A Cooperative Diversity Based Handoff Management Scheme

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***Abstract*—Cooperative diversity has emerged as a promising technique to facilitate fast handoff mechanisms in mobile ad-hoc environments. The key concept behind a prominent cooperative diversity based protocol, namely, Partner-based Hierarchical Mobile IPv6 (PHMIPv6), is to enable mobile nodes anticipate handover events by selecting suitable partners to communicate on their behalves with Mobility Anchor Points (MAPs). In the original design of PHMIPv6, mobile hosts choose partners based on their signal strength. Such a naive selection procedure may lead to scenarios where mobile hosts lose communication with the selected partners before the completion of the handoff operations. In addition, PHMIPv6 overlooks security considerations, which can easily lead to vulnerable mobile hosts and/or partner entities. As a solution to these two shortcomings of PHMIPv6, this paper first proposes an extended version of PHMIPv6 called Connection Stability Aware PHMIPv6 (CSA-PHMIPv6). In CSA-PHMIPv6, mobile hosts select partners with whom communication can last for a sufficiently long time by employing the Link Expiration Time (LET) parameter. To tackle the security issues, the simple yet effective use of two distinct authentication keys is envisioned. Furthermore, to shorten the communication time between mobile hosts and their corresponding partners, a second handoff management approach called Partner Less Dependable PHMIPv6 (PLD-PHMIPv6) is proposed.**

***Index Terms*—Mobile IP, MIPv6, HMIPv6, PHMIPv6, mobility management, and mobile networks.**

I. INTRODUCTION

IN today's networking world, two key high-tech forces impel the telecommunications industry, namely, the Internet and the wireless cellular systems. As these forces continue to converge, we are now witnessing a tremendous need and demand for new services, killer applications, increased bandwidth, and pervasive connectivity. Along with the exponential growth of the Internet and the continuous success of wireless and cellular communication networks, the telecommunications era has entered a fascinating phase where communication needs are no longer restricted to wired/wireless networks and have moved towards a whole new paradigm. This paradigm states the prime objective of the ongoing emergence of mobile and personal communication services which aims at effectively enabling pervasive communication, i.e., with a given client at any time, at any location, and in any form preferred by the client. To meet the ever-growing needs and challenging demands for ubiquitous services, communications over mobile systems have been gaining ground at a phenomenal pace during the last few years [1] [2]. The Internet-based applications and the data traffic load generated by these applications have transformed the mobile network into an all-IP configuration framework. From these rapid transformations, one can foresee the inevitable fact whereby the next-generation mobile systems, which offer end-user services including Voice over Telephone (VoIP), multimedia streaming, and so forth, will be based on IP to a large extent (if not solely). Therefore, finding efficient and optimum solutions for handling the IP mobility has become an imperative topic of research.

As originally specified, the IP suite does not support mobility for a number of reasons related to the protocol syntax and semantics. To support global mobility in IP networks, the Mobile IP Working Group within the Internet Engineering Task Force (IETF) proposed a packet-based mobility management protocol, called Mobile Internet Protocol (MIP) [3]. It has been subsequently modified, in line with the new version of IP, towards the so-called MIPv6 [4]. In MIP, each Mobile Node (MN) is identified by two different IP addresses, namely the unique and permanent Home Address (HoA) and a temporary Care of Address (CoA) based on the current position of the node in the network. Unlike HoA, the MN's CoA changes as it roams to a network other than its home network. The MN can obtain the CoA of the visiting subnet by issuing a Router Solicitation (RS) message to its Foreign Agent (FA). The standard MIP consists of two procedures, namely Binding Update (BU) and data delivery. The BU mechanism aims at associating the HoA and CoA addresses of each MN.

MIP fails to present itself as an effective solution in high mobility scenarios since a wide population of roaming users contribute to a large number of BU requests, all most likely in a single burst [5]. In case of mobile users roaming far away from their respective home networks, the system performance further degrades and the signaling delays for BUs increase remarkably. This results in the loss of a significant amount of in-flight packets which eventually affects the overall Quality of Service (QoS) of the system. In order to make MIP scalable for a large and highly mobile network, and at the same time to reduce the amount of signaling messages and the lengths of the signaling paths, IETF proposed the Hierarchical Mobile IPv6 (HMIPv6) protocol [6], [8], which aims at separating local mobility from the global one. HMIPv6 is based on the deployment of a number of local agents called Mobility Anchor Points (MAPs), each of which administrates a set of Access Routers (ARs) forming a single network domain.

However, when it comes to handoff management issues, HMIPv6 is not without its shortcomings. Indeed, handoff management is of vital importance for guaranteeing seamless

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connectivity and high Quality of Experience (QoE) perceived by the users. Also, the fact that contemporary mobile terminals (which are equipped with different interfaces) can simultaneously access different wireless technologies increases the probability of handoff events even more. In addition, when a mobile node is roaming at a high speed and/or the overlapping area between two adjacent access points is small, long handoff delays in the original HMIPv6 scheme may result in a significant loss of in-flight packets and service disruption undermining the QoS. To address such shortcomings of HMIPv6 pertaining to handoff management, Chen *et al.* [9] introduced the Partner-based HMIPv6 (PHMIPv6) protocol, which attempts to speed up the handoff process by initializing it prior to the entrance of the mobile node into the overlapping zone. PHMIPv6 serves as a pioneering work in the field of cooperative diversity, whereby a trigger scheme is used [12] to select a Partner Node[1] (PN), which carries out various steps involved in the handoff operation on behalf of a Mobile Host (MH).

Although PHMIPv6 serves as an inspiring work toward reducing the total handoff delay, it employs a rather naive (and insecure) strategy of choosing the mobile node with the highest signal strength (in its ad hoc mode) as the PN. However, depending on its speed, it is easily possible that the PN with the strongest signal may fade away from the mobile host or the new Access Point (AP) before the handoff operation is finalized. In addition to the cost associated with the gratuitous exchange of signaling messages between the MH and PN, this will get the mobile host back to the former situation where it has to initialize the handoff by itself. To address this issue, we propose the use of Link Expiration Time (LET) [13] as a parameter in the selection of the best possible PN, which will be able to communicate with the new AP for a sufficiently long time. We also incorporate security with our proposed solution to deal with potential malicious threats. In addition, most of the operations involved in assisting the mobile host in performing handover are delegated from the mobile partner nodes to the new access point in order to avoid certain reliability and security issues. Extensive simulations are conducted to evaluate the performance of the proposed enhancements and the simulation results demonstrate that the main concerns are solved and the design goals are achieved.

