A Cross-Layer (Layer 2 + 3) Handoff Management Protocol for Next-Generation Wireless Systems

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Abstract—Next-generation wireless systems (NGWS) integrate different wireless networks, each of which is optimized for some specific services and coverage area to provide ubiquitous communications to the mobile users. It is an important and challenging issue to support seamless handoff management in this integrated architecture. The existing handoff management protocols are not sufficient to guarantee handoff support that is transparent to the applications in NGWS. In this work, a cross-layer (Layer 2 + 3) handoff management protocol, CHMP, is developed to support seamless intra and intersystem handoff management in NGWS. Cross-layer handoff management protocol uses mobile's speed and handoff signaling delay information to enhance the handoff performance of Mobile IP that is proposed to support mobility management in wireless IP networks. First, the handoff performance of Mobile IP is analyzed with respect to its sensitivity to the link layer (Layer 2) and network layer (Layer 3) parameters. Then, a cross-layer handoff management architecture is developed using the insights learnt from the analysis. Based on this architecture, the detailed design of CHMP is carried out. Finally, extensive simulation experiments are carried out to evaluate the performance of CHMP. The theoretical analysis and simulation results show that CHMP significantly enhances the performance of both intra and intersystem handoffs.

Index Terms—Next-generation wireless systems, handoff management, cross-layer protocol design, ubiquitous communications.

1 Introduction

Rapid progress in the research and development of wireless networking and communication technologies has created different types of wireless communication systems, such as Bluetooth for personal area, IEEE 802.11-based WLANs for local area, Universal Mobile Telecommunications System (UMTS) for wide area, and satellite networks for global networking. These networks are complementary to each other and, hence, their integration can realize unified next-generation wireless systems (NGWS) that have the best features of the individual networks to provide ubiquitous "always best connection" [11] to the mobile users [3].

In the integrated NGWS, users are always connected to the best available networks and switch between different networks based on their service needs [3]. It is an important and challenging issue to support seamless mobility management in the NGWS. Mobility management contains two components: location management and handoff management [2]. Location management enables the system to track the locations of mobile users between consecutive communications. On the other hand, handoff management is the process by which users keep their connections active when they move from one base station (BS) to another. There exist efficient location management techniques in the literature for NGWS [36], [37]. However, seamless support of handoff management in NGWS is still an open research issue [4].

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Fig. 1 shows a typical handoff scenario in the NGWS. The integrated architecture in Fig. 1 consists of two different wireless systems, System A and System B. These two systems are integrated through the Internet backbone [3]. It may be noted that, in a real scenario, the integrated architecture may consist of many different wireless systems. Fig. 1 shows the architectural components of the hierarchical Mobile IP [12] protocol. In NGWS, two types of handoff scenarios may arise: horizontal handoff and vertical handoff [4], [31].

- *Horizontal Handoff*. Handoff between two BSs of the same system. Horizontal handoff can be further classified into
  - *Link-Layer Handoff*. Horizontal handoff between two BSs that are under the same foreign agent (FA), e.g., the handoff of a Mobile Terminal (MT) from BS10 to BS11 in Fig. 1.
  - *Intrasystem Handoff*. Horizontal handoff between two BSs that belong to two different FAs and both the FAs belong to the same system and, hence, to same gateway foreign agent (GFA), e.g., the handoff of the MT from BS11 to BS12 in Fig. 1.
- *Vertical Handoff (Intersystem Handoff)*. Handoff between two BSs that belong to two different systems and, hence, to two different GFAs, e.g., the handoff of the MT from BS12 to BS20 in Fig. 1.

Efficient algorithms are present in the literature to support seamless link-layer handoff [39]. Therefore, in this work, we do not address the link-layer handoff. On the other hand, seamless support for intra and intersystem handoff is still an open issue [4]. The large value of signaling delay associated with the intra and intersystem

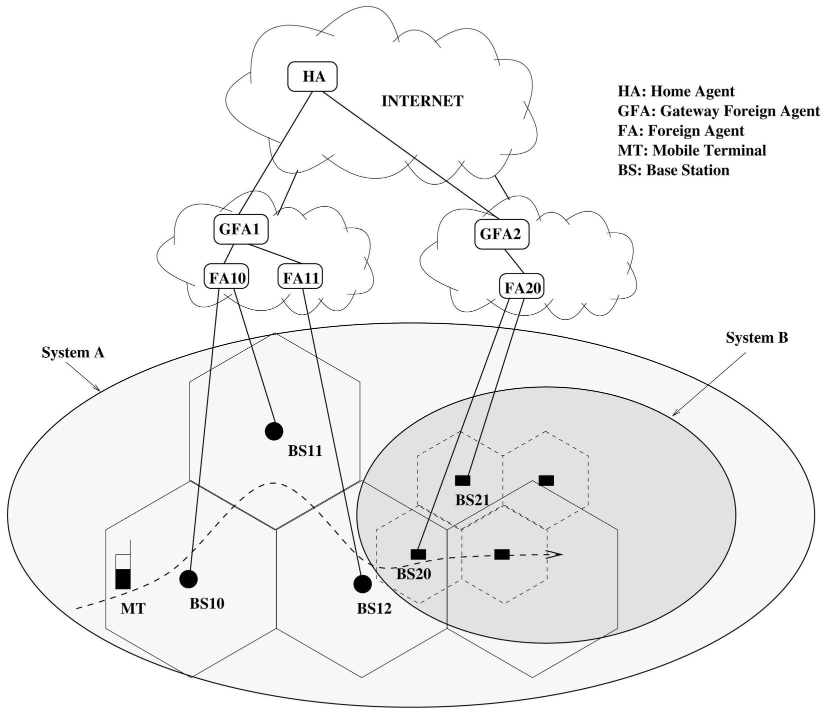


Fig. 1. Handoff in the integrated NGWS architecture.

handoff [9] can be higher than the threshold required for the support of delay-sensitive and real-time services [19]. In addition, the packets in transit during this high handoff latency period cannot be delivered to the MT. This results in significant packet loss during intra and intersystem handoffs. We advocate that efficient intra and intersystem handoff protocols should have the following characteristics to support seamless handoff in NGWS:

- **Minimum handoff latency**. The handoff management protocols should introduce only minimum handoff latency to the ongoing communications.
- **Low packet loss**. Packet loss during handoffs should be minimized.
- **Limited handoff failure**. Handover failure probability should be limited to a desired value.

Handoff management protocols operating from different layers of the TCP/IP protocol stack (e.g., link layer, network layer, transport layer, and application layer) are proposed in the literature [4]. Mobile IP [26] that operates from the network layer is proposed to support mobility management in IP-based networks. It forwards packets to mobile users that are away from their home networks using IP-in-IP tunnels [26]. Mobile-IP-based handoffs have significant handoff latency [4]. Transport layer mobility management protocols are proposed to support handoff management between different networks. These protocols eliminate the need for tunneling of the data packets. TCP-Migrate is proposed in [30] to support end-to-end transport layer handoff management. An architecture called MSOCKS is proposed in [20] for transport layer handoff management. MSOCKS implements transport layer handoff using a split-connection proxy architecture and a new technique called TCP Splice that gives split-connection proxy systems the same end-to-end semantics as usual TCP connections [20]. Moreover, work is going on in the IETF to modify the Stream Control Transmission Protocol [32] to allow it to dynamically change endpoint addresses in the midst of a connection [10], [13]. Recently, application layer handoff using Session Initiation Protocol (SIP) is proposed in [35]. SIP-based handoff does not require any changes to the TCP/IP protocol stack.

The standard network layer mobility management protocol, Mobile IP [26], is simple to implement, but has several shortcomings, such as *triangular routing*, *high global signaling load*, and *high handoff latency* [4]. Mobile IP route optimization [27] eliminates the triangular routing problem. Hierarchical Mobile IP [12] and other micromobility protocols such as Cellular IP [34], IDMP [22], and HAWAII [28] address the problem of high global signaling load and high handoff latency by introducing another layer of hierarchy to the base Mobile IP architecture to localize the signaling messages to one domain. Mobile IP handoff latency is composed of latencies for handoff requirement detection and Mobile IP registration [38]. The proposed hierarchical Mobile IP and micromobility solutions [22], [28], [34] particularly achieve reduction in registration signaling delay, but fail to address the problem of handoff requirement detection delay [38].

Therefore, recently, the use of link layer information to reduce the handoff requirement detection delay has gained attention [1], [4], [19]. The basic idea behind this approach is to use the link layer information to anticipate the possibility of an intra or intersystem handoff in advance so that the handoff procedures can be carried out successfully before the MT moves out of the coverage area of the serving base station (BS). The use of link layer information significantly reduces the handoff latency and handoff failure probability of handoff management protocols [4].

