IDMP-based Fast Handoffs and Paging in IP-based 4G Mobile Networks

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Abstract— **In this paper, we consider the use of our recently proposed Intra-Domain Mobility Management Protocol (IDMP) in 4^{th} generation (4G) mobile networks. On evaluating the heterogeneous access technologies, cellular layouts and application characteristics of 4G environments, we realize a need to reduce both the handoff latency and the frequency of mobility-related signaling. We first present IDMP's fast intra-domain handoff mechanism that uses a duration-limited, proactive packet 'multicasting' solution. We quantify the expected buffering requirements of our proposed multicasting scheme for typical 4G network characteristics and compare it with alternative IP-based fast handoff solutions. We also present a paging scheme under IDMP that replicates the current cellular paging structure. Our paging mechanism supports generic paging strategies and can significantly reduce the mobility-related IP signaling load.**

I. INTRODUCTION

There has recently been an almost universal recognition that Mobile IP [1], the current standard for IP-based mobility management, needs to be enhanced to meet the need for future 4^{th}-generation (4G) cellular environments. In particular, the absence of a location management hierarchy leads to concerns about the signaling scalability and the handoff latency, especially for a future infrastructure that must provide global mobility support to potentially billions of mobile nodes and accommodate the stringent performance bounds associated with real-time multimedia traffic.

In tandem with alternative proposals [2], [3] to develop a hierarchical IP-based mobility management framework in 3^{rd}-generation (3G) cellular networks, we have recently proposed the *Intra-Domain Mobility Management Protocol* (IDMP) [4] for managing node mobility within a specific *domain*. Like most proposals, IDMP envisions that multiple IP-subnets are aggregated into a single domain; as long as the mobile node (MN) moves within a single domain, all its mobility-related signaling remains localized to specialized nodes within that domain. Since the MN changes domains fairly infrequently, this localization drastically reduces both the global signaling load and the update latency. Conceptually, IDMP is a two-level generalization of the Mobile IP architecture, with a special node called the *Mobility Agent* (MA) providing an MN a domain-wide stable point of packet redirection. Based on our observation that the global communications infrastructure is likely to employ a multiplicity of protocols for ensuring ubiquitous global connectivity, we have intentionally designed IDMP to be independent of any specific solution for *global* (inter-domain) mobility management.

A careful consideration of the features of, and operating scenarios envisioned in, 4G networks however shows the need for further improvements and enhancements to IDMP. In this article, we emphasize the following characteristics of the 4G cellular environment and the consequent need for certain additional mobility-related features:

a) Heterogeneous Access Technologies:
The aim of 4G cellular networks is to develop a framework for truly ubiquitous IP-based access by mobile users, with special emphasis on the ability to use a wide variety of wireless and wired access technologies to access the common information infrastructure. While the 3G initiative is almost exclusively directed at defining *wide-area* packet-based cellular technologies, the 4G vision embraces additional *local-area* access technologies, such as IEEE 802.11-based wireless local area networks (WLANs) and Bluetooth-based wireless personal area networks (WPANs). The development of mobile terminals with multiple physical or software-defined interfaces is expected to allow users to seamlessly switch between different access technologies, often with overlapping areas of coverage and with dramatically different cell sizes.
Figure 1 shows one example of this multi-technology vi-

sion at work in a corporate campus located in an urban environment. While conventional wide-area cellular coverage is available in all outdoor locations, the corporation also offers 802.11-based access in public indoor locations such as the cafeteria and parking lots, as well as Bluetooth-based access to the Internet in every individual office. As mobile users drive in to work, their ongoing Voice-over-IP (VoIP) calls are seamlessly switched, first from the wide-area cellular to the wireless LAN infrastructure, and subsequently from the 802.11 Access Point (AP) to the Bluetooth AP located in their individual cubicles or offices. Since a *domain* can comprise multiple access technologies, mobility management protocols should be capable of handling *vertical handoffs*, i.e., handoffs between heterogeneous technologies. *Accordingly, we believe that it is preferable to define any additional mobility-related feature at the IP-layer, and not rely upon or assume the existence of specific features from the underlying link layers.*

b) Optional Fast Handoff Support:
While current proposals for intra-domain mobility management do localize the scope of signaling messages generated during intra-domain movement to nodes within the domain, the resultant latency may still prove to be unacceptably high for certain 4G applications. Indeed, the support of various real-time or high-bandwidth multimedia services, such as VoIP and video conferencing, which have very strict bounds on the handoff delay, is central to the 4G vision.