The remainder of this paper is as follows. Section II highlights the relevance of this work to the state-of-art in the context of cooperative diversity. The distinct features that are incorporated in the proposed enhancements to the PHMIPv6 scheme are described in Section III. Section IV portrays the simulation environment and presents the simulation results. Concluding remarks are provided in Section V.

II. Related Work

In recent times, many researchers have aimed at incorporating cooperative diversity based strategies in wireless and mobile ad hoc environments. The cooperative diversity paradigm refers to two distinct collaborative contexts. One definition of cooperative diversity refers to an antenna diversity whereby distributed antennas of the wireless nodes are used to decode, at the receiver, the information from the combination of two signals. In other words, in addition to the direct signal between the two end-hosts, the signal contributed or relayed by some other wireless node is also taken into account rather than discarding it as noise. Another notion of cooperative diversity is in terms of the collaboration between the wireless terminals in which each user node relays the other user's signal (e.g., information pertaining to authentication, confirmation, handover, and so forth). As a consequence, this particular concept is useful in multi-hop relay network systems to amplify, forward, and even decode useful information effectively. The design objectives of most of the research work in this domain consist in developing and analyzing low-compelxity cooperative diversity protocols [14], which (i) improve the Signal-to-Noise Ratio (SNR) by improving fading scenarios induced by multipath propagation in wireless networks and (ii) lower the number of signaling messages between end-hosts. A further application of cooperative diversity can be found in the work conducted by Zhang *et al.* [15] that presented distributed and Power-Aware cooperative Relay Selection (PARS) strategies in wireless ad hoc networks for maximizing the network lifetime. This particular work demonstrates the importance of combining the appropriate partner selection criteria (i.e., the most suitable parameters to attain design goals) in adopting cooperative diversity based techniques. The issue of grouping and selecting appropriate partners in collaborative wireless environments has been further addressed by Nosratinia *et al.* [16]. In their considered cooperative diversity protocols, every user decides and acts in an autonomous manner in collaborating and assisting the rest of the users. By investigating the outage probability of these protocols, Nosratinia *et al.* demonstrate that the cooperative systems are much more effective in contrast with their non-cooperative counterparts. The work also revealed that the full diversity in the number of cooperating users can indeed be obtained by adopting an appropriately devised protocol.

Cooperative diversity can also help in mobility management to ensure seamless communications. Mobility management approaches can be categorized into two groups, namely end-to-end based and network-infrastructure based schemes. In the former, the mobility issue is resolved by adding adequate enhancements to end hosts and keeping the network unchanged. A notable example of such schemes is the Session Initiation Protocol (SIP) [17]. Via the introduction of new states, TCP-R [18] and Migrate [19] are two other end-to-end mobility management schemes that enable the end-to-end handling of TCP connections. A major drawback of these schemes is that they do not represent a complete end-to-end mobility solution for various applications and their performance is limited under numerous mobility scenarios (e.g., simultaneous movements).

Network-infrastructure based mobility management techniques can be classified into two categories: Micro-mobility and Macro-mobility. The former handles handoffs locally without any Home Agents (HAs). Notable examples are Cellular IP [20] and Handoff-Aware Wireless Access Internet Infrastructure (HAWAII) [21]. Cellular IP is specifically designed to support handoff for frequently moving hosts. It is

[1]Throughout this paper, when we say a node i is a partner of node j, it means node i assists in the handoff of node j. The cooperation is not necessarily reciprocal.

applied on a local level and can inter-work with Mobile IP (MIP) to support mobility among Cellular IP networks. The HAWAII protocol divides the network into hierarchies based on domains, each of which has a gateway called the domain router. Each host node has an IP address and a home doman. The HA and any Correspondent Node (CN) are unaware of the node's mobility within the host domain. The host based forwarding entries installed in the gateways using a set of specialized path setup schemes help to reduce both the data path disruptions and the number of BUs.

On the other hand, in macro-mobility, when a mobile node roams to a different network area, the node solicits for a new Care-of-Address (CoA). A BU message is then sent to the HA. The major issue with macro-mobility pertains to the significant handoff signaling delays for users roaming far away from their home networks. These delays disrupt active connections each time a handoff to a new attachment point of the network is performed. A new standard has emerged [7] to effectively facilitate Macro Diversity HandOver (MDHO) events in Mobile Multi-hop Relay (MMR) networks. In MDHO, the subscribing MH maintains simultaneous connections with multiple APs before it may seamlessly switch to the AP having the best connection quality. To this end, the old and the new APs dispatch the same MAC/PHY message to the MH's downlink (DL) and the MH transmits along its uplink (UL) the same message to both the APs. The adopted standard considers relay stations in the envisioned network infrastructure in nine distinct network topologies. In each of these topologies, handoffs in the same MMR cell and also between two distinct MMR cells are considered. The MDHO handover mechanisms and their respective MAC management messages through the relay stations are incorporated in such a manner that an IEEE 802.16e-based MH can perform smooth handoffs both within an IEEE 802.16j standard and a MMR network.

The emergence of the Fourth Generation (4G) wireless technologies has directed contemporary research work to focus on fast and smart handoff, and mobility control in heterogeneous wireless IP networks. Among prominent research projects in this area, the Transport and Application Layer Architecture for Vertical Mobility with Context-awareness (Tramcar) [10] brings a new dimension. The cross-layer design of Tramcar allows it to use the application and transport layers to meet user preferences and to reduce handoff delays, respectively. Unlike simple handoff decision algorithms that rely on naive parameters such as only signal strength and so forth, Tramcar illustrates the importance of taking into consideration various criteria as handoff decision parameters including cost of service, security, power consumption, network conditions, and network performance. However, Tramcar does not provide any direction in making use of relay nodes by exploiting cooperative diversity which may reduce the handoff time even further.