The user mobility profile (UMP) is used in [1] to support enhanced handoff management. The concept of intersystem boundary cells are used in [21] to prepare the users for a possible intersystem handoff in advance. This reduces the intersystem handoff failure probability significantly. A generic link layer technique is used in [19] to improve the handoff performance of Mobile IP. However, it does not specify any particular mechanism for obtaining the link layer triggers. Different link-layer-assisted handoff algorithms that use received signal strength (RSS) information to reduce handoff latency and handoff failure probability are proposed in [7], [38], [40]. However, these studies are limited to handoff between third-generation (3G) cellular networks and WLANs. There are some other studies such as S-MIP [15] that use RSS to track the MTs and then use their trajectory information to support low latency Mobile IP handoff.

The above link-layer-assisted handoff protocols implicitly assume that the handoff latency of the intra and intersystem handoffs are constant. Based on this assumption, these protocols initiate a handoff when the RSS of the serving BS drops below a predefined fixed threshold value. However, in a real scenario, signaling delay of the intra and intersystem handoffs depends on the traffic load in the backbone network, wireless link quality [6], and distance between a user and its home network at the handoff instance. Therefore, the protocols that are designed assuming a fixed signaling delay for intra and intersystem handoffs have poor performance when the handoff signaling delay varies. Moreover, the existing link-layer-assisted handoff protocols do not consider the influence of users' speed on the performance of the handoff protocols. Our analysis in Section 2 shows that users' speed has a significant effect on the performance of the handoff protocols. In addition, to the best of our knowledge, there is no existing work that determines how the link layer information can be used to guarantee desired performance in terms of handoff latency and handoff failure probability.

In this work, first, we analyze the performance of the existing network layer handoff management protocol, hierarchical Mobile IP (HMIP), with respect to its sensitivity to the link layer (Layer 2), e.g., users' speed, and network layer (Layer 3), e.g., handoff signaling delay parameters. We develop a cross-layer handoff management architecture using the results of our analysis. Then, using the architecture, we develop a cross-layer handoff management protocol, CHMP, to support enhanced handoff management in NGWS. The proposed CHMP uses mobile's speed and handoff signaling delay information and enhances the performance of HMIP handoff significantly. Finally, extensive simulation experiments are carried out to evaluate the performance of CHMP. The theoretical analysis and simulation results show that CHMP significantly enhances the performance of both intra and intersystem handoffs. CHMP jointly addresses all the desired characteristics of an efficient handoff management protocol mentioned earlier.

The remainder of this paper is organized as follows: We analyze the relationship between the handoff performance and different parameters such as mobile's speed and handoff signaling delay in Section 2. In Section 3, we develop our proposed CHMP protocol and carry out its performance evaluation in Section 4. Finally, we summarize the advantages of CHMP in Section 5.

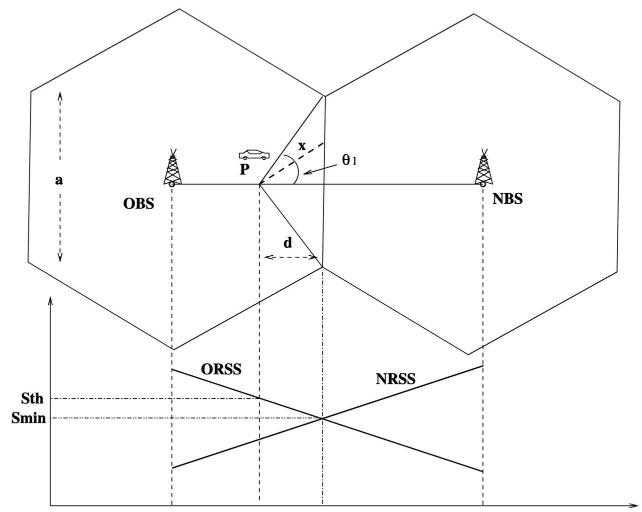


Fig. 2. Analysis of the handoff process.

2 Effect of Layer 2 and Layer 3 Parameters on the Performance of Handoff Management Protocols

In this section, we develop an analytical framework that answers the question: **How should the Layer 2 and Layer 3 information be used to make sure that the handoff performance remains the same irrespective of users' speed and network dynamics?**

We define the following notations with reference to Fig. 2, which shows a handoff from the current BS, referred as old BS (OBS), to the future BS, referred as new BS (NBS).

- S_{th}: The threshold value of the RSS to initiate the HMIP [12] handover process. Therefore, when the RSS of old BS (OBS), referred to as ORSS, in Fig. 2 drops below S_{th}, the HMIP registration procedures are initiated for MT's handover to the new BS (NBS).
- S_{min}: The minimum value of RSS required for successful communication between an MT and OBS.
- a: The cell size. We assume that the cells are of hexagonal shape.

We consider a scenario where an MT is currently served by OBS. We consider that the MT is moving with a speed v. We assume that v is uniformly distributed in $[v_{min}, v_{max}]$. Therefore, the probability density function (pdf) of v is given by

$$f_v(v) = \frac{1}{v_{max} - v_{min}} \quad v_{min} < v < v_{max}. \tag{1}$$

During its course of movement, the MT discovers that it is going to move into the coverage area of the NBS and, hence, needs to perform HMIP registration with the FA serving the NBS. We refer to this FA as new FA (NFA). The MT may learn about the possibility of moving into another cell when the RSS of OBS decreases continuously.

Once the MT discovers that it may enter into the coverage area of the NBS, the next challenge is to decide the right time to initiate HMIP registration procedures with the NFA. The existing link-layer-assisted HMIP protocols propose to initiate the HMIP registration when the RSS from the serving BS, e.g., OBS in Fig. 2, drops below a fixed threshold value (S_{th}). Below, we analyze the performance of these solutions.

We assume that, during the course of its movement, when the MT reaches the point P (the distance of P from the cell boundary is d) as shown in Fig. 2, the RSS from the OBS drops below S_{th}. Therefore, when the MT reaches P, it initiates the HMIP registration with the NFA. At this point, the RSS received by the MT from NBS shown as NRSS in Fig. 2 may not be sufficient for the MT to send the HMIP registration messages to NFA through NBS. Hence, the MT may send the HMIP registration messages to NFA through OBS. This is called preregistration [19]. For a smooth and successful handoff from OBS to NBS, MT's HMIP registration with NFA and link and MAC layer associations with NBS must be completed before the RSS of OBS drops below S_{min}, i.e., before the MT moves beyond the coverage area of OBS.

When the MT is located at point P (as shown in Fig. 2), we assume that it can move in any direction with equal probability, i.e., the pdf of MT's direction of motion θ is

$$f_\theta(\theta) = \frac{1}{2\pi} \quad -\pi < \theta < \pi. \tag{2}$$

We also assume that MT's direction of motion and speed remain the same from point P until it moves out of the coverage area of OBS. As the distance of P from the boundary of OBS is not very large, this assumption is realistic. For example, for an MT moving at 100 km/h, considering the handoff signaling delay of 2 sec, $d = 50$ m. A vehicle moving at this speed is not quite expected to change its speed and direction within a distance of 50 meters. For a smaller value of v and handoff delay, d will be much smaller (typically on the order of 10-30 meters).

From Fig. 2, it is clear that the need for handoff to NBS arises only if MT's direction of motion from P is in the range $[\theta \in (-\theta_1, \theta_1)]$, where $\theta_1 = \arctan(\frac{a}{2d})$. Otherwise, the handoff initiation is a false one. Therefore, using (2), the probability of false handoff initiation is

$$\begin{aligned} p_a &= 1 - \int_{-\theta_1}^{\theta_1} f_\theta(\theta) d\theta \\ &= 1 - \frac{2\theta_1}{2\pi} = 1 - \frac{1}{\pi} \arctan\left(\frac{a}{2d}\right). \end{aligned} \tag{3}$$

When the direction of motion of the MT from P $\beta \in [(-\theta_1, \theta_1)]$, the time it takes to move out of the coverage area of OBS is given by

$$t = \frac{d \sec\beta}{v}. \tag{4}$$

We know that the pdf of β is

$$f_\beta(\beta) = \begin{cases} \frac{1}{2\theta_1} & -\theta_1 < \beta < \theta_1 \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

From (4), t is a function of β, i.e., $t = g(\beta)$, where $g(\beta) = \frac{d \sec\beta}{v}$. Therefore, the pdf of t is given by [25],

$$f_t(t) = \sum_i \frac{f_\beta(\beta_i)}{|\acute{g}(\beta_i)|}, \tag{6}$$

where β_i are the roots of the equation $t = g(\beta)$ in $[-\theta_1, \theta_1]$. The equation $t = g(\beta)$ has two roots in the interval $[-\theta_1, \theta_1]$ and, for each of these roots, $f_\beta(\beta_i) = \frac{1}{2\theta_1}$, for $i = 1$ and 2. Therefore, (6) becomes

$$f_t(t) = \frac{1}{\theta_1 |g'(\beta_i)|}, \tag{7}$$

where $g'(\beta)$ is the derivative of $g(\beta)$ given by

$$g'(\beta) = \frac{d \sec\beta \tan\beta}{v} = t\sqrt{\frac{v^2t^2}{d^2} - 1}. \tag{8}$$