c) Paging Support:
The base Mobile IP specification does not provide any form of paging support. Hence to maintain connectivity with the backbone infrastructure, an MN must generate location updates every time it changes its point of attachment, even if it is currently in dormant or standby mode. Such mobility-related signaling leads to significant wastage of an MN's battery power, especially in pico-cellular environments (such as 802.11-based cellular topologies) where the MN may change its subnet of attachment very frequently (possibly once every 10 seconds). It is thus absolutely essential to define some form of flexible paging support in the intra-domain mobility management scheme.

In this paper, we present the extensions to the base IDMP specifications [4] for fast handoff and paging support, and analyze their applicability to 4G cellular architectures. We assume an all-IP access network where IP-layer functionality extends all the way to the nodes at the wireless edge of the access domain. We refer to this IP-capable point of attachment to the wired infrastructure as the Base Station (BS); in this scenario, we assume that the *Subnet Agent* (SA), a specialized IDMP node that provides subnet-specific support to the MN, is co-located with the BS. Generalizations to alternative architectures, where IP functionality does not specifically extend to the BS, are easy to make.

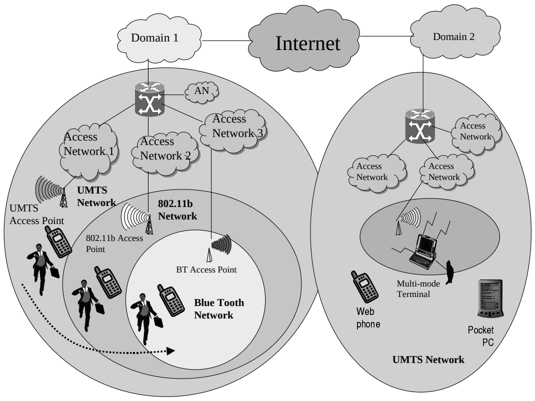

Figure 1: Example of Seamless Vertical Handoff in a 4G Environment

Under basic IDMP operation, an MN encounters a handoff delay equal to the time taken to update its designated MA about its new point of attachment; during this transient, packets may be incorrectly forwarded to the MN's old point of attachment and hence be lost. IDMP's *fast handoff* mechanism provides an IP-layer solution to reduce the duration of this service interruption and minimize the loss of in-flight packets during an inter-BS handoff. The mechanism uses either MN-initiated or BS-initiated handoff triggers and is applicable to multiple future link-layer technologies. Such triggers notify the MA of an impending handoff, whereupon the MA proactively multicasts in-bound packets (destined to the MN) to the set of neighboring SAs (see Figure 2). By caching these packets for a specified duration, the SA can minimize the loss of in-flight packets and forward such packets to the MN immediately after the MN refreshes its IP configuration parameters at the new subnet.

IDMP's IP-layer paging mechanism allows an idle MN to be located even though it does not perform IP-layer registrations at every change in subnet (BS). By performing the essential paging functions at the IP layer, we can make the mechanism relatively independent of the radio technology.

The rest of the paper is organized as follows. In section II, we present a summary of the current proposals for hierarchical IP-based mobility management and give an overview of the basic operation of IDMP. While section III describes IDMP's fast handoff mechanism and its prototype implementation, section IV details the enhancements needed to provide flexible IP-layer paging support. Finally, section V concludes the paper with a brief discussion of our plans for future work.