To reduce handoff-signaling delays in macro-mobility, a large body of prior work was proposed. The central theme in these pioneering studies pertains to the adoption of hierarchical management strategies using local agents. Hierarchical MIPv6 (HMIPv6) [8] is a notable example. Generally speaking, the total handoff delay consists of the link layer handoff delay and the network layer handoff delay. The former, in turn,

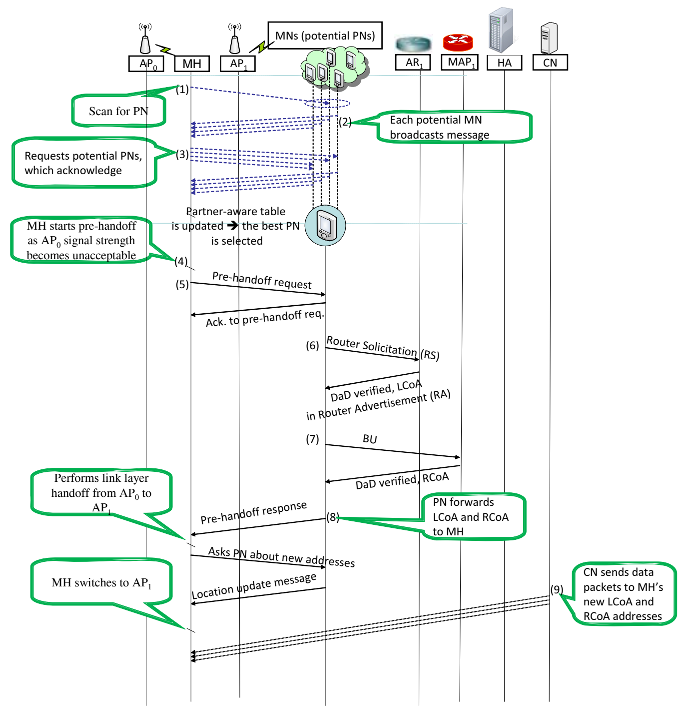


Fig. 1. Exchange of signaling messages in PHMIPv6 upon an inter-MAP handoff.

consists of two phases, namely the discovery phase that is associated with a probe delay, and the re-authentication phase that is associated with the authentication and re-association delays. The probe delay is the most dominating one. Different fast handoff schemes have been devised in the recent literature to reduce the delays associated with both the discovery phase [12], [25] and the re-authentication phase [22]–[24]. The network layer handoff delay comprises the rendezvous time, the Duplicate Address Detection (DAD) delay, and the binding update time. For HMIPv6-based protocols, the DAD delay is the most significant one. Many research work have attempted reducing the DAD delay by initiating the handoff before its actual time [9], [26]. In [9], when a MH (i.e., a MN which is going to change its point of attachment) roams within the same MAP, the mobility management is handled in the same way as in HMIPv6. In case that the MH, which is currently being serviced by the access point AP_0 belonging to MAP_0, is about to perform handoff to an access point, AP_1, administrated by a different MAP (e.g., MAP_1), the handoff operation is managed as shown in Fig. 1 by following the below steps.

Step 1: This involves the MH that approaches the edge of AP_0 to initiate a scanning operation seeking an adequate PN by transmitting periodic broadcast messages.

Step 2: The MNs that may serve as potential PNs periodcially broadcast messages containing information of the serving AR. Upon receiving such a message from a PN, MH stores the same in its partner-aware table.

Step 3: The MH sends a request to each potential PN, which in turn issues a response message. The MH updates the partner-aware table based on the responses from the potential PNs and attempts to select the best possible PN.

Step 4: Once the signal strength from the old access point (i.e., AP_0) becomes lower than a pre-defined threshold, MH initiates the pre-handoff operation by scanning for the next possible AP [12]. If the next AP is within the same MAP, the node performs the link layer handoff and immediately connects to the new AP.

Step 5: Since the new access point AP_1 lies within the domain of MAP_1 (i.e., a different MAP), a pre-handoff request message is sent to the selected PN with the strongest signal. In response to the pre-handoff request message, the selected PN sends back an ACK message to MH.

Step 6: The PN then sends a Router Solicitation (RS) message to the new access router, AR_1. In response, AR_1 generates a new LCoA and validates it by performing the DAD procedure.

Step 7: The PN, at this stage, informs the new MAP (i.e., MAP_1) of the new LCoA and performs BU. In response, MAP_1 generates a new RCoA and validates it by using the DAD procedure.

Step 8: At this stage, the PN issues a pre-handoff response message to MH. While performing link layer handoff from AP_0 to AP_1, MH inquires the PN regarding its LCoA and RCoA addresses. The PN then forwards these addresses to MH via a Location Update message.

Step 9: The CN transmits data packets to the new LCoA and RCoA of the MH.

In this manner, by having the cooperation of a partner node, a mobile node can significantly shorten its network layer handoff latency and ultimately speed up the handoff operation. However, one missing point in the design of the PHMIPv6 scheme consists in the fact that the selection of partner nodes is naive and depends on only signal strength, without taking into account the relative moving direction of the nodes. This argument can be supported by existing work in literature. For instance, Kanai *et al.* [11] suggest measuring the relative distance in addition to taking into account the relative field strength or signal strength. Also, as described earlier, a number of factors (other than the signal strength) that may determine the actual handoff descision have been considered by the Tramcar framework envisioned by Nasser *et al.* [10]. These previous studies suggest that HMIPv6 requires a more appropriate decision parameter (or a set of parameters) in making a handoff decision. Indeed, it is easily possible that while the PN is performing the pre-handoff operation on behalf of the mobile host, the two nodes lose communication as they mutually become outside the reach of their ad hoc communication range. It is also possible that the PN becomes outside the coverage area of the new AP and the pre-handoff operation may consequently fail. Fig. 2 illustrates the idea with more clarity. We consider a wireless network with three nodes, namely A, B, and S. The figure on the left shows the initial locations of the nodes and the figure on the right shows their new positions after a few milliseconds. The circle shows the ad hoc range of node S, which is assumed not to be moving. By applying a naive partner selection scheme as in PHMIPv6, node S will be selecting node A as its partner given its geographical proximity and thus its stronger signal. This selection is obviously not appropriate as node A will be soon outside the ad hoc range of node S. From this example, it becomes apparent the need for a partner selection mechanism that takes into account not only the signal strength but also the duration for which nodes will be able to communicate among themselves.