Using (7) and (8), the pdf of t is given by

$$f_t(t) = \begin{cases} \frac{d}{\theta_1 t\sqrt{v^2t^2 - d^2}}, & \frac{d}{v} < t < \frac{\sqrt{\frac{a^2}{4} + d^2}}{v} \\ 0 & \text{otherwise.} \end{cases} \tag{9}$$

The probability of handoff failure is given by

$$p_f = \begin{cases} 1 & \tau > \frac{\sqrt{\frac{a^2}{4} + d^2}}{v} \\ p(t < \tau) & \frac{d}{v} < \tau < \frac{\sqrt{\frac{a^2}{4} + d^2}}{v} \\ 0 & \tau \le \frac{d}{v}, \end{cases} \tag{10}$$

where τ is the handoff signaling delay and $p(t < \tau)$ is the probability that $t < \tau$. When $\frac{d}{v} < \tau < \frac{\sqrt{\frac{a^2}{4} + d^2}}{v}$, using (9),

$$\begin{aligned} p(t < \tau) &= \int_0^\tau f_t(t) dt \\ &= \int_{\frac{d}{v}}^\tau \frac{d}{\pi t\sqrt{v^2t^2 - d^2}} dt \\ &\approx \frac{1}{\theta_1} \arccos\left(\frac{d}{v\tau}\right). \end{aligned} \tag{11}$$

Now, using (10) and (11),

$$p_f = \begin{cases} 1 & \tau > \frac{\sqrt{\frac{a^2}{4} + d^2}}{v} \\ \frac{1}{\theta_1} \arccos\left(\frac{d}{v\tau}\right) & \frac{d}{v} < \tau < \frac{\sqrt{\frac{a^2}{4} + d^2}}{v} \\ 0 & \frac{d}{v} \ge \tau. \end{cases} \tag{12}$$

In the following sections, we provide a detailed discussion about the performance of HMIP handoff using the above mathematical formulations.

2.1 False Handoff Initiation Probability

It is clear from (3) that, if an unnecessarily large value for d (hence, the corresponding value of S_{th}) is used for handoff initiation, the probability of false handoff initiation increases. This results in the wastage of limited wireless system resources. Moreover, this increases the load on the network that arises because of the handoff initiation. The relationship between probability of false handoff initiation and d is shown in Fig. 3 for different cell sizes, a. Fig. 3 shows that, for a particular value of a, the probability of false handoff

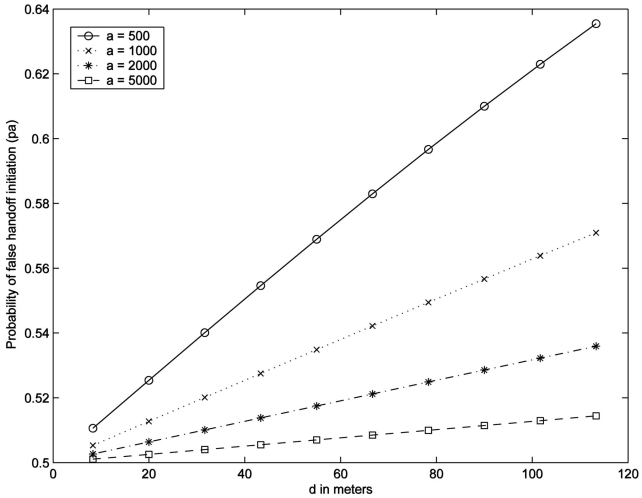


Fig. 3. Relationship between false handoff initiation probability and d.

initiation increases as d increases. It also shows that the problem of false handoff initiation becomes more and more severe when the cell size decreases. The cell size of wireless systems is decreasing so that the capacity and data rate may increase. Hence, in NGWS, it is important to select the proper value of d to reduce the false handoff initiation probability.

2.2 Relationship between Handoff Failure Probability and Speed

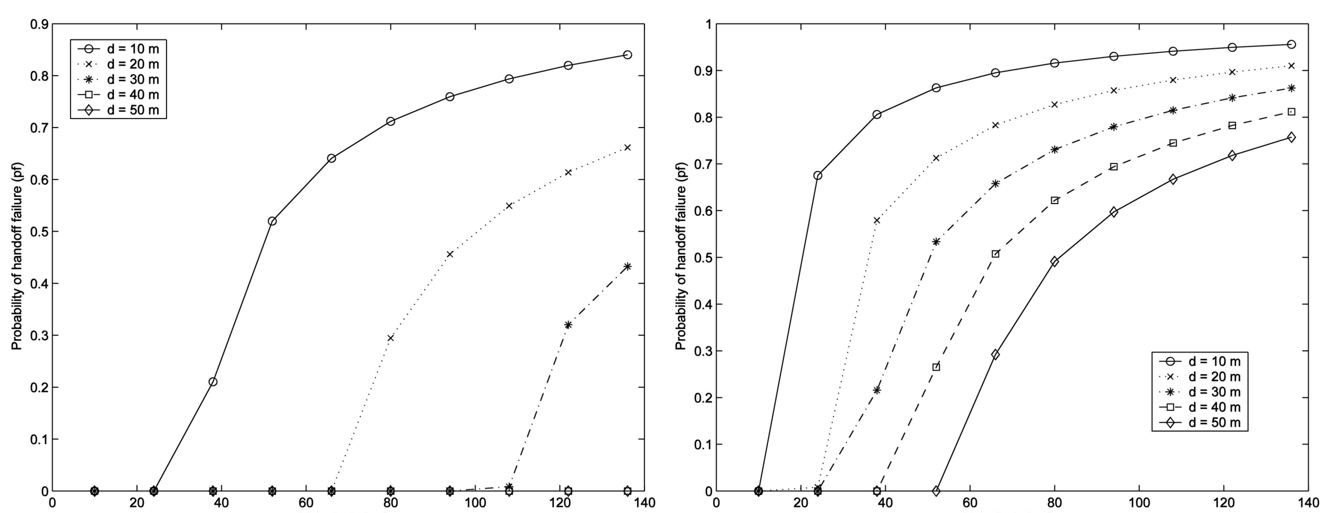
When

$$\frac{d}{v} < \tau < \frac{\sqrt{\frac{a^2}{4}+d^2}}{v},$$

(12) shows that, if a fixed value of S_{th} (hence, a fixed value of corresponding d) is used, the handoff failure probability depends on the speed of the MT. The probability of handoff failure, p_f, increases when MT's speed increases. The relationship between p_f and MT's speed is shown in Fig. 4a and Fig. 4b for intra and intersystem handoff, respectively. These figures show the numerical value of p_f for different values of d (corresponding to different values of S_{th}). We considered a cell size of 1 km for this simulation. The main difference between intra and intersystem handoff is the latency associated with the handoff process. The latency of intersystem handoff is significantly larger than that of intrasystem handoff because, during an intersystem handoff before HMIP registration, authentication and billing procedures are carried out [8], adding extra delay to the handoff process. Moreover, the intersystem HMIP signaling messages are handled by MT's home agent (HA) instead of gateway foreign agent (GFA), adding extra delay to the signal propagation as the distance of MT from HA is typically larger than that of MT from the GFA. We considered handoff latency, τ, of 1 sec and 3 sec for intra and intersystem handoff procedures, respectively. Fig. 4a and Fig. 4b show that, for a particular value of d, as speed increases, the handoff failure probability increases for both intra and intersystem handoff. This is because, as speed increases, on average, the MT requires less time to cross the coverage region of OBS. These figures also show that, when a particular value of S_{th} is used, p_f becomes higher for intersystem handoff compared to intrasystem handoff for a different speed. Therefore, it is not efficient to use the same value of S_{th} for intra and intersystem handoff. To summarize, this analysis shows that the value of d and, therefore, the value of S_{th}, should be adaptive to the speed of the MT and to the type of handoff to guarantee a desired handoff failure probability.

2.3 Relationship between Handoff Failure Probability and Handoff Signaling Delay

As we discussed earlier, handoff signaling latency in case of intra and intersystem handoff varies depending on network dynamics, e.g., congestion level, wireless link condition, and location of a user from its home network. Fig. 5 shows the relationship between handoff failure probability and handoff signaling delay when a fixed value of S_{th} is used;



(a) (b)

Fig. 4. Relationship between handoff failure probability and MT's speed: (a) for intrasystem handoff with $\tau = 1$ sec and (b) for intersystem handoff with $\tau = 3$ sec.