II. PREVIOUS AND RELATED WORK

Mobile IP (or MIP) [1], the current standard for IP-based mobility management, was designed primarily to provide transparent packet redirection to non-real time TCP applications running in conventional network hosts. Mobile IP works by assigning each mobile node a temporary care-of address (CoA), which correctly identifies the MN's current point of attachment, and using designated agent nodes to maintain the binding between this CoA and the MN's permanently assigned address. For cellular environments with potentially billions of MNs and real-time traffic, the MIP suffers from several shortcomings, including high update latency, large global signaling load and lack of paging support. These problems are also present in other variants of Mobile IP, such as route-optimized Mobile IPv4 and Mobile IPv6. Mechanisms have also been proposed [7] to use SIP-based signaling as an alternative application-layer mobility management solution, especially for real-time multimedia applications. In general, the SIP-based solution is analogous to Mobile IPv6, with the MN sending each active correspondent node (CN) a Re-INVITE (asking it to rejoin at the new CoA) and the appropriate SIP Server a new REGISTER (updating the binding between the SIP UserID and the current CoA). VoIP traffic benefits from such a mechanism, as it allows a CN to send traffic directly to the MN's co-located CoA (without tunneling), and as it permits the application to control the characteristics of an ongoing session as the MN changes subnets.

IDMP is one of several proposals for IP-based hierarchical mobility management, all of which aim to localize the signaling on intra-domain movement to nodes within the domain. One approach to intra-domain mobility management is the route-modification approach, characterized by Cellular IP (CIP) [2] and HAWAII [3], in which the MN is assigned a CoA that is valid throughout the domain, and *host-specific routes* are used to track the MN's precise location in the domain. The other approach is the multi-CoA approach in which an MN is assigned multiple CoAs, each resolving the MN's location at an intermediate level in the hierarchy. Among these schemes, Mobile IP Regional Registration (MIP-RR) [9] uses a Gateway Foreign Agent (GFA) to provide an MN a stable global CoA; the GFA acts as a proxy for the HA (Home Agent) during any subsequent intra-domain movement. Similarly, Hierarchical MIPv6 (HMIPv6) [8] introduces an agent called the Mobility Anchor Point (MAP) to localize the management of intra-domain mobility. Comparisons with alternative fast handoff and paging proposals will be discussed later in the relevant sections (III and IV).

A. IDMP Overview

IDMP is also a multi-CoA intra-domain mobility solution. However, unlike HAWAII, MIP-RR or HMIPv6, the protocol IDMP is designed as a stand-alone solution for intra-domain mobility management and does not assume the use of MIP for global mobility management. Figure 2 depicts the functional layout of IDMP. The Mobility Agent (MA) is similar to a MIP-RR GFA and acts as a domain-wide point for packet redirection. A Subnet Agent (SA) is similar to a MIP FA and provides subnet-specific mobility services. Under IDMP, an MN obtains two concurrent CoAs:

a) Local Care-of Address (LCoA): This is similar to MIP's CoA in the sense that it identifies the MN's present subnet of attachment. However, unlikely MIP's CoA, the local care-of address in IDMP only has local (domain-wide) scope. By updating its MA of any changes in the LCoA, the MN ensures that packets are correctly forwarded within the domain.

b) Global Care-of address (GCoA): This address resolves the MN's current location only up to a domain-level granularity and hence remains unchanged as long as the MN stays within a single domain. By issuing global binding updates that contain this GCoA, the MN ensures that packets are routed correctly to its present domain.

Under IDMP, packets from a remote CN are forwarded (with or without tunneling) to the GCoA and are intercepted by the MA. As shown in Figure 2, the MA then tunnels these packets to the MN's current LCoA. Since global binding updates are generated only when the MN changes domains and obtains a new GCoA, this approach drastically reduces the global signaling load. IDMP provides a uniform scheme for intra-domain mobility management, allowing cellular network providers to support multiple global protocols using a single common access infrastructure. For example, the TeleMIP architecture [5] combines IDMP with Mobile IP to provide seamless packet redirection at the network layer for TCP-based applications. Moreover, IDMP allows the network to dynamically assign one or more Mobility Agents to different mobile nodes; accordingly, IDMP is used in the Dynamic Mobility Agent (DMA) architecture [6] for providing Quality of Service (QoS) assurances to mobile networks in a scalable and robust manner.

