ABC^2 : A New Approach to Seamless Mobility between Cellular Networks and WLAN

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Abstract

With the advent of new innovative mobility protocols, it is hard to realize seamless mobility. There are several reasons for this problem. First, service providers have to deploy in the entire networks and this demands a lot of financial investment. Second, even with those innovations, new mobility protocols are likely to be ignored by customers if it costs a lot of money for subscribers. Third, it is likely that most mobility protocols does not support both high bandwidth and large range.

Although the widespread deployment of cellular networks guarantees mobility in large range, it cannot completely support multimedia data. Similarly, although the explosive growth of WLAN provides the convenience of wireless with high bandwidth, it lacks large range support. Thus, in this paper, we propose a new approach, ABC^2, for seamless mobility such that our approach provides both high bandwidth and large range. ABC^2 will provide not only an "Always Best Connected" but also an "Always Best Complemented" interworking architecture between cellular networks and WLAN.

ABC^2 architecture is novel in that packet data network is layered on top of circuit switch network such that it can use current legacy telephone networks for mobility management and it can provide multimedia data with low cost investment as the Internet advances to the higher bandwidth. In our analysis, we show that ABC^2 performs better in terms of location updates, handoff latency, and signaling delay compared to most

mobility protocols dependent on Mobile IP.

1 Introduction

In order to realize seamless mobility, mobility should not only be unbounded in small, middle, and large range but also come with services for high bandwidth like multimedia data. In our daily experiences, we can see mobility patterns like micro, macro, and global mobility easily. As a micro mobility example, people tend to stay in specific areas for a long time such as home, school, and office and move around in a small range. As a macro mobility example, people routinely commute between home and office or school. As a global mobility example, people often travel in different cities for work or for vacation. Thus, a mobility protocol must consider all these mobility patterns in its design. In addition to mobility concerns, people tend to use high bandwidth data services with multimedia entertainments. Thus, people need to be serviced with high bandwidth of data communication as well as seamless mobility.

People today are exposed to diverse access technologies such as Bluetooth, WLAN and cellular networks but none of them fully support seamless mobility with unbounded range and high bandwidth. The last decade has witnessed the explosive growth of Wireless LAN (WLAN) and the high bandwidth of data communication but it is short of supporting mobility. On the other hand, the widespread deployment of cellular networks such as 2G, 2.5G, and 3G succeed in providing a large range of voice communication but they have a strict limitation of bandwidth to support high bandwidth data communication such as multimedia data. 3G cellular networks and WLAN are compared in Table 1. Noticeably, the large range of 3G up to 10 km is an advantage over the small range of WLAN up to 200 m whereas the high bandwidth of WLAN up to 54 Mbps is an advantage over the mediocre bandwidth of 3G up to 2 Mbps. The complementary nature of 3G and WLAN motivates interworking 3G and WLAN.

Table 1: Comparisons between 3G and WLAN

	3G	WLAN
Range	Large (200 m $\sim$ 10 km)	Small (50 m indoors, 200 m outdoors)
Data Rates	Low (144 Kbps $\sim$ 2 Mbps)	Fast (11 Mbps $\sim$ 54 Mbps)
Mobility Support	Fast Mobility	Semi Mobility

In the future, people will be more exposed to heterogeneous wireless access technologies, and to run applications in the future networks must have high bandwidth and large range. In this sense, interworking cellular networks and WLAN will be required. WLAN networks are satisfactory solutions for high data bandwidth but lack large range support whereas cellular networks are proven solutions for large range but lack high bandwidth support. Since different wireless networks are complementary, it is inevitable that those wireless networks [6] will be integrated. In designing interworking among heterogeneous networks, vertical handoff was first introduced in [54]. While horizontal handoffs coordinate between two homogeneous networks, vertical handoffs handle two heterogeneous networks. The development of Media Independent Handover Services of IEEE 802.21 standard will ease the integration for heterogeneous wireless access technologies [2].

Although the benefits of the interworking architecture between cellular networks and WLAN are clear, we need to be concerned about the incentives of service providers and subscribers. Service providers need incentives to deploy a new technology; the promise of revenues must outweigh the investment. Subscribers, on the other hand, need incentives to pay for services; the promise of better service must outweigh the cost. Therefore, the interworking architecture between cellular networks and WLAN requires not only the minimum investment for service providers but also the maximum benefit to subscribers.