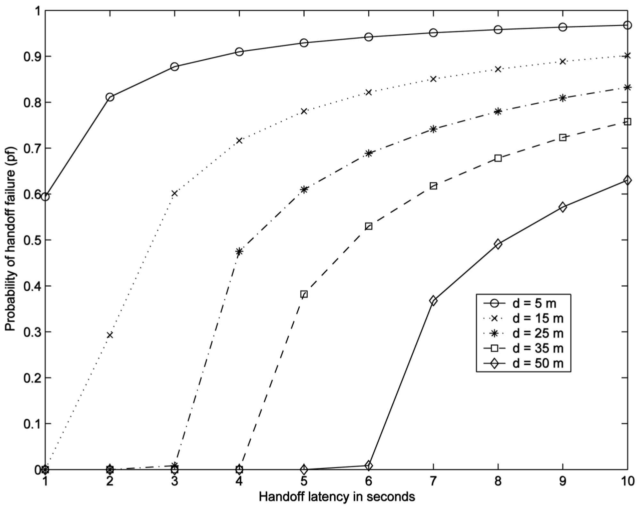


Fig. 5. Relationship between handoff failure probability and τ.

therefore, a fixed value of d is used. The higher values of τ correspond to intersystem handoff scenarios and the lower values of τ correspond to intrasystem handoff scenarios. Fig. 5 shows that, when a fixed value for S_{th} is used, handoff failure probability increases as handoff signaling delay increases. Therefore, to keep the handoff failure probability limited, it is essential to predict handoff signaling delay in advance and accordingly use an adaptive value for S_{th}.

To summarize, our analysis shows that, when a fixed value for S_{th} is used, handoff failure probability increases as MT's speed increases (as shown in Fig. 4a and Fig. 4b). Moreover, for a fixed value of S_{th}, handoff failure probability increases as handoff signaling delay increases (as shown in Fig. 5). Our analysis shows that an unnecessarily large value of S_{th} should not be used as it increases the probability of false handoff initiation (as shown in Fig. 3) and, hence, affects the performance of the system negatively. Therefore, we propose the use of adaptive S_{th} for handoff initiation. The exact value of S_{th} will depend on MT's speed and handoff signaling delay at a particular time. Our objective is to use adaptive S_{th} to limit handoff failure probability and, at the same time, to reduce unnecessary load on the system that arises because of false handoff initiation.

3 Cross-Layer (Layer 2 + 3) Handoff Management

Our analysis in the previous section shows that performance of intra and intersystem handoff algorithms depends on the mobile's speed and handoff signaling delay. Therefore, using speed and handoff signaling delay information, performance of the existing handoff management protocols (that do not consider mobile's speed and network dynamics) can be enhanced to achieve the design goals pointed out in Section 1.

We design architecture to implement handoff management adaptive to the link layer (Layer 2) and network layer (Layer 3) parameters. Then, we develop a handoff management protocol using this architecture. As the proposed handoff management protocol uses information derived from different layers of TCP/IP protocol stack (e.g., speed information from link layer and handoff signaling delay information from network layer), we call it cross-layer handoff management protocol (CHMP). The architecture of our proposed CHMP is shown in Fig. 6 that shows the different modules of CHMP. Some of these modules collect the link and network layer information useful for handoff management and other modules use this information to decide the appropriate time to initiate and execute the handoff procedures. The modules that collect information include the *neighbor discovery unit* and the *handoff signaling delay estimation unit* implemented in the network layer and the *speed estimation unit* and the *RSS measurement unit* implemented in the link layer. The modules that use the Layer 2 and Layer 3 information to carry out the handoff procedures are *handoff trigger unit* and *handoff execution unit*. The functionalities of these units are as follows:

- The *neighbor discovery unit* assists the MT to learn about the neighboring BSs. It implements network discovery protocols or has interface with the network discovery protocols, such as the candidate access router discovery (CARD) [18] protocol.
- The *handoff signaling delay estimation unit* estimates the delay associated with intra and intersystem handoffs. More discussion about handoff signaling estimation is provided later in this section.
- The *speed estimation unit* estimates mobile's speed using our own algorithm, VEPSD (velocity estimation using the power spectral density of the received signal envelope), proposed in [23]. The maximum

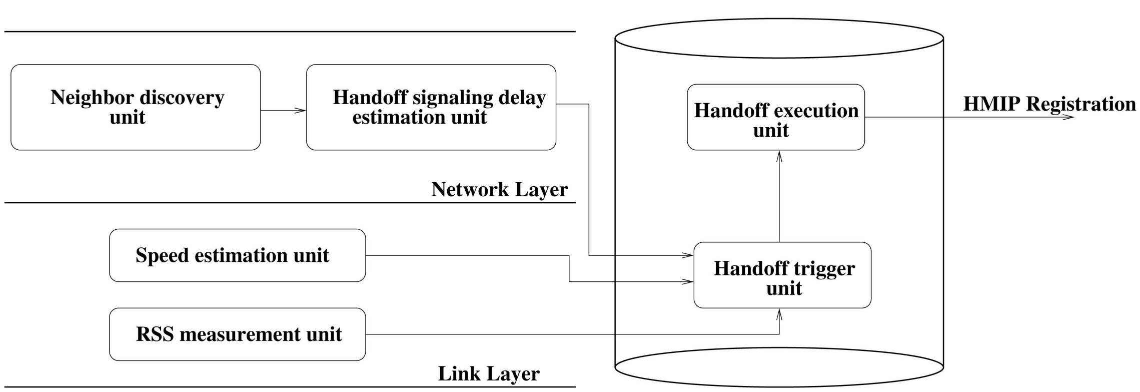


Fig. 6. The modules of cross-layer handoff management architecture.

Doppler frequency (f_m) is related to speed (v) of a mobile user, speed of light in free space (c), and carrier frequency of the received signal (f_c) through

$$v = \left(\frac{c}{f_c}\right) f_m. \tag{13}$$

VEPSD uses f_m of received signal envelope to estimate speed of a mobile user. It estimates f_m using the slope of power spectral density (PSD) of the received signal envelope. The slope of PSD of received signal envelope has maxima at frequencies $f_c \pm f_m$ in mobile environments [23]. VEPSD detects the maximum value of received signal envelope's PSD that corresponds to the highest frequency component ($f_c + f_m$) to estimate f_m. We select this algorithm over other speed estimation algorithms such as [5], [14] because the latter suffer from larger estimation errors [23].

- The *handoff trigger unit* collects information from the handoff signaling delay estimation unit, speed estimation unit, and RSS measurement unit and determines the appropriate time to start handoff procedures. The details of handoff initiation time estimation are discussed in Section 3.2.
- Finally, the *handoff execution unit* starts the HMIP registration process at the handoff initiation time calculated by the handoff trigger unit.

3.1 Operation of CHMP

To provide further insight into the guidelines behind the operation of CHMP, we subdivide the entire handoff process into the following steps.

3.1.1 Neighborhood Discovery

When an MT is served by a BS, it learns about its neighboring BSs using the neighbor discovery unit. By neighboring BSs, we mean the BSs that are the immediate neighbors of the serving BS. Some of these BSs may belong to the serving FA, whereas others may belong to different FAs. When the MT moves into the coverage of a neighboring BS that belongs to its serving FA, the resulting handoff is a link-layer handoff. In this case, the MT uses the existing link-layer handoff algorithms [39] and CHMP procedures are not invoked. When the neighboring BS belongs to a different FA under the serving system, the corresponding handoff is an intrasystem handoff. On the other hand, when the neighboring BS belongs to a different system, the resulting handoff is an intersystem handoff. We use CHMP for both intra and intersystem handoffs. Using the neighbor discovery protocol, the MT also learns the details of its neighboring BSs, such as the IP addresses of the FAs that serve these BSs.