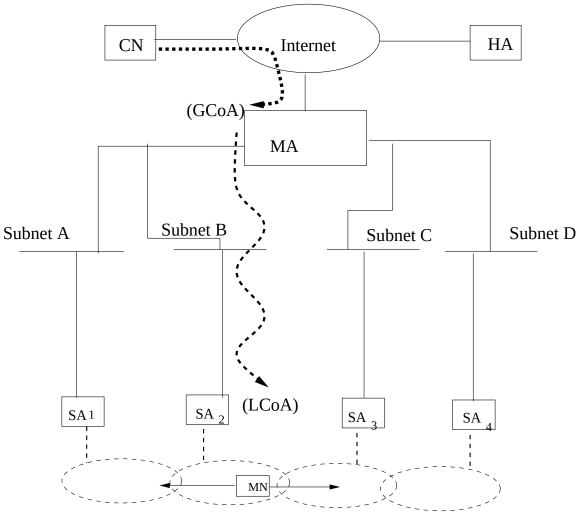

Figure 2: IDMP Logical Elements and Architecture

III. FAST HANDOFF SCHEME IN IDMP

In basic IDMP, the handoff delay equals the time taken for the MA to become aware of the MN's new point of attachment (LCoA). This delay consists of three separate components:

- *Link-Layer Establishment Delay (Δ_1):* This corresponds to the establishment of a link-layer or a physical channel (such as a slot-selection in TDMA or code sychronization in CDMA) with the new BS/SA.

- *IP Subnet Registration (Δ_2):* An MN must use IP-layer configuration protocols to obtain the new LCoA. If IDMP's SA mode is used, then the MN must obtain an Agent Advertisement beacon and then request a new LCoA. The SA will then respond with an Acknowledgment message. If the co-located mode is used, the MN must exchange DHCP configuration messages with the DHCP Server before obtaining a valid LCoA.
- *Intra-domain Update Delay (Δ_3):* The MN must finally inform the MA of this new LCoA via an Intra-domain location update message. Upon reception of this update, the MA will redirect packets to the MN's new LCoA.

To gain an idea of the handoff latency incurred by current IP-based intra-domain mobility protocols, we performed experiments with our implementation of IDMP, and the publicly available implementation of Cellular IP, on our 802.11-based testbed. Figure 3 shows the number of consecutive packets lost during a handoff as the packet inter-arrival time is varied. We can see that the handoff delay with IDMP in this scenario (where the MA was located one hop away from the SAs) is approximately around 12-15 msecs.

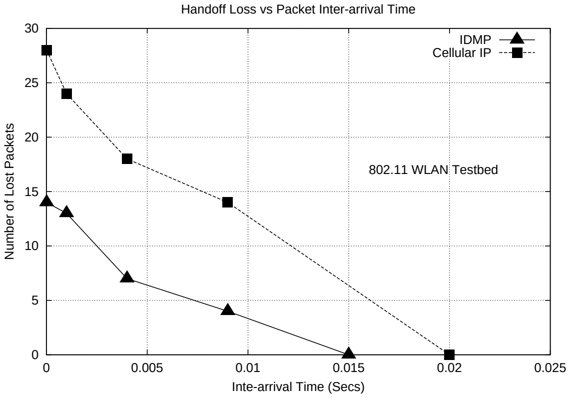

Figure 3: Packet Loss in IDMP and CIP Handoff

IDMP's fast handoff mechanism is designed to eliminate the Δ_3 component in service interruption. Δ_1, while a link-layer specific parameter, can be expected to be quite low. For example, in CDMA-based soft handoffs, Δ_1 is effectively 0, since, in a well-designed network, communication with the old BS is not discontinued until the connection with the new BS is firmly established. *IDMP's IP-based fast handoff technique provides a solution that does not require IP-layer information to be carried in layer-2 signaling messages or require the adjacent BSs to be aware of each other's identity.* Since we do not re-establish packet forwarding until the MN has performed a subnet-level registration at the new BS, IDMP's fast handoff process does not eliminate Δ_2, the delay incurred in the subnet-level registration process.