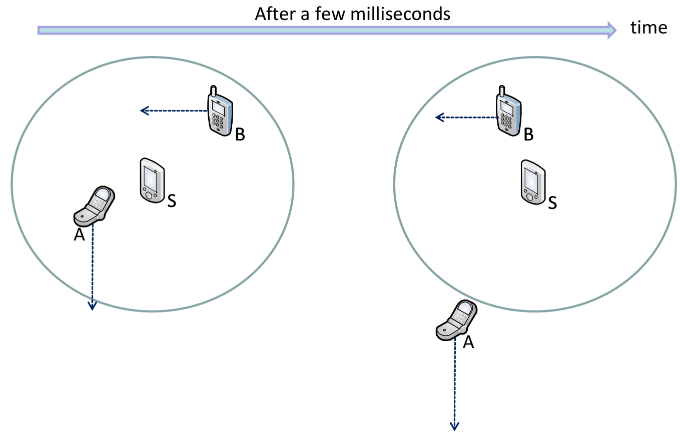


Fig. 2. A simple scenario that illustrates the inadequacy of the partner selection scheme based on only signal strength of the mobile nodes.

III. Proposed Enhancements to PHMIPv6

At the beginning of this section, we broadly address a number of security concerns pertaining to the original version of PHMIPv6. To address these security issues and also to reflect the stability of the connection between a particular MH and its PN in the partner node's selection procedure, we then introduce a new version of PHMIPv6 based on the Link Expiration Time (LET) parameter. Furthermore, we introduce a second enhancement of PHMIPv6 that aims at reducing the dependability of a MN on its selected PN by shortening the duration for which they need to be connected with each other. The overhead in terms of signaling messages between PNs and APs will be also reduced via this second approach.

A. Towards more Security in PHMIPv6

In PHMIPv6, a MH entrusts an unknown PN with its handoff operation. This may cause a number of security threats that need to be carefully addressed.

Indeed, in the original design of PHMIPv6, a MH provides its PN with its security key for Authentication Authorization and Accounting (AAA) purposes. A malicious PN may use this security key in a later instance for its own benefit. This is possible in case the security key corresponds to a service level higher than what the PN is entitled for. This security flaw can be overcome by assigning two distinct security keys for each mobile node, one can be handed to the PN for pre-handoff request and the other is used directly by the MH to authenticate with the wireless network operator or service provider.

Another security threat consists in having a malicious mobile host requesting a number of partner nodes to simultaneously perform numerous pre-handoff operations on its behalf for the purpose of flooding the access point or access router with pre-handoff requests and ultimately causing a Denial of Service (DoS). This threat can be easily dealt with by allowing only one pre-handoff request per MH. As mentioned earlier, mobile nodes will be identified by unique security keys used for pre-handoff requests.

Indeed, there may be attacks also at the data forwarding phase in the network layer. A MN may present itself to the MH as a potentially promising PN during the PNs discovery phase. If a malicious MN is selected as the PN, it may not forward the requests, responses, and other messages between the involved entities. In addition, the malicious PN can also willingly delay forwarding these messages which will cause the handoff-time to increase appreciably. To avoid such scnearios, the MH should employ a considerably small time-out value within which if it does not receive the response, it may consider either selecting another PN or carry on performing handoff to the new AP on its own. Furthermore, a malicious PN can falsify vital information such as the new LoCA and/or RoCA. To prevent this, we may delegate more responsibility to the new access point rather than the PN as the cooperative partner of the MH. Our second envisioned enhancement to PHMIPv6, Partner Less Dependent PHMIPv6 (PLD-PHMIPv6), is in spirit with this idea.

B. LET Computation

In this section, we provide an overview on how to compute the value of LET parameter. Although the use of GPS should become commonplace in mobile nodes, we introduce a scheme to estimate the LET without the need for GPS (in case the GPS is not able to effectively estimate the velocity of nodes or is simply not available). We use the Doppler shift subjected to packets to calculate the relative velocity of nodes. The distance between nodes is calculated using the scheme used in [27], which uses the power of signals to calculate the distance between the nodes by using the simplified free space propagation model given in [28]. For the mobility model, it is assumed that mobile nodes are pseudo-linear and highly mobile in nature.

The estimated initial LET using the Doppler shift of packets and the power of signal (of packets) is given by:

$$LET = \frac{1}{2v}(\sqrt{2d^2 - 4(d^2 - R^2)} + d\sqrt{2}) \tag{1}$$

if $\frac{f}{f_0} < 1$ ... for approaching nodes.

$$LET = \frac{1}{2v}(\sqrt{2d^2 - 4(d^2 - R^2)} - d\sqrt{2}) \tag{2}$$

if $\frac{f}{f_0} > 1$ ... for receding nodes. where

- f is the actual frequency of the signal,
- f_o is the observed frequency,
- R is the maximum communication range between two mobile nodes,
- d is the initial distance between two nodes given by $d = \frac{\lambda}{4\pi}\sqrt{\frac{p_t}{p_r}}$,
- p_r is the initial received signal power,
- p_t is the known transmission signal power, and
- λ is the carrier's wavelength.

In order to minimize the effect of atmospheric attenuation, the control packets must be propagated using a much lower frequency than the actual data transmission and hence, they should be able to effectively estimate the LET. It should be noted that if $(\frac{f}{f_0})$ is one, the LET is infinite. As a consequence, nodes will indefinitely remain within each other's range.