3.1.2 Handoff Signaling Delay Estimation

It is difficult to predict which particular BS the MT will move unless the handoff instance is very close. Our objective is to estimate the handoff signaling delay in advance without knowing which particular BS the MT will move. This can be done in many ways. For example, techniques such as [16], [17] can be used to estimate the delay between different network entities that are involved in the handoff process and, using this information, the handoff signaling delay for intra and intersystem handoff can be estimated. We propose a simple technique that uses the existing HMIP protocol to estimate the handoff signaling delay. From the neighborhood discovery step, the MT learns the BSs and the corresponding FAs involved in a possible intra or intersystem handoff. Now, the objective is to estimate the signaling delay for these handoffs in advance. To estimate the signaling delay of a possible handoff to a particular neighboring BS, the MT sends the HMIP registration messages to the GFA with an invalid *Mobile-GFA Authentication Extension* if the corresponding handoff is intrasystem. Otherwise, it sends the HMIP registration messages to the HA with an invalid *Mobile-Home Authentication Extension* if the corresponding handoff is intersystem. The objective of using an invalid *Authentication Extension* is to just learn the handoff signaling delay without changing the mobility binding at GFA or HA. When GFA or HA receives the HMIP registration messages and learns the presence of the invalid *Authentication Extension*, they return the HMIP *Registration Reply* with the appropriate code [26] that signifies mobile node (MN) failed authentication. The handoff signaling delay is estimated by comparing the time difference between the transmission time of an HMIP registration request and the reception time of an HMIP registration reply. In this way, the MT predicts the handoff signaling delay in the event of its movement to the BS. Similarly, it also learns the signaling delay of the associated handoffs to other neighboring BSs. Our handoff signaling delay prediction technique introduces extra signaling overhead to the system. However, we advocate its use because of its simplicity. Moreover, this technique can be implemented using the existing HMIP protocol; hence, no extra implementation is required. Considering the significant performance improvement (as discussed in Section 4), this signaling overhead is tolerable. If this extra signaling overhead is undesirable for a particular deployment scenario, then the existing delay estimation algorithms [16], [17] can be used to estimate the handoff signaling delay.

It may be noted that prior estimation of handoff signaling delay captures different factors such as type of handoff to be performed, location of the MT from its home network, and load on the network. For example, if the handoff is intrasystem, then there are fewer signaling messages exchanged [8], [12]; hence, handoff delay is lower compared to intersystem handoff. Similarly, if either the user is far from its home network or the network is experiencing higher load, handoff signaling delay increases. This shows that, by estimating handoff signaling delay in advance, CHMP eliminates the adverse effects of the above parameters on handoff performance.

3.1.3 Handoff Anticipation

When the RSS of the serving BS measured by the RSS measurement unit decreases continuously, a handoff is anticipated. Moreover, using the existing movement prediction techniques [1], [15], the MT learns its next BS. Then, the handoff trigger unit learns the signaling delay for that particular BS from the handoff signaling delay estimation unit. Note that the objective of estimating the handoff delays for each neighboring BS in advance is to avoid estimating the delay after learning which particular BS the MT will move to. This eliminates the latency associated with handoff signaling delay estimation if it were to be done after the handoff anticipation. The extra delay

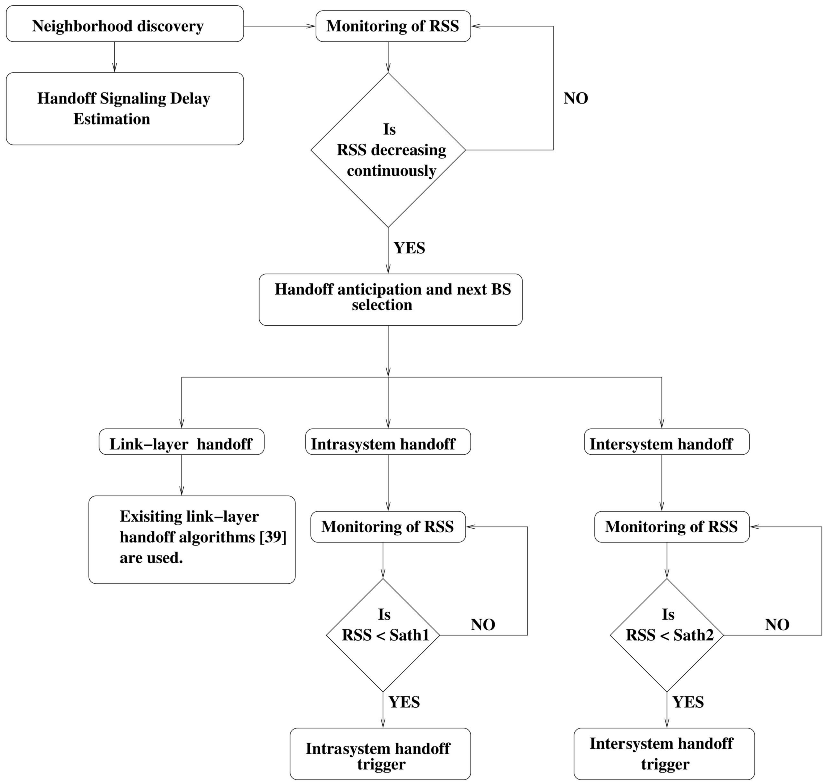


Fig. 7. Flow diagram of CHMP operation.

associated with the signaling delay estimation would have resulted in an unsuccessful handoff [19].

3.1.4 Handoff Initiation

Once the MT learns the BS that it is going to move, the next challenge is to estimate the right time to start the HMIP registration. The handoff trigger unit uses speed and handoff signaling delay information to estimate S_{ath} as discussed in Section 3.2. When the RSS of the serving BS drops below S_{ath}, the handoff trigger unit sends a trigger to the handoff execution unit to start the HMIP handoff procedures.

3.1.5 Handoff Execution

When the handoff execution unit receives the handoff trigger from the handoff trigger unit, it starts the HMIP registration. Once the HMIP registration is completed, the MT is switched to the new BS. The MT keeps its HMIP registration with the old BS for a specified time period to avoid the ping-pong effect during handoff. This is implemented by using the simultaneous binding option of HMIP protocol. The MT binds the CoA of the old FA (OFA) and new FA (NFA) at the GFA in the case of intrasystem handoff and at the HA in the case of intersystem handoff. Therefore, the GFA and HA forwards packets destined for the MT to both the CoAs during this time interval. It may be noted that, in the case of an intersystem handoff, these two CoAs may belong to two different network interfaces when the MT moves between networks employing different wireless access technologies. Therefore, multiple interfaces of the MT can be used to reduce the ping-pong effect during an intersystem handoff. If the MT returns to the old BS during this time period, there is no need to carry out the HMIP handoff procedures again. If the MT does not return to the old BS within this time duration, it deregisters from the old BS.

The operation of CHMP is summarized in Fig. 7. First, the MT learns about its neighborhood using a neighborhood discovery protocol. Then, it determines the type of handoff (e.g., link-layer handoff, intrasystem, or intersystem handoff) in the event of its movement to these BSs. When the MT learns about the neighboring BSs, the handoff signaling delay unit estimates the signaling delay associated with the handoff to the neighboring BSs that would result in either intra or intersystem handoffs. The RSS monitoring unit starts to monitor the RSS of the serving BS and anticipates a handoff when this RSS decreases continuously. The MT learns about the next BS using the existing movement detection techniques [1], [15]. Then, one of the following three steps is carried out:

- If the associated handoff to the next BS is a link-layer handoff, the existing link-layer handoff algorithms [39] are used and CHMP does not take any action.
- If the associated handoff to the next BS is an intrasystem handoff, the handoff trigger unit estimates the dynamic RSS threshold, S_{ath1}, as discussed in Section 3.2. When the RSS of the current BS drops below S_{ath1}, the MT starts HMIP handoff procedures with the next BS.
- If the associated handoff to the next BS is an intersystem handoff, the steps are similar to that of intrasystem handoff. The dynamic RSS threshold corresponding to an intersystem handoff is referred to as S_{ath2} in Fig. 7. The HMIP intersystem handoff procedures are carried out when the RSS of the serving BS drops below S_{ath2}.

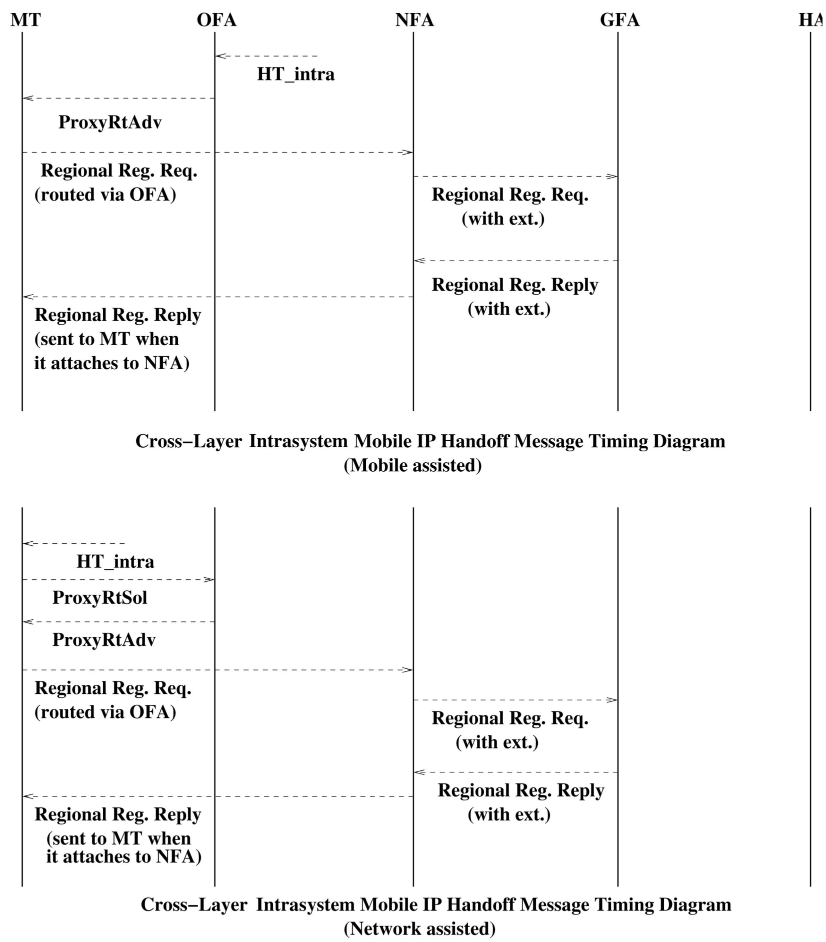


Fig. 8. Timing diagram for cross-layer intrasystem HMIP handoff.