A. The Fast Handoff Procedure

We assume that a layer-2 trigger will be available (either to the MN or to the old BS) indicating an imminent change in connectivity. We explain the fast handoff mechanism using Figure 4, which shows an MN moving from SA_2 to SA_3. To minimize the service interruption during the handoff process, IDMP requires either the MN or the old SA (SA_2) to generate a *MovementImminent* message to the MA serving the MN. Upon reception of this message, the MA multicasts all inbound packets to the entire set of neighboring SAs (SA_3 and SA_1 in this case). Each of these candidate SAs buffers such arriving packets in per-MN buffers, thus minimizing the loss of in-flight packets during the handoff transient. When the MN subsequently performs a subnet-level registration (using IDMP) with SA_3, this subnet agent SA_3 can immediately forward all such buffered packets over the wireless interface, without waiting for the MA to receive the corresponding Intra-domain Location Update.

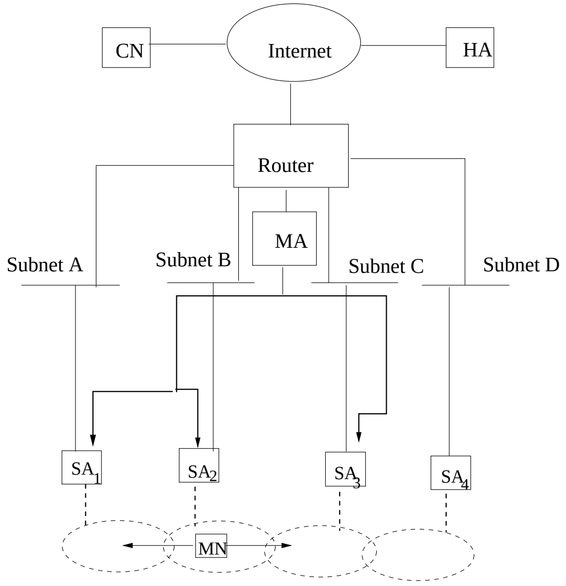

Figure 4: IDMP Fast Handoff

Several features of this proposal make it attractive for future IP-based networks.

a) Unlike other existing fast handoff proposals, IDMP's *MovementImminent* message does not specify the IP address of the target (new) BS in this message. This keeps the message size short; in fact, the MN can piggyback such a message simply by setting a bit in frames used for existing link-layer signaling. Moreover, by allowing the old BS to generate this message for the MA, we also accommodate some possible (hard) handoff scenarios, where the MN loses connectivity with the old SA before establishing radio-connectivity with the new BS. In such a scenario, the MovementImminent message is forwarded in parallel to the establishment of the new link. Accordingly, multicast forwarding is likely to be invoked concurrently with the subnet-level registration phase, thereby reducing (if not completely eliminating) the Δ_3 component of the delay.

b) IDMP utilizes a *network-controlled* (network or mobile-initiated) handoff technique. It is the MA which decides the set of target BSs to which in-flight packets are multicast. This is especially useful in scenarios where the MN may be in contact with multiple BSs and is unable to specify the future point of attachment exactly. While current cellular networks use a network-controlled handoff technique (where the base station controller (BSC) determines the candidate BS based on link-layer measurements supplied by the MN or BS), the IP mobility model is typically MN-driven, with the MN selecting an FA from a list announced via agent advertisements. IDMP preserves the network-controlled handoff model for future IP-based cellular networks, without compromising the MN's ability to select such fast handoff support.

c) Our multicasting scheme prevents unnecessary wastage of wireless bandwidth, since a BS does not unilaterally transmit all arriving multicast packets over the wireless interface. Such proactively multicast packets are temporarily buffered by an BS in per-user buffers and forwarded to the MN over the wireless interface only if it happens to register at that BS. In case the MN does not register at a particular SA, the buffered packets are discarded after a specified maximum time interval.

d) IDMP's fast handoff scheme does not eliminate Δ_2 from the service interruption time; it merely delays the transmission of packets arriving during this instant. By requiring the MN to first perform an IDMP subnet-registration before receiving any such packets, we avoid the need to define new extensions to layer-2 protocols for transporting IP-layer information (such as the CoA). By buffering packets during this transient, we are however able to avoid the loss of in-flight packets. Most multimedia applications, such as VoIP, are typically able to tolerate variations in the per-packet delay, as long as the packets are not actually lost. It is thus acceptable to suffer longer delay (due to Δ_2), as long as we can minimize the handoff-related packet loss.

