

The extra overhead of our scheme includes the cost to record movement history and do prediction, the transmission and processing cost of Forwarding Request and Stop Forwarding messages, and the cost to duplicate and forward data packets.

D. Path Prediction Algorithm

There have been a number of mobility models, such as the fluid flow model and the random walk model. These models describe the aggregate behavior of the MNs, and each MN's movement is independent and random from the system's view. These models also describe movement in terms of the change in the physical location of the terminals, rather than in terms of the change in the subnets they attach to. Therefore, we adopted an improved version of the motion prediction algorithm proposed by Liu and Maguire [15]. This method is designed for tracking individual MNs using historical movement patterns, and is based on logical movements rather than geographical movments.

In this model, an MN enters a new state when it connects to the radio link of a subnet. If it stays connected to this subnet for more than a specified period of time, this state is a *stationary* state. Otherwise it is a *transitional* state. A *movement track* (MT) models the movement of a MN on a regular route, starting from and ending at different stationary states. A *movement circle* (MC) models the MN's long-term regular behavior, and starts from and ends at the same stationary state.

For prediction purposes, the algorithm attempts to correlate current movement (i.e., a sequence of subnets that has just been visited) with past movement (i.e., a sequence of subnets that was visited at some previous time and stored in the pattern database). There are three types of matching for correlation analysis. The first type is *state-matching*, which indicates the fraction of states in common between the current sequence and a past sequence. In Equation 1, m_s is the number of identical states and N_s is the total number of states.

$$\mu = \frac{m_s}{N_s} \tag{1}$$

The second type of matching is *velocity-matching*. This indicates the similarity between the movement velocities of the current sequence and a past sequence. In Equation 2, $(t_{i+1} - t_i)_j$ is the interval between state i and state $i+1$ of sequence j.

$$\eta = \frac{\sum_{i=1}^{N_s-1} |(t_{i+1} - t_i)_{current} - (t_{i+1} - t_i)_{past}|}{N_s - 1} \tag{2}$$

We propose a third type of matching, called *occurrence-matching*. Let $T_{current}$ be the starting time of the current sequence, $T_{past,L}$ be the time of the last occurrence of some past sequence, and $\tau_{past,k}$ be the kth interval between two consecutive occurrences of this past sequence. Equation 3 computes how close the interval between the current sequence and the last occurrence of a past sequence matches the interval between any two consecutive occurrences of the past sequence.

$$\Phi = \min_k \frac{|(T_{current} - T_{past,L}) - \tau_{past,k}|}{\tau_{past,k}} \tag{3}$$

When an MN connects to the radio link of a new subnet, it enters a new transitional state. If it stays attached long enough, this state becomes stationary, and the MN starts pattern detection. It uses state-matching to correlate the current sequence in the movement history cache with each MT and MC stored in the pattern database. If there is no match, the current sequence is added to the pattern database, otherwise the information of this MC/MT in the pattern database is updated. Then the current sequence is removed from the movement history cache if necessary. When a Mobile Trigger fires, the MN initiates the handoff process and starts motion prediction. It correlates the current sequence in the movement history cache to the stored MCs and MTs, using (in order) state-matching, then velocity-matching, and after that occurrence-matching, until one of the MC/MT matches the current sequence. The subnet at the corresponding position of the final matched MC/MT is the predicted subnet. The number of predicted subnets can be adjusted as required by the MN. The MN can also optionally maintain a transition probability matrix among the subnets, for use in case the current movement does not match any previously-stored pattern.

IV. Performance Evaluation

There are several ways to evaluate the performance of the proposed proactive handoff scheme. To evaluate its effectiveness, we use handoff latency and prediction miss rate. To evaluate its efficiency, we use the fraction of duplicated packets in all packets, which indicates how many extra data packets are generated by our scheme.

A. Simulation Scenario

For purposes of evaluation, we simulated handoff behavior of a set of mobile nodes. This simulation is based on an actual trace taken from the campus-wide wireless network of

Dartmouth College [4]. It recorded the activities of almost 2000 MNs for an academic term in an IEEE 802.11b network which covers 161 buildings and contains 81 subnets. The trace includes characteristics of both residential and work-related movements, since it recorded the network activity in both dorms and academic buildings.