Additionally, GPS can be used to determine the distance between two given nodes. From [29], if we consider two mobile nodes i and j with a transmission or line-of-sight (LOS) range of r, speeds v_i and v_j, coordinates (x_i, y_i) and (x_j, y_j), and velocity angles β_i and β_j (Fig. 5) respectively, the LET can be represented as:

$$LET = \frac{-(ab+cd)+\sqrt{(a^2+c^2)r^2-(ad-bc)^2}}{a^2+c^2} \tag{3}$$

where

$a = v_i \cos\beta_i - v_j \cos\beta_j$,
$b = x_i - x_j$,
$c = v_i \sin\beta_i - v_j \sin\beta_j$, and
$d = y_i - y_j$.

C. Connection Stability Aware (CSA) PHMIPv6

The functionality of our enhancement to the original PHMIPv6 scheme, which we refer to as Connection Stability Aware PHMIPv6 (CSA-PHMIPv6), is depicted in Fig. 3. Let t_{pre} and t_{dur} denote the pre-handoff time and the duration for which PN should be able to access AP_1, respectively. In CSA-PHMIPv6, the values of t_{pre} and t_{dur} are estimated by employing history of these values and averaging them using the Exponential Moving Average (EMA) method. Based upon these estimated values, the most appropriate PN is selected as follows.

- The group N_a of MNs, the LET of which with MH exceeds t_{pre}, is sorted.
- From group N_a, the group N_b of MNs, whose LET with AP_1 exceeds t_{dur}, is sorted.
- In case $(N_a = \emptyset)$, the CSA-PHMIPv6 scheme functions in the same way as the original PHMIPv6.
- Else if $(N_b = \emptyset)$, then the MN, whose LET value with MH is the maximum, is selected from N_a as PN.
- Else the MN, whose LET with MH is the maximum, is chosen from N_b as PN.

t_{pre} and t_{dur} can be respectively expressed as follows:

$$t_{pre} = (t_1 + t + t_2) \tag{4}$$

$$\begin{aligned} t_{dur} &\simeq t_{pre} + Delay(MH, PN) \\ &+ Delay(PN, AP_1) + \Delta_{Processing} \end{aligned} \tag{5}$$

t_1, t, t_2 are as shown in Fig. 3. They indicate the time required for selecting an adequate PN and sending a pre-handoff request, the time required by PN to perform handoff, and the time required so that PN notifies MH of a successful pre-handoff operation. It should be noted that the values of t_1, t, and t_2 can be estimated from the propagation delays of the links involved in the communication (e.g., PN to AP_1, AP_1 to AR_1) averaged over a certain period of time by using methods such as the EMA scheme as mentioned earlier. $Delay(A, B)$ indicates the propagation delay between nodes A and B. $\Delta_{Processing}$ refers to the sume of the individual processing delays at the involved entities, namely at MH, PN, and AP_1.

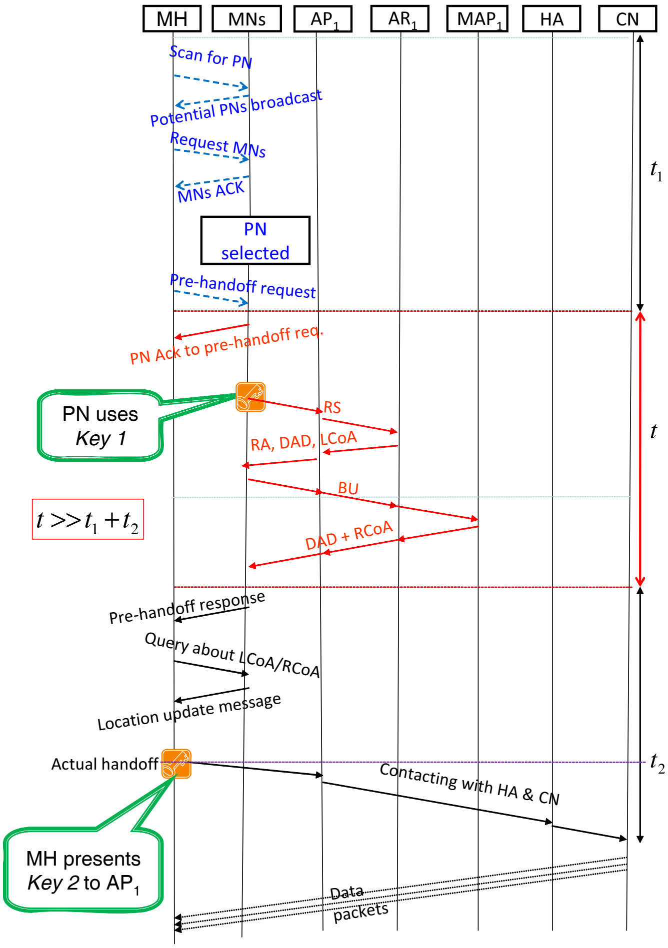


Fig. 3. Connection stability aware PHMIPv6.

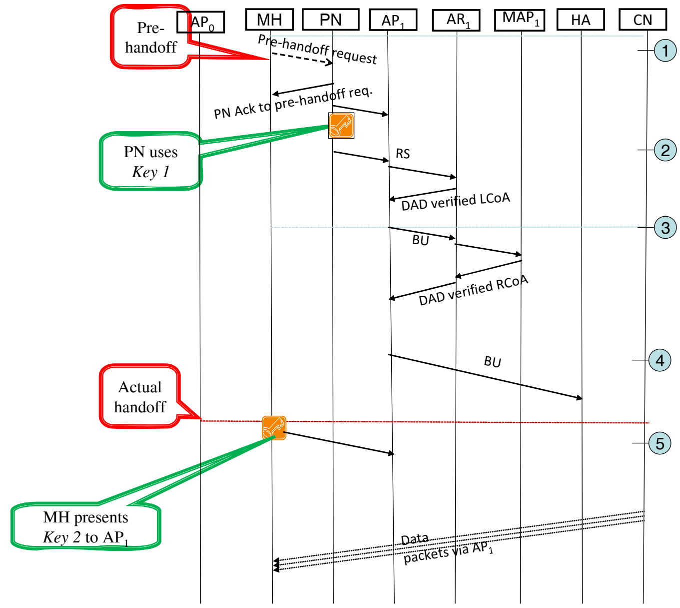


Fig. 4. PN Less Dependable PHMIPv6.