The different functionalities of CHMP can be implemented either at the MT or at the network side. Accordingly, the handoff management using CHMP can be classified into mobile assisted network controlled handoff (MAHO) or network assisted mobile controlled handoff (NAHO). In case of MAHO, the MT implements the speed estimation, RSS measurement, and handoff signaling delay units of CHMP. The network implements the handoff trigger unit that collects the information about speed and handoff signaling delay measurement from MT and estimates dynamic RSS threshold (S_{ath}). When the RSS of the serving BS drops below S_{ath}, the network generates the handoff trigger for intra or intersystem handoff referred to as *HT_intra* or *HT_inter*, respectively. Then, the network initiates the handoff procedures by sending *Proxy Router Advertisement* message (shown as *ProxyRtAdv* message in Fig. 8 and Fig. 9) [19] to the MT. On the other hand, in NAHO, the network assists the MT with the neighborhood discovery and in the selection of next BS. The MT calculates the dynamic value of RSS threshold (S_{ath}) and generates the handoff triggers *HT_intra* or *HT_inter* and initiates the handoff procedures when the RSS of the serving BS drops below (S_{ath}) by sending *Proxy Router Solicitation* message (shown as *ProxyRtSol* message in Fig. 8 and Fig. 9) [19] to the new FA. The timing diagrams of intra and intersystem handoff using CHMP for both MAHO and NAHO scenarios are shown in Fig. 8 and Fig. 9, respectively.

In case of intrasystem MAHO, OFA sends a *Proxy Router Advertisement* message (shown as a *ProxyRtAdv* message in Fig. 8) to the MT in response to *HT_intra* trigger. When the MT receives a *ProxyRtAdv* message, it sends a Mobile IP regional registration request message (shown as a *Regional Reg. Req.* message in Fig. 8) to the NFA, which forwards the message with appropriate extensions [12] to the GFA. After processing the Mobile IP regional registration request message, GFA sends a Mobile IP regional registration reply message (shown as a *Regional Reg. Reply* message in Fig. 8) to the NFA, which forwards it to the MT. Similarly, the message flows for other types of handoffs shown in Fig. 8 and Fig. 9 can be explained.

In NGWS, there exist two types of intrasystem handoff scenarios and four types of intersystem handoff scenarios depending on the cell-size of the wireless systems. The intrasystem handoff can be between two cells of a macrocellular system, referred as macro-intra handoff (Intra_MA_HO) or between two cells of a microcellular system, referred as micro-intra handoff (Intra_MI_HO).

Similarly, the intersystem handoff can be one of the following four types:

- Intersystem handoff from a macrocellular system to another macrocellular system, referred to as macro-inter handoff (Inter_MA_HO).

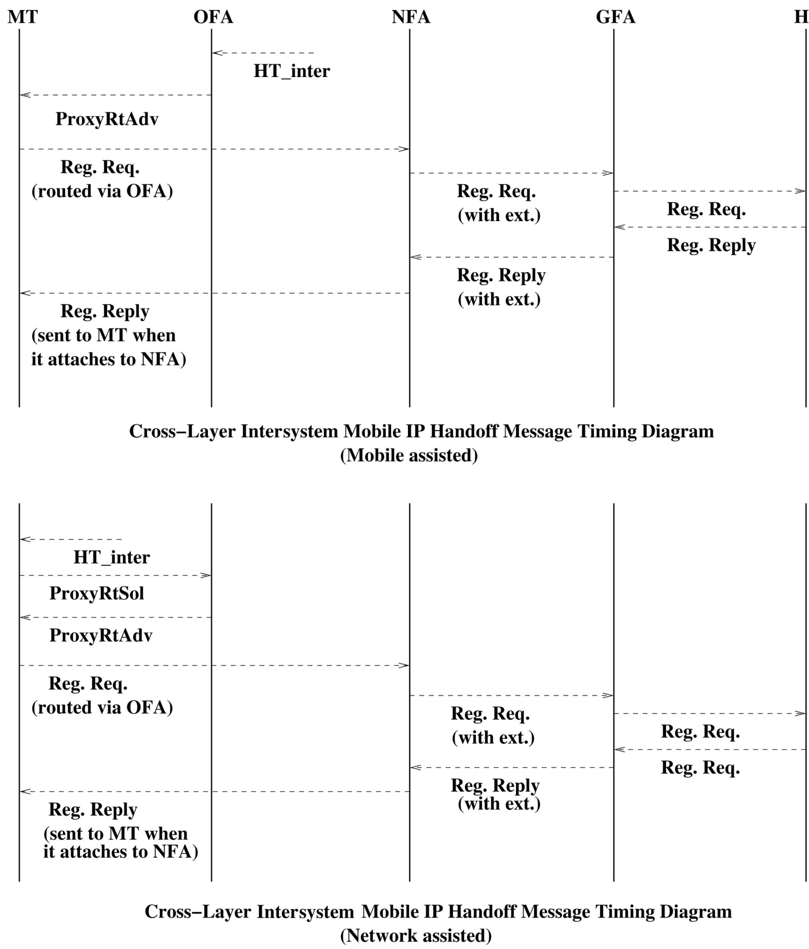


Fig. 9. Timing diagram for cross-layer intersystem HMIP handoff.

- Intersystem handoff from a macrocellular system to a microcellular system, referred to as macro-micro-inter handoff (Inter_MAMI_HO).
- Intersystem handoff from a microcellular system to another microcellular system, referred to as micro-inter handoff (Inter_MI_HO).
- Intersystem handoff from a microcellular system to a macrocellular system, referred to as micro-macro-inter handoff (Inter_MIMA_HO).

It may be noted that microcellular systems are usually overlapped by the macrocellular systems. Therefore, during a macrocell to microcell intersystem handoff (Inter_MA-MI_HO), there is no handoff failure as the macrocell coverage is always available.

3.2 Handoff Initiation Time Estimation

The handoff trigger unit determines the value of adaptive RSS threshold (S_{ath}) to initiate the HMIP handoff procedures using speed and handoff signaling delay information. S_{ath} is estimated as follows: First, we calculate d for a desired value of p_f using

$$p_f = \frac{1}{\theta_1}\arccos\left(\frac{d}{v\tau}\right); \;\; \frac{d}{v} < \tau < \frac{\sqrt{\frac{a^2}{4}+d^2}}{v}, \tag{14}$$

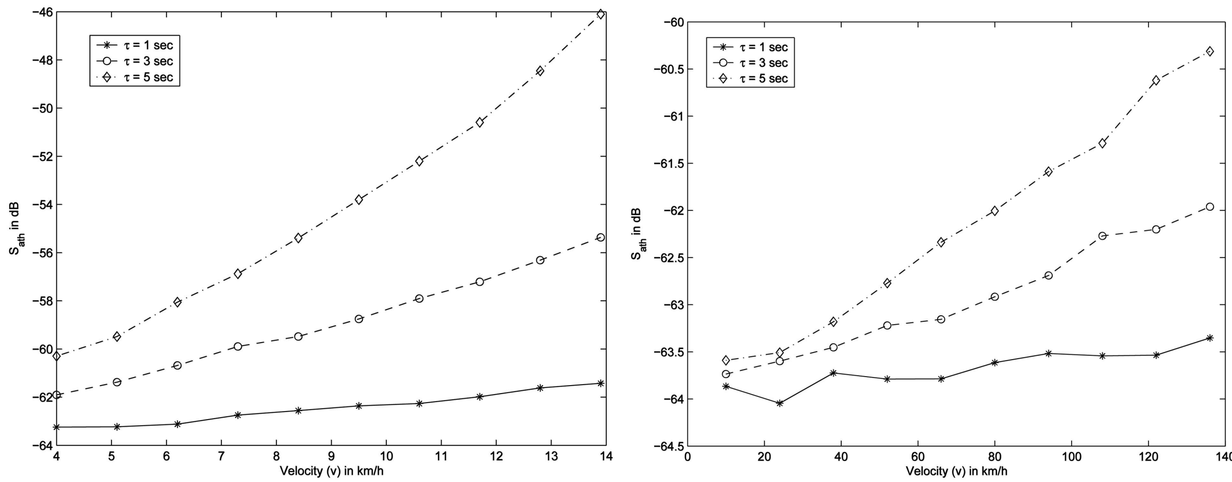
where v is MT's speed, d is MT's distance from the boundary of the serving BS, and τ is the handoff signaling delay. The derivation of (14) is carried out in Section 2. Equation (14) is a nonlinear equation of d. A closed form expression may not be always possible. However, an approximate value of d can be calculated using

$$p_f = \frac{\cos^{-1}\left(\frac{d}{v\tau}\right)}{\tan^{-1}\left(\frac{a}{2d}\right)} = \frac{\frac{\pi}{2} - \frac{d}{v\tau}}{\frac{\pi}{2} - \frac{2d}{\sqrt{4d^2+a^2}}}. \tag{15}$$