B. *Implementing Fast Handoff*

For a prototype implementation, we use IP multicast to proactively distribute such packets to possible points of attachment. IDMP requires only one multicast group per neighbor set; all the BSs that are neighbors of a specific BS are members of this multicast group. Since a single BS can be a neighbor of multiple BSs, each BS can indeed be a member of multiple multicast groups. Our approach does not require the establishment of dynamic multicast groups for individual MNs. The membership of the neighborhood set is also not dynamic: given a fixed network topology, the set of neighboring BSs stays constant. Each BS is thus permanently subscribed to one or more multicast groups, each of which always has a well-defined distribution tree. Accordingly, the fast handoff scheme does not require a BS to dynamically join or leave a group, and hence, does not suffer from any transient tree-establishment latencies.

On receiving a *MovementImminent* message, the MA encapsulates an in-flight packet and then tunnels it to the appropriate multicast address. (For such multicast forwarding, the MA does not perform the conventional tunneling towards the current LCoA). On receiving such a tunneled multicast packet, each SA will first decapsulate the outer-most header. It then buffers the decapsulated packet in a per-user buffer, using the destination address in the inner-header (which is unique to a specific MN) as an index. When an MN subsequently performs a subnet-specific registration with an SA (say SA_3 in Figure 4), the SA can then forward any cached packets to the MN before the intra-domain location update process is complete.

Simple calculations indicate that even a small user buffer is effective in reducing the loss of in-flight packets. For example, if the intra-domain update latency (L) is 200 msec, and the incoming traffic rate (R) is 144 Kbps, then a buffer size of (L*R) 3.6 KBytes is able to protect against buffer overflow due to multicast packets transmitted during the handoff transient.

C. *Alternative Fast Handoff Suggestions*

The IETF is currently considering [11] several alternative approaches for supporting fast handoffs within the Mobile IPv4 context. In the pre-registration approach, the MN is assumed to initiate a new Mobile IP registration with the new FA via its current FA; the current FA tunnels such a registration request to the new FA. This mechanism requires the current FA to be aware of the identity of the neighboring (candidate) FAs and to advertise their IP-layer identities using *proxy* router advertisements. This proposal eliminates the sequential delay due to $\Delta_1 + \Delta_2$, since the new MIP registration (via the old FA) can occur concurrently with the establishment of radio connectivity at the new FA (Δ_1). However, unlike IDMP's fast handoff mechanism, this approach requires FAs to be aware of the identities of their neighbors and to pre-establish secure tunnels with them.

In the post-registration approach, layer-2 triggers are used to establish a transient tunnel between the current FA and the new FA. This mechanism requires the current FA to proactively tunnel all inbound packets to the new FA via this layer-2 triggered tunnel, thus allowing an MN to maintain its IP connectivity via the old FA even while it is performing a new Mobile IP registration at the new FA. As before, this approach requires an FA to be either aware of the identity of its neighboring FAs or to instantaneously form secure tunnels with a designated FA. Moreover, this proposal assumes that layer-2 authentication is adequate to (temporarily) authenticate the MN at the new FA; packets are forwarded to the MN by the new FA before the IP subnet registration process (Δ_2) is completed.

Similar fast handoff mechanisms have also been proposed [10] for Mobile IPv6. These mechanisms essentially rely on the establishment of a transient tunnel between the MN's old and new point of attachments, and the ability to use link-layer signaling to indicate IP-layer connectivity parameters.

IV. PAGING SUPPORT IN IDMP

While IDMP's use of multicasting for fast handoffs minimizes the loss of in-flight packets during an intra-domain handoff, it does not reduce the frequency of intra-domain location updates. In the absence of paging support, an MN must obtain a local care-of address and re-register with its MA every time it changes its current subnet. This can lead to significant power wastage, especially in future 4G networks where:

i) A single device may have multiple wireless interfaces and hence, need to maintain multiple simultaneous bindings.
ii) Pico-cellular layouts, especially for local area wireless access technologies, can lead to very frequent changes in the point of attachment.