D. Partner Less Dependable PHMIPv6 (PLD-PHMIPv6)

In the remainder of this section, we aim for enhancements to HMIPv6 that reduce both the time required for the MHs and their corresponding PNs to remain in touch and the time required for PNs to be within the coverage area of AP_1. The major operations of this Partner Less Dependable PHMIPv6 (PLD-PHMIPv6) are depicted in Fig. 4. The key idea behind PLD-PHMIPv6 is to restrict the role of PNs in only forwarding the pre-handoff request message to AP_1 and let the latter perform all the other operations. In this way, the concerned MH does not have to stay within the communication range of the PN for a long time and the same is applicable to PNs with regard to APs. The delegation of responsibility to AP_1, which is a more trustworthy entity compared to the roaming MNs, also mitigates some of the security threats mentioned in Section III-A. Furthermore, since the PNs are in charge of only forwarding a single pre-handoff request message to AP_1 as shown in Fig. 4, PLD-PHMIPv6 reduces the otherwise-induced signaling overhead, and makes efficient and fair usage of the scarce battery-power available at the disposal of the PN. The major steps of the PLD-PHMIPv6 scheme (after finding a suitable PN) are as follows (Fig. 4).

Step 1: The MH operates in its ad hoc mode to send a pre-handoff request message to the selected PN. In response, the PN issues an ACK to MH. The PN authenticates with AP_1 and also forwards the pre-handoff request message to AP_1, which then replaces the PN as the cooperative relay node.

Step 2: Upon receiving the pre-handoff request message, AP_1 forwards a RS message to AR_1. This prompts AR_1 to generate a new LCoA, validate this new LCoA by performing DAD, and finally send it to AP_1.

Step 3: On behalf of MH (and also PN), AP_1 performs BU with MAP_1, which in its own turn generates a new RCoA and performs DAD to check whether there exists a duplicate address, which may conflict with this newly formed RCoA.

Step 4: Again on behalf of MH, AP_1 performs BU with HA.

Step 5: Upon disconnecting with AP_0, MH authenticates and connects to AP_1, and starts receiving data from CN via the new AP_1.

IV. Performance Evaluation

A. Simulation Setup

In this section, we evaluate the performance of the proposed CSA-PHMIPv6 and PLD-PHMIPv6 schemes. The performance evaluation relies on computer simulations using the Network Simulator (NS2) [30]. Particular attention is paid to the design of an accurate and realistic simulation setup, which is described below, justifying the choices made along the way. Unless otherwise noted, the parameters specified below are those used in all the experiments throughout the paper. As comparison terms, we use both the original PHMIPv6 and HMIPv6 schemes.

The abstract configuration of the considered network is depicted in Fig. 5. The wireless part of the network consists of two neighboring wireless cells. The coverage radius of each wireless cell is set to 400 meters. The distance between the two neighboring APs is fixed to 800 meters, yielding an overlapping area of a maximum distance equal to 50 meters.

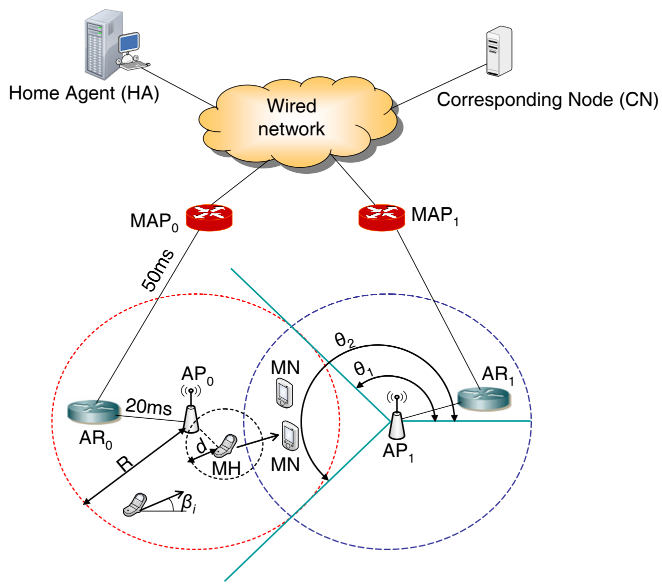


Fig. 5. Simulation topology.

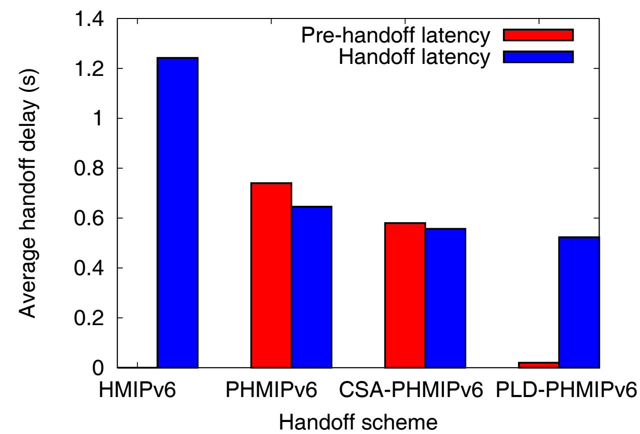


Fig. 6. Handoff delay for the four considered schemes.

These parameters are chosen with no specific purpose in mind and do not change any of the fundamental observations about the simulation results.

The two APs are connected to the wired network through a two-layered network made of two ARs and two MAPs. The choice behind adopting such a two-layered network represents a general and simple case. In the considered topology, MAP_i serves AR_i and AP_i, where $i \in \{0,1\}$. The MAPs are connected to a HA and a server (which acts as the CN) via a wired network (e.g., Internet). The one-way propagation delay over the wired network to MAPs is set to 100ms. As for other links, the delay of AP-AR and AR-MAP links are set to 20ms and 50ms, respectively. In general scenarios, wireless links have smaller bandwidth compared to their wireline counterparts. In the simulations, the capacity of each link is set to 100Mbps. In this regard, it is worth stressing out that setting the bandwidth of wireless and wireline links to different rates should have no effect on the fundamental observations about the proposed schemes.