Moreover, numerical methods can be used to calculate d. We use the Bisection numerical method [24] to solve for d. (It takes only a few iterations to calculate d when the Bisection method [24] is used. Hence, calculation of d does not have much computational complexity and can be easily implemented at the MT or at the network side, e.g., the BS or FA.) Once d is calculated, the corresponding value of S_{ath} is calculated using the path loss model and the cell size of the serving BS. We use the path loss model given by [33],

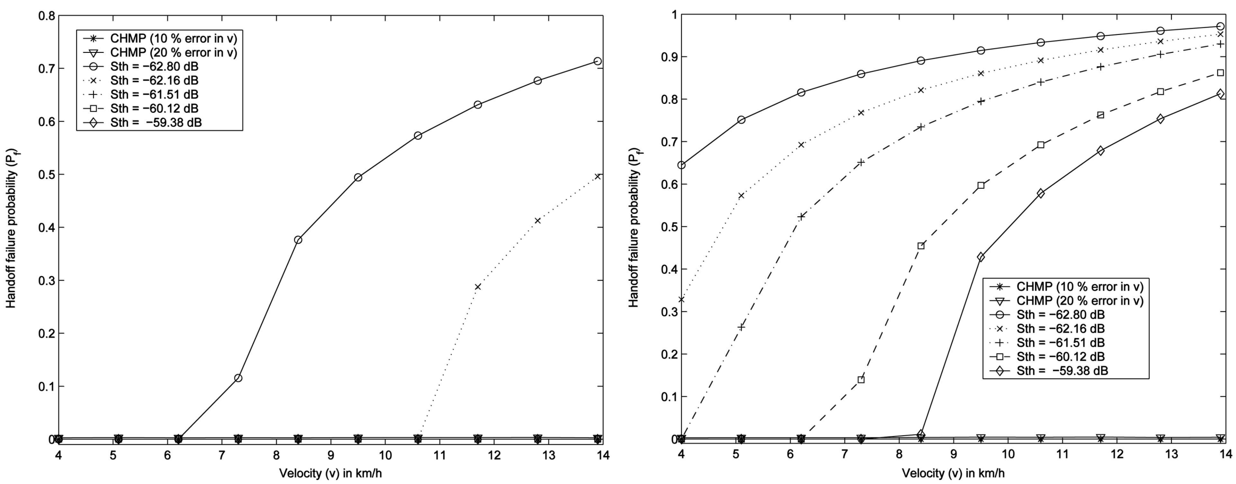
$$P_r(x) = P_r(d_0)\left(\frac{d_0}{x}\right)^{\alpha} + \epsilon, \tag{16}$$

where x is the distance between the base station and an MT, and $P_r(d_0)$ is the received power at a known reference distance (d_0). The typical value of d_0 is 1 km for macrocells, 100 m for outdoor microcells, and 1 m for indoor picocells [33]. The numerical value of $P_r(d_0)$ depends on different factors, such as frequency, antenna heights, and antenna



(a) (b)

Fig. 10. RSS threshold (S_{ath}) for different speed values when the OBS belongs to a: (a) microcellular system and (b) macrocellular system.



(a) (b)

Fig. 11. Relationship between handoff failure probability of CHMP and speed when the OBS belongs to a microcellular system: (a) intrasystem handoff scenario and (b) intersystem handoff scenario.

gains. α is the path loss exponent. The numerical value of α is dependent on the cell size and local terrain characteristics. The typical value of α ranges from 3 to 4 and 2 to 8 for a typical macrocellular and microcellular environment, respectively. ϵ is a zero-mean Gaussian random variable that represents the statistical variation in $P_r(x)$ caused by shadowing. Typical standard deviation of ϵ is 8 dB [33]. Its actual value depends on the cell size. Using (16), the RSS value when the MT is at a d distance from the cell boundary is given by

$$S_{ath} = 10 \log_{10}[P_r(a - d)]. \tag{17}$$

We refer to S_{ath} as S_{ath1} and S_{ath2} for intrasystem and intersystem handoff, respectively, in Fig. 7. Once S_{ath} is calculated, the handoff trigger unit monitors the RSS from the serving BS and sends a trigger to handoff execution unit to start the HMIP registration procedures when RSS from the serving BS drops below S_{ath}.

4 Performance Evaluation of CHMP

In this section, we carry out the performance evaluation of CHMP. For our simulation, we consider a macrocellular system with a cell size of $a = 1$ km, a microcellular system with a cell size of $a = 30$ meters, a macrocell reference distance $d_0 = 100$ m, a microcell reference distance $d_0 = 1$ m, a standard deviation of shadow fading parameter $\epsilon = 8$ dB, and a path-loss coefficient $\alpha = 4$ for macro and microcells. We assume that the target handoff failure probability is $p_f = 0.02$. We consider that the maximum values of mobile's speed in a microcellular and macrocellular system are 14 km/h and 140 km/h, respectively. Moreover, we assume that the minimum value of RSS required for successful communication between an MT and a BS is $S_{min} = -64$ dBm. In the following sections, we analyze handoff performance during MT's movement from an old base station (OBS) to a new base station (NBS).

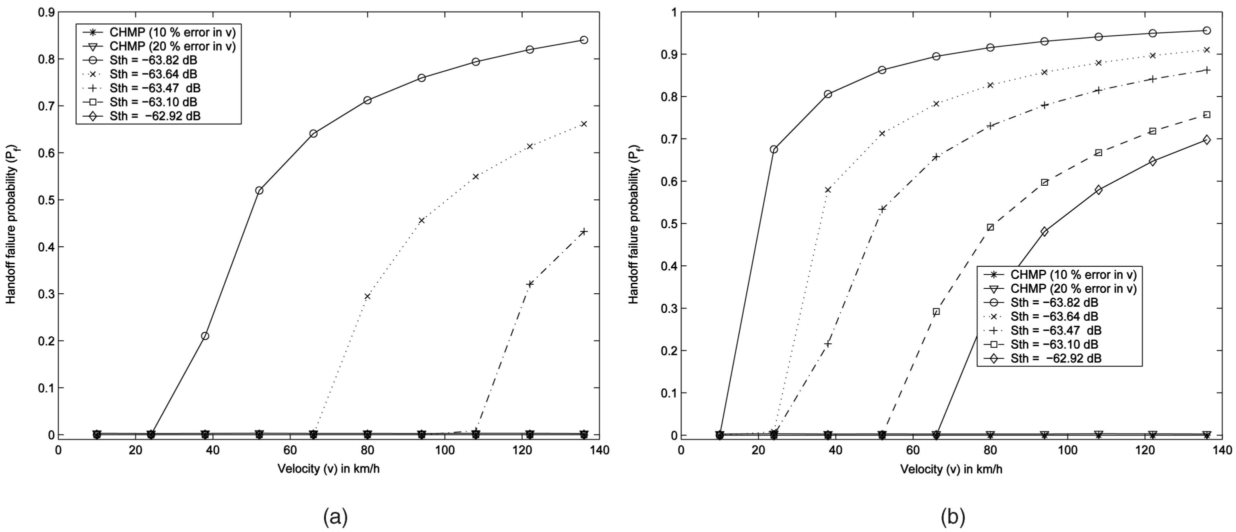


Fig. 12. Relationship between handoff failure probability of CHMP and speed when the OBS belongs to a macrocellular system: (a) intrasystem handoff scenario and (b) intersystem handoff scenario.