The trace contains time-stamps and information on MNs' association and reassociation activities with access points, but lacks details about the network topology, or reliable disassociation signaling. It also does not distinguish a direct handoff with the case that an MN was turned off, moved to another subnet and turn back on. Due to the limitation of the trace, we made the following assumptions in our simulation:

1) Each subnet has one and only one AP.
2) Each transition from a subnet to another subnet is a direct handoff.
3) Each MN stays at a subnet until it associates with another subnet.
4) Two subnets are neighbors if and only if there is at least one transition between them.
5) Reassociation to the same subnet is not a handoff.

There is no training period in our simulation. For purposes of computing packet loss and duplication rates, we used a simulated CBR traffic, with a packet interarrival time of 3.75ms for easier comparison with other proposed schemes. Since our scheme is for highly mobile users, we only show the simulation result for the mobile nodes with at least an average of 6 handoffs daily; there were 585 such MNs. For performance comparison purposes, we assume link-layer handoff latency is 50ms, and Mobile IP registration latency is uniformly distributed between 200ms and 700ms. We simulated the performance of our scheme for the case of one predicted subnet, and two predicted subnets.

B. Handoff Latency

Figure 2 shows the distribution of the average network-layer handoff latency of each MN, using our scheme with prediction of one or two subnets. It can be seen that the latency of our scheme is much less than that of Mobile IP, and quite close to link-layer handoff latency. With prediction of two subnets, the latency of our scheme is less than 160ms for about 80% of the MNs. This is 3X faster than normal Mobile IP handoff latency.

The average time to compute a prediction was less than 0.15 ms per handoff on a Pentium IV 1.7GHz PC with 256MB memory. Therefore we speculate that the algorithm is more than fast enough to support proactive handoff, even on a PDA-type device.

C. Prediction Miss Rate

In Figure 3, we show the distribution of prediction miss rate of each MN, using our scheme with prediction of one or two subnets. With prediction of two subnets, about 80% of the MNs have a prediction miss rate less than 0.3. With prediction of one subnet, about 80% of the MNs have a prediction miss rate of less than 0.46. Compared with the miss rate of randomly selecting one or two neighboring subnets, our proposed scheme has a much lower miss rate. Only about 8% of the MNs have a miss rate less than 0.3 when randomly selecting 2 neighbor subnets. Neighborcasting sends packets to all neighboring subnets, and so should represent the lower limit of the prediction miss rate. Its miss rate is shown by the leftmost line in the figure, and is greater than zero because a miss is incurred when a movement from one specific subnet to another occurs for the first time. Our result using prediction of two subnets is quite close to this limit. This confirms the value of predicting MN movement based on past history. We believe that prediction using more complete traces, with information about network topology and MN power-down events, should do even better.

Using our scheme with prediction of two subnets, the average number of packet losses per handoff due to prediction misses is about 19, compared with 133 for Mobile IP and 5 for neighborcasting.