All simulations are run for a duration of 600s, which is long enough to ensure that the system has attained a consistent behavior. The first 60s are used to initialize the simulations and the last 60s are used to make sure that the results have stabilized. All results are an average of multiple simulation runs.

In the performance evaluation, we consider the following mobility model. As shown in Fig. 5, a population of 100 MNs is simulated and is randomly scattered over a region, over the coverage areas of AP_0 and AP_1, restricted by angles θ_1 and θ_2, respectively. The moving directions of the MNs are simulated in a way that mobile nodes perform handoffs between AP_0 and AP_1 at different times. The moving speed of mobile nodes is, thus, deliberately derived from a uniform distribution. By considering users in both an urban (e.g., downtown) scenario and a highway scenario, the minimum and maximum values of the distribution are set to a slow node moving speed, 4Km/h, and a high node moving speed, 120km/h, respectively. To ensure a certain level of stability in the results, all nodes remain immobile for a short period of time from the commencement of each simulation run. The radius of the ad hoc transmission range of mobile nodes is denoted as d and is varied, during the simulations, from 30 to 70 meters.

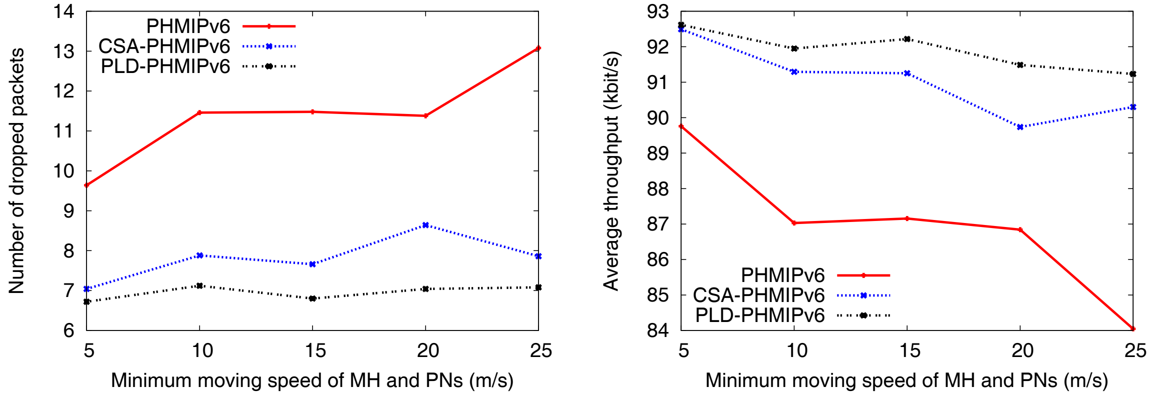
As quantifying metrics, we use the following parameters:

- Average handoff delay experienced in the case of the four schemes,
- Number of dropped packes and throughput,
- Pre-handoff success ratio,
- Pre-handoff failure ratio, and
- LET between a MH and its selected PN.

Here, a pre-handoff to an access point AP_i fails if a MH loses communication with its selected PN or the latter leaves the coverage area of AP_i before the handoff operation is finalized. In case a MH desires to perform handoff but does not find an adequate PN, this pre-handoff is not considered as a failure. For this reason, the sum of the pre-handoff success ratio and the pre-handoff ratio does not necessarily have to be equal to one.

B. Simulation Results

Fig. 6 shows the average handoff delay experienced in case of the four schemes. The value of the red rectangle shows the time elapsed since the selected PN received a pre-handoff request message from a MH till it notified the MH of the successful pre-handoff operation. If the PN remains in connection with the corresponding MH or AP for a time less than this value, the pre-handoff is deemed failed. Since there is no pre-handoff operation in HMIPv6, the pre-handoff latency is set to zero in this case. The figure indicates that the latency of the pre-handoff operation in the PLD-PHMIPv6 scheme is the shortest. This result is rather trivial due to the fact that the concerned PN forwards only the message that it receives from its corresponding MH. The average handoff delay experienced in PHMIPv6 is slightly longer than that experienced in CSA-PHMIPv6 and PLD-PHMIPv6. This is attributable to the fact that in case of PHMIPv6, more pre-handoff operations fail and nodes have to perform handoff operations following the HMIPv6 scheme. Hence, the original



(a) Packet drops vs. moving speeds of the mobile nodes for PHMIPv6, CSA-PHMIPv6, and PLD-PHMIPv6 schemes.

(b) Average throughput vs. moving speeds of the mobile nodes for PHMIPv6, CSA-PHMIPv6, and PLD-PHMIPv6 schemes.

Fig. 7. Comparison between the four schemes in terms of packet drops and throughput.

PHMIPv6 approach experiences an increase in the average handoff delay.

The number of dropped packets is plotted for PHMIPv6 and its enhanced counterparts in Fig. 7(a). The original PHMIPv6 suffers from the highest number of packet drops and this becomes worse as the moving speeds of the considered MH and its corresponding PN(s) increase. In contrast, CSA-PHMIPv6 attains much lower packet drops. On the other hand, the number of dropped packets is minimum for PLD-PHMIPv6 and remains rather constant (close to seven) for varying speeds of the roaming nodes. This is attributable to the fact that PLD-PHMIPv6 uses the AP as the cooperating node as much as possible. As a consequence, even if the PN leaves the communication range of the MH at a later time while the pre-handoff (or handoff) is in progress, the new AP acts as a more reliable partner. Indeed, these results reflect the contrasting throughputs achieved in these three schemes as shown in Fig. 7(b). Both PLD-PHMIPv6 and CSA-PHMIPv6 achieve high throughputs (over 90 Kbps) even when the mobile nodes travel at a relatively high speed of 25 m/s. On the other hand, the maximum throughput that the original PHMIPv6 approach can attain is, at best, close to 90 Kbps when the roaming speed of each considered node is a meagre 5m/s. As the nodes start to move faster, the throughput of the PHMIPv6 approach gradually drops and eventually degrades to 84 Kbps when the nodes travel much faster, i.e., at 25 m/s.