4.1 Relationship between S_{ath} and Speed

We analyze the relationship between S_{ath} and MT's speed (v) for different values of handoff signaling delay (τ). For different values of v, we calculate the required value of d using (14). Then, using (17), we calculate the required value of S_{ath}. Fig. 10a shows the relationship between S_{ath} and v for different values of τ when MT's old BS (OBS) belongs to a microcellular system. Fig. 10b shows the similar results when the OBS belongs to a macrocellular system. It may be noted that the results shown in Fig. 10a are applicable for Intra_MI_HO, Inter_MI_HO, and Inter_MIMA_HO, whereas the results shown in Fig. 10b are applicable for Intra_MA_HO, Inter_MA_HO, and Inter_MAMI_HO. Fig. 10a and Fig. 10b show that, for a particular value of τ, S_{ath} increases as MT's speed increases. This implies that, for an MT moving with high speed, the handoff should be initiated earlier as compared to a slow-moving MT to guarantee the desired handoff failure probability independent of MT's speed. Fig. 10a and Fig. 10b also show that S_{ath} increases as τ increases. This is because, when τ is large, the handoff must start earlier compared to when τ is small. The small and large values of τ correspond to intra and intersystem handoffs, respectively. Therefore, CHMP calculates S_{ath} that is adaptive to v and τ.

A slight variation in S_{ath} estimation is introduced because of the error in speed and handoff signaling delay estimation and the effect of shadow fading. To eliminate the negative effects of variation in S_{ath} on handoff performance, we increase the value of d calculated in (14) by 10 percent and use that for calculation of S_{ath} in (17).

4.2 Relationship between the Handoff Failure Probability of CHMP and Speed

We investigate the handoff failure probability of CHMP for different types of intra and intersystem handoffs and compare that with the handoff failure probability of the existing fixed RSS-threshold-based handoff protocols. Toward this, in CHMP, we calculate S_{ath} using speed and handoff signaling delay information. We consider that up to 20 percent error is introduced in speed estimation. Then, we use S_{ath} to initiate the handoff and determine the handoff failure probability. Fig. 11a and Fig. 11b show the handoff failure probability (p_f) of CHMP and the existing fixed RSS-threshold-based handoff algorithms for different values of speed when the OBS belongs to a microcellular system. Fig. 11a shows p_f for Intra_MI_HO, whereas Fig. 11b shows p_f for Inter_MI_HO and Inter_MIMA_HO. These figures show that when MT's speed is known, 70 percent to 80 percent reduction in p_f is achieved in CHMP compared to fixed RSS-based handoff algorithms. They also show that, when CHMP is used, p_f becomes independent of MT's speed. On the other hand, for fixed RSS-threshold-based algorithms, p_f depends on the numerical value of S_{th} and MT's speed. A comparison of Fig. 11a and Fig. 11b shows that, for a particular value of fixed RSS threshold, the numerical value of p_f is different for intra and intersystem handoff. This shows that the handoff protocols need to be adaptive to the type of handoff. CHMP implements this by learning the neighboring BSs and then determining the type of handoff in case of MT's movements to those BSs. Fig. 12a

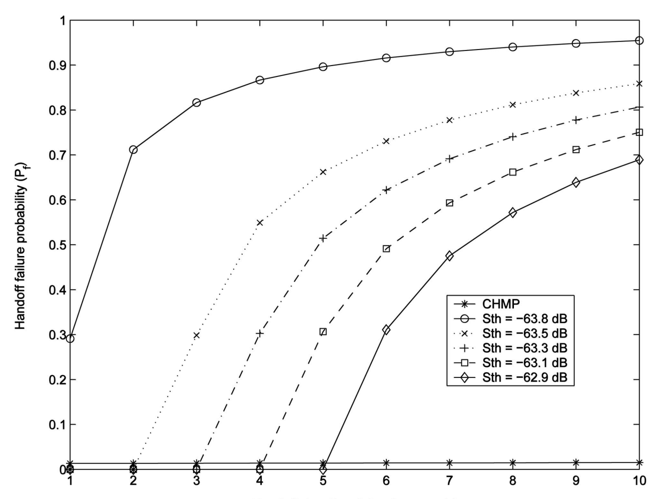


Fig. 13. Relationship between handoff failure probability of CHMP and handoff signaling delay.

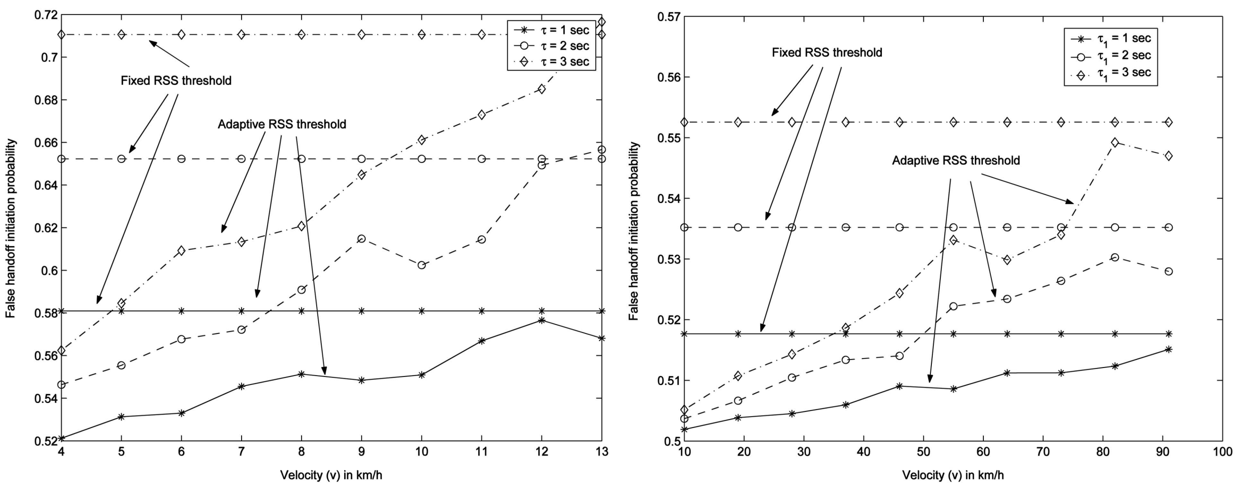


Fig. 14. Relationship between false handoff initiation probability of CHMP and speed when the OBS belongs to a: (a) microcellular system and (b) macrocellular system.

and Fig. 12b show the similar results when the OBS belongs to a macrocellular system.

4.3 Relationship between the Handoff Failure Probability of CHMP and Handoff Signaling Delay

Fig. 13 shows the handoff failure probability of CHMP for different values of handoff signaling delay (τ). The results show that, unlike the fixed RSS-based handoff protocols, p_f remains independent of τ in the case of CHMP. This is because CHMP estimates τ and uses it for the calculation of dynamic RSS threshold. Fig. 13 shows that a 70-80 percent reduction in p_f is achieved in case of CHMP compared to the fixed RSS-based handoff protocols. The lower and higher values of τ correspond to intra and intersystem handoffs, respectively. Therefore, by incorporating the estimated value of τ into dynamic RSS calculation, p_f is limited to the desired value irrespective of mobile's speed and variation of handoff signaling delay.

4.4 Relationship between False Handoff Initiation Probability of CHMP and Speed

The use of adaptive RSS threshold initiates the handoff procedures in such a way that just enough time is there for the successful execution of the handoff. Therefore, an adaptive value of RSS threshold (S_{ath}) avoids initiation of the handoff process too early or too late. The former limits false handoff initiation probability. The later limits the handoff failure probability. Thus, CHMP strikes an optimum balance between false handoff initiation probability and handoff failure probability. We consider that, when the fixed value of RSS threshold S_{th} is used, it is calculated such that a user with highest speed is guaranteed the desired value of handoff failure probability (p_f). Fig. 14a and Fig. 14b show the comparison of the false handoff initiation probability of CHMP and the fixed RSS-threshold-based algorithms when the OBS belongs to a microcellular system and macrocellular system, respectively. These figures show that the false handoff initiation probability of CHMP is 5 percent to 15 percent lower compared to the fixed RSS-threshold-based algorithms. Thus, CHMP achieves up to 15 percent reduction in the cost associated with false handoff initiation.

5 Conclusion

In this work, we first discuss the different types of handoff in the next-generation wireless systems and the recent trend of link-layer-assisted handoff management protocol design. Then, we analyze the performance of handoff management protocols that use a fixed value of RSS threshold (S_{th}) to initiate the handoff process. Through our analysis, we observe that, when a fixed value of S_{th} is used, handoff failure probability increases when either speed or handoff signaling delay increases. Using the insights from our analysis, we develop a cross-layer handoff management protocol called CHMP, which estimates mobile's speed and predicts the handoff signaling delay of possible handoffs. CHMP uses this information to calculate a dynamic value of RSS threshold (S_{ath}) for handoff initiation. Our analysis and simulation results show that CHMP significantly enhances the performance of both intra and intersystem handoffs. CHMP also significantly reduces the cost associated with the false handoff initiation because it achieves lower false handoff initiation probability.

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