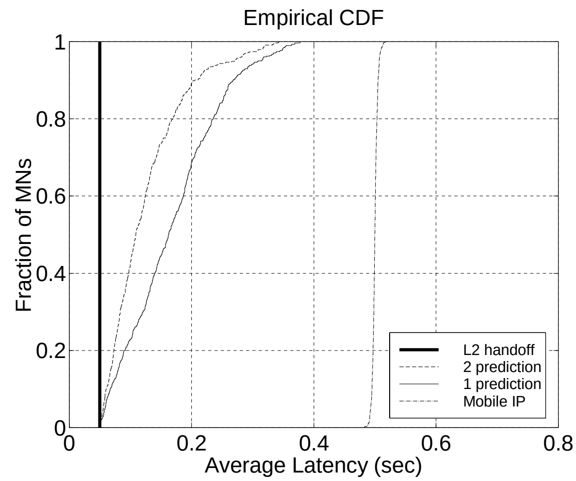

Fig. 2. CDF Plot of Average Handoff Latency

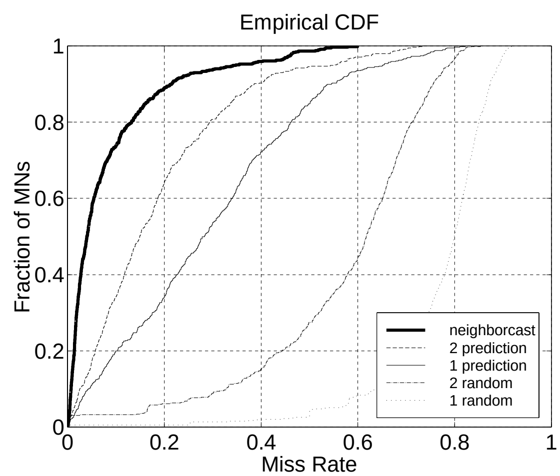

Fig. 3. CDF Plot of Prediction Miss Rate

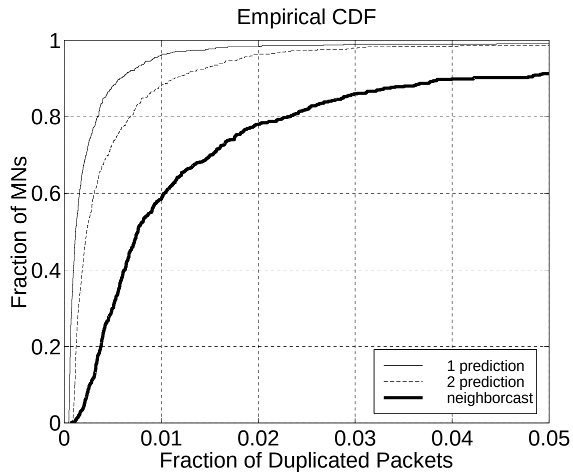

Fig. 4. CDF Plot of Fraction of Duplicated Packets

D. Extra Handoff Overhead

Section III discussed the extra overhead of the proposed scheme. Since our scheme is fully distributed, movement recording and prediction don't incur any cost to the network. The number of Forwarding Request and Stop Forwarding messages is trivial compared with the potential number of duplicated data packets, so we focus on measuring these duplicated data packets.

Figure 4 shows the distribution of the fraction of duplicated packets in the 585 MNs, based on CBR traffic sources. With prediction of two subnets, the fraction of duplicated packet is less than 0.011 for about 90% of the MNs, and less than 0.007 for 80% of the MNs. This is much better than neighborcasting. For instance, only about 45% of the MNs have a fraction of duplicated packets less than 0.007 with neighborcasting. Our scheme is even more efficient when there are multiple MNs leaving the same subnet at the same time and a burst of duplicated data packet occurs.

V. CONCLUSION AND FUTURE WORK

In this paper we proposed an explicit proactive handoff scheme based on the movement patterns of mobile nodes. An MN can anticipate a handoff from the L2 trigger, and use locally stored movement patterns to dynamically predict the next subnet. As a result, handoff latency and packet loss rate is dramatically reduced, with a cost of a small number of duplicated packets. This scheme works in a fully distributed fashion and introduces much less duplicated packets than another proactive handoff scheme, neighborcasting. It also eliminates the need to wait for beacon signals, and solves the problem of handoff target discovery when the coverage areas of multiple subnets overlap with each other. It does not require specific radio technology, or special routing techniques such as multicast. It keeps the current Mobile IP infrastructure and augments it to improve performance.

Our future work includes using a better trace, if available, to further demonstrate the benefits of the proposed scheme. We plan to extend this approach to the case of multi-tier wireless networks as the MN can proactively switch to subnets on different tiers according to its own pattern. We also plan to use it to enforce QoS in handoffs since an MN can negotiate handoff parameters with FAs according to its QoS requirements. Adoption of this scheme in Mobile IPv6 and implementation are also under consideration.

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