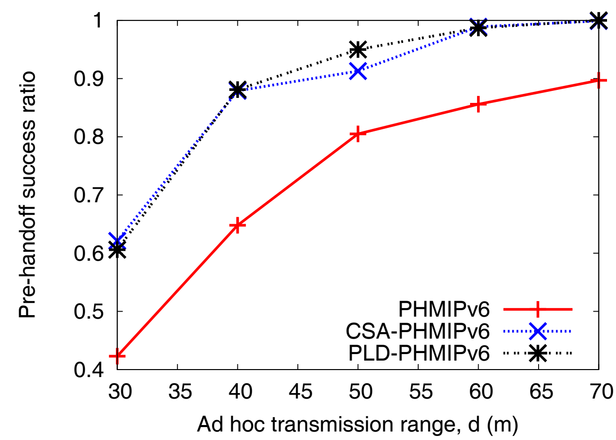


Fig. 8. Pre-handoff success ratio.

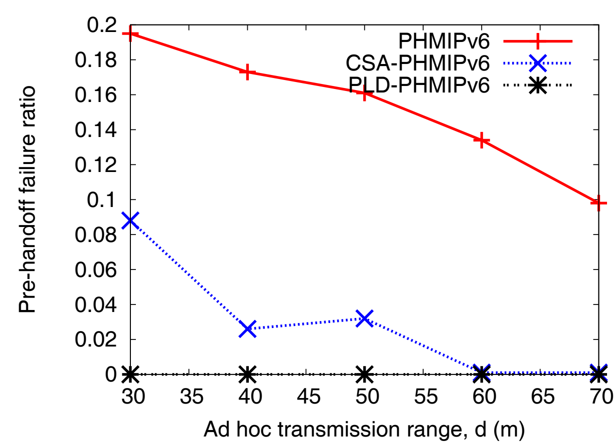


Fig. 9. Pre-handoff failure ratio.

Fig. 8 demonstrates the pre-handoff success ratio for different values of the radius of the nodes' ad hoc transmission range, d. For larger values of d, a MH is capable of selecting a PN from a larger number of MNs and the communication time between the two nodes becomes longer. This yields higher pre-handoff success rates as confirmed by the figure. However, in PHMIPv6, the partner selection is based on only the signal strength of nodes, and a MH sometimes selects a partner that may fade away during the pre-handoff operation. This explains the lower success rate of PHMIPv6. However, in case of the two proposed schemes, since the partner selection is based on the LET parameter, the pre-handoff success ratio is higher, reaching nearly 100% when the ad hoc transmission range is set to values larger than 60 meters.

Fig. 9 shows the pre-handoff failure ratio experienced in case of PHMIPv6, CSA-PHMIPv6, and PLD-PHMIPv6. The figure demonstrates that in case of PLD-PHMIPv6, the failure ratio is null and that is the case for all simulated values of d. This is mainly due to the fact that in PLD-PHMIPv6, the role of PN is limited to only forwarding the pre-handoff request message to AP. Longer communication times between MNs and PNs are thus not required in PLD-PHMIPv6. The figure also clearly indicates that many pre-handoff operations fail in case of PHMIPv6. This is mainly due to failure in selecting an adequate partner. In most failed cases, the selected

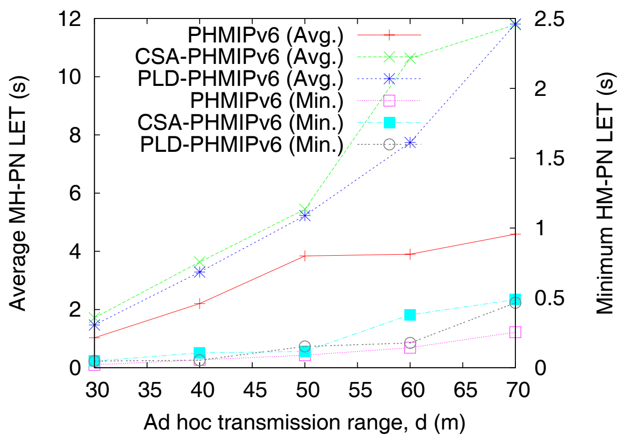


Fig. 10. PN's LET values over different transmission ranges.

PNs lose communication with their respective MNs as they mutually become outside the reach of their ad hoc modes. To show the idea with more clarity, we plot, in Fig. 10, the average and minimum values of LET between a MH and its respective PN for different ad hoc transmission ranges in case of PHMIPv6, CSA-PHMIPv6, and PLD-PHMIPv6 schemes. From the figure, it becomes apparent that except in case of $d = 70\ meters$, the minimum LET experienced in PHMIPv6 is smaller than the average pre-handoff delay (Fig. 6). This explains the high pre-handoff failure ratio experienced in case of PHMIPv6. When $d = 70\ meters$, the minimum LET experienced in PHMIPv6 is larger than the average pre-handoff delay, yet some pre-handoff operations failed. This is most probably due to the fact that the selected PNs went out from the coverage area of the respective AP before finalizing the pre-handoff operation. In case of CSA-PHMIPv6, such situations do not occur as frequently since its partner selection scheme takes into consideration the LETs between PNs and their respective MHs, and also LETs between PNs and APs.

V. Conclusion

In this paper, we have envisioned two extended versions of the original PHMIPv6 protocol to overcome its inadequacies and shortcomings. Our proposed schemes allow adaptation of handoff mechanisms to exploit cooperative diversity more effectively. The first proposed approach takes into account the nodes' dynamicity in terms of the Link Expiration Time used to carry out the cooperative handoff steps by maintaining stability of the connections between a MH, its respective PN, and other involved entities. The second proposed scheme aims at transferring most of the responsibilities of the partner node to the new access point. This mitigates the risks associated with the partner node which may move out of the mobile host's range during the pre-handoff or actual handoff phases. In addition, the envisaged designs incorporate security features to circumvent malicious threats against the mobile hosts and/or the partner nodes. Through simulations, we have demonstrated the viability of the proposed CSA-PHMIPv6 and PLD-PHMIPv6 approaches. Efficient adoption of cooperative diversity based communications through the two proposed approaches may indeed prove quite useful to roaming nodes in ad hoc wireless networks and ensure high QoE as validated by the simulation results.

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