A. Paging Operation for Idle Hosts

IDMP's IP-layer paging solution provides a flexible and radio-technology independent solution to this important problem and helps to minimize the power wasted by an MN in unnecessary mobility-related signaling. To motivate IDMP's paging solution, note that the 'multicasting' scheme described for fast handoff support in section III inherently sends multiple copies of the same data to multiple FAs/subnet routers that are judged to be in the vicinity of the MN's current point of attachment. Since limited broadcast of solicitations is really the central feature of paging, the idea of multicast groups can be extended to provide paging support as well. IDMP's paging operation assumes that SAs (subnets or BSs) are grouped into Paging Areas (PA) identified by unique identifiers, called Paging Area Identifiers (PAI). An MN in passive/idle mode is then able to detect changes in its current PA by listening to these unique identifiers in the subnet-level advertisements (e.g., SA Agent Advertisements). In fact, such IP-layer advertisements may optionally be combined with link-layer beacons.

IDMP's paging scheme is visually illustrated in Figure 5. In this model of operation, Subnets B, C and D belong to the same PA, while subnet A is part of a different PA. We assume that the MN switches to idle state in subnet B. Then, as long as it moves to C or D, it detects changes in its subnet of attachment but no change in its current PA. Consequently, not only does the MN not update its MA about its current LCoA, it does not even bother to obtain a new LCoA. However, when it moves to subnet A and realizes that it has changed to a new PA, the MN obtains a new LCoA at SA_1 and sends a location update to the MA, indicating the new PA.

When the MA receives packets for an MN which is currently registered, but which does not have a valid LCoA assigned, it 'multicasts' a *PageSolicitation* packet to all the subnets associated with the MN's current PA (to SA_2, SA_3 and SA_4) and buffers the incoming packet. When the MN re-registers with the MA, buffered packets are forwarded to the MN. We assume that temporary buffering is acceptable as the intra-domain location update process is assumed to have reasonably low latency ($\sim 2 \times \Delta$, where Δ is the update latency between the MN and its MA). For example, call setup delays in VoIP are typically around 2.5 sec; accordingly the paging latency is expected to fall within the targeted bounds.

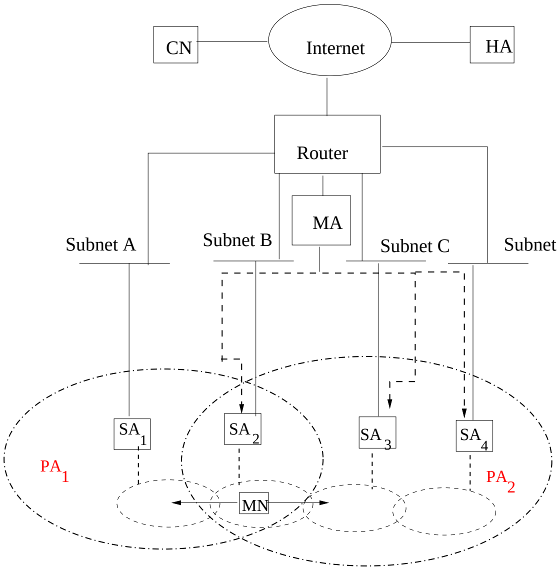

Figure 5: IDMP Paging Mechanism

B. Paging Implementation

Each PA is identified by a unique domain-specific multicast address; a BS belonging to a specific PA must permanently subscribe to the corresponding multicast group. Note also that, similar to the overlapping *registration area* (RA) concept in current cellular networks, a BS can subscribe to multiple multicast groups and hence, be associated with multiple PAs (Figure 5).

The base IDMP specifications need minor modifications for supporting paging. An MN must now actively inform its MA when it switches from the active to the idle state, thereby activating the paging functionality at the MA. In the absence of active "idle state notification", the MN would move to neighboring subnets without performing local registration, while the MA would continue to (mistakenly) unicast arriving packets to the MN's last registered local care-of address. Moreover, when an MN is in idle state, it performs an intra-domain location update by indicating its new PAI only when it changes its current PA; otherwise, the mobile is content to passively monitor the periodic link-layer multicast beacons.