One of the primary hurdles of mobility problems centers around IP addresses. Undoubtedly, IP is the core part for All-IP networks in the future wireless networks [16]. In designing the interworking architecture between cellular networks and WLAN, IP mobility problems must be considered. Initially, IP addresses are not suitable for mobility support. In the design principles of the Internet [15], computers are assumed to be fixed and unique addressing is associated for both routing and identification. This dual functions of IP address problems are resolved in HIP [37] and I^3 [56]. IP addresses are used for two kinds of identifiers: home addresses and identifications. Home addresses are used for location identifications and are topologically dependent. For example, home addresses are used for mail delivery in the real world. Identifications are for identifying persons and are topologically independent. Identifications can be thought of as Social Security Numbers in the real world. Since IP addresses are used for both home addresses and identifications, it is problematic if a mobile moves from one location to another. In our approach, we decouple the two functions of IP addresses. IP addresses will be only used for routing. The decoupling of two functions is required for IP mobility such that the result is home addresses are used for packet forwarding and identifications are used for location management.

The goal of this paper is to introduce the best connected and complemented interworking architecture. In terms of seamless mobility, the Always Best Connected (ABC) Concept is introduced in [25]. [25] points out that “Always Connected” is envisaged by cellular networks and “Best Connected” is required for combining the worldwide coverage of cellular systems with the high bandwidth of WLAN hot spots. Our approach goes beyond the ABC [25] concept and provides “Best Complemented” since we synergize two different architectures: cellular networks and WLAN. Based on this concept, our interworking architecture is Always Best Connected and Complemented (ABC^2).

This paper makes three contributions. First, we propose an alternative mobility protocol other than Mobile IP (MIP) and we rethink mobility support in the interworking architecture between cellular networks and WLAN. Second, we provide a way to reuse the existing architectures and we give incentives to service providers. Third, we devise an evolutionary and practical solution for mobility support and describes how it can be easily, partially, and independently deployed.

The rest of the paper is organized as follows. Section 2 explores the previous work on the interworking architectures, and mobility protocols as MIP variants and non-MIP variants. Section 3 discusses the motivation of our work and presents the design principles of ABC^2 based on our motivation. Section 4 gives the overall picture of ABC^2 and Section 5 describes ABC^2 architecture in depth. Section 6 evaluates ABC^2 architecture compared with other mobility protocols on location updates, signaling delay, and handoff delay. Finally, Section 7 summarizes and discusses our work.

2 Related Work

The complementary natures of 3G and WLAN attract research on interworking 3GPP and WLAN [5, 14] and between 3GPP2 and WLAN [12]. Furthermore, two standards are proposed as in [3, 4] for 3GPP and 3GPP2 respectively. Commonly, these standards adopt MIP as a basis for mobility support. Although MIP is well received in the interworking architectures between WLAN and 3G, the problems of MIP like triangle routing, registration delays, and handoff delays are inherent in this architecture. In this paper, we design an interworking architecture between cellular networks and WLAN without MIP.

Diverse interworking architectures based on Mobile Ad-hoc Network (MANET) mode are surveyed and discussed in [14]. The complexity of interworking cellular networks and WLAN in MANET mode is unlikely to evolve the interworking architecture with MANET mode. Multihop routing problems inherent in MANET mode are even more difficult to resolve with the addition of interworking mechanisms. Infrastructure mode, on the other hand, does not involve with the complexity of multihop routing problems. In this paper, we focus on interworking cellular networks and WLAN based on infrastructure mode.

MIP is a novel approach for supporting mobility on the Internet [41] and has become a de facto standard for mobility support in IPv4 [40] and IPv6 [32]. MIP resolves the problems of IP addresses location dependent by differentiating home and foreign networks. The locations of mobiles are tracked by their home agents such that mobiles are communicated via their home agents when mobiles move away from their home networks. When a mobile moves to foreign networks, it registers its location by its care of address (CoA) to its foreign agent. Thus, MIP has inherent problems such as triangle routing, registration delay, and lack of micro mobility since the packets are always forwarded through the mobile's home agent.