C. Comparison with Alternative IP Paging Schemes

We now compare IDMP's paging mechanism with some of the recently proposed approaches to IP-layer paging in wireless cellular networks:

- The P-MIP proposal [12] for paging in Mobile IP is very similar to our IDMP paging specifications. Like IDMP, P-MIP associates a Mobile IP FA with one or more paging area identifiers; an MN in dormant (idle) mode performs Mobile IP registrations upon crossing into a new paging area. The P-MIP specifications, however, assume the use of Mobile IP as the underlying mobility management protocol and requires all FAs to be aware of the identity of their neighboring FAs. In contrast, IDMP's paging functionality does not assume the use of Mobile IP and hence, does not rely on Mobile IP security mechanisms; moreover, IDMP requires only the MA to be aware of the identity of all Subnet Agents associated with a particular paging area.

- Proposals for paging in Cellular IP and HAWAII essentially distribute the paging operation over multiple nodes in the access domain. While these protocols also use the paging area concept to reduce the number of updates generated by dormant MNs, the extent of a specific PA is only *implicitly* defined by the location of *paging caches*. To resolve the location of a currently unregistered MN, a paging request is broadcast over all domain nodes that lie downstream of this paging cache; it is thus difficult to dynamically alter the size or shape of a specific PA without actually changing the location of the paging cache. Moreover, such an implicit definition of a paging area makes it difficult to define overlapping PAs; it is well known that paging areas need to be overlapped to avoid the problems of ping-ponging. Perhaps, most importantly, it is difficult to apply such paging mechanisms in 4G environments, where an access domain may comprise multiple access technologies with overlapping cellular layouts, and thus does not exhibit a strictly hierarchical topology. IDMP, in contrast, defines a paging area in a topology-independent manner, based on an explicit set of SAs that subscribe to the corresponding multicast group.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we presented two enhancements to the IDMP solution for IP-based hierarchical mobility management. We considered a 4^{th} generation cellular environment, and motivated the need for developing IP-layer fast handoff and paging solutions that would work across heterogeneous access technologies.

To minimize packet loss during intra-domain handoffs, we presented a *time-bound* localized 'multicasting' approach. By proactively informing its associated Mobility Agent (MA) of an impending change, an MN enables the MA to multicast packets for a limited duration to a set of *neighboring* subnets. Specific nodes on those subnets (SAs/ designated routers) buffer such multicast packets for a short while; if the MN enters its subnet, such a node is able to immediately forward these packets to the mobile, significantly eliminating packet loss and delays. Our approach does not assume specific link-layer capabilities (such as the ability to transport specific IP parameters) and does not require an individual SA to establish a transient tunnel with another explicitly defined neighboring SA.

We also extended this localized 'multicasting' idea to provide paging support under IDMP. In our approach, each subnet would be associated with one or more Paging Areas (PA). A non-active MN would perform intra-domain location updates only when it changes its PA; to determine the MN's exact location within its current PA, the MA would 'multicast' a paging packet to all subnets to this PA. Unlike some other proposals for IP-based paging, our mechanism does not assume a tree-like topology and allows easy configuration of variable-size and overlapping PAs. Table I summarizes the commonalities and differences between the mechanisms used for fast handoffs and paging in IDMP.

TABLE I
OVERVIEW OF IDMP FAST HANDOFF AND PAGING

Function	Primary Mechanism	Handling of In-flight Packets
Fast Handoff	Multicasting from MA to candidate SAs	Buffered by candidate SAs
Paging	Multicasting by MA to SAs within Paging Area	Buffered by MA

We currently have a Linux and FreeBSD based implementation of IDMP deployed in our testbed. Additional details of the implementation, as well as preliminary performance results, are available in [6]. We are currently working to measure the performance improvements offered by our fast handoff and paging procedures.

VI. ACKNOWLEDGMENTS

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