This triangle routing problem can be resolved by route optimization [42]. Route optimization, however, requires IP stack changes and only home agents can initiate the route optimization. Furthermore, the registration to a mobile's home agent is required and it contributes to significant handoff delays when a mobile is distant from a correspondence node. As the number of mobiles increases, the latency rises during the location update process [18]. Thus, triangle routing problems are not solved totally by route optimization in MIP. Since the lack of micro mobility in MIP causes high handoff latency and packet loss, it gives rise to a lot of MIP variants (Table 2). Regardless of their approach, all the MIP variants are based on MIP for global mobility. Only FHMIPv6 [33] supports global, macro and micro mobility. Importantly, all these mobilities should be supported for seamless mobility.

Table 2: Comparisons of Mobility Support Protocols

	Micro	Macro	Global
MIP			√
HMIP		√	√
TR45.6		√	√
HAWAII		√	√
MIP-RR		√	√
TeleMIP		√	
Cellular IP	√	√	
TIMIP	√	√	
IDMP	√	√	
FMIPv6	√		
FHMIPv6	√	√	√
ABC^2	√	√	√

Localization, hierarchical architecture, and paging are widely used for mobility management in cellular networks. MIP variants try to enhance the performance of mobility by emulating mobility management in cellular networks. Localization is common to all MIP variants [46], and is necessary for micro mobility support since it prevents the propagation of traffic to core networks and reduces handoff delay. Hierarchical architecture is introduced in MIP Regional Registration (MIP-RR) [26], Hierarchical MIP (HMIP) [53], and Intra Domain Mobility Management Protocol (IDMP) [17, 36]. On the other hand, HMIP, Cellular IP (CIP) [13], and Handoff-Aware Wireless Access Internet Infrastructure (HAWAII) [46] are based on paging. Two CoAs are used in IDMP and Telecommunications-Enhanced MIP (TeleMIP) [18]. Compared to other MIP variants, Terminal Independent Mobility for IP (TIMIP) [24] is different from other variants in that it adopts context transfer mechanisms for seamless mobility. Additionally, TR45.6 TIA Standard [59] is designed for 3G cellular wireless systems. Thus, mobility management schemes like localization, hierarchical architecture, and paging in cellular networks are proven to perform well to support mobility in MIP variants.

Although micro mobility is achieved in MIP variants, several problems still remains. MIP variants reduce the number of signaling messages but packets are still redirected to home agents such that additional delays are outstanding if home networks are distant from correspondence nodes or foreign networks. With these enhancements, MIP variants are still suffering from high packet loss and high handoff latency [28]. Specifically, CIP and HAWAII require IP stack changes.

Compared to MIP variants, several non-MIP variants have been proposed such as Seamless IP diversity based Generalized Mobility Architecture (SIGMA) [23], Session Initiation Protocol (SIP) [39], DNS-based Approach [52], Host Identifier Protocol (HIP) [37, 27], and S-MIP [63]. While MIP is a network layer approach, non-MIP variants are based on the different layers such as the application layer, the transport layer, the link layer and even the cross-layer between the link layer and the network layer. As mobility is handled on the higher layers, it is less dependent on the physical layer and the link layer, but nevertheless it introduces additional delays for processing packets in the higher layers. Compared to the additional delays, movement detection is faster in the lower layer like link layer.

As an application layer approach, SIP [39] is noticeable. SIP uses email-like ids for identifications and it achieves terminal, personal, session and service mobility. Since SIP is implemented in the application layer, it is independent of access technologies. SIP, however, is dependent on diverse entities such as user agents, redirect servers, proxy servers, and registrars. Since the major functions of these servers locate the users, these servers behave like DNS servers. Additional delays by application processing of the messages are the huddles for mobility support. Moreover, SIP mobility cannot support TCP connections and is not suitable for micro and macro mobility [18]. In [8], two interfaces must be used for soft handoff.

For the transport layer approach, SIGMA [23] and the DNS-based approach [52] are noticeable. SIGMA uses IP diversity for mobility support so that multihoming is required. In order for performance gains, Stream Control Transmission Protocol (SCTP) [55] is used. In assigning a new IP address for mobiles, dynamic address reconfiguration messages of SCTP are used. Although SIGMA is deployable without SCTP, performance is not analyzed without SCTP. Another approach for the transport layer is the DNS-based approach [52]. Although it achieves an end-to-end mobility scheme, this approach is largely dependent on the performance of DNS, which is not explored in the paper. Major challenges of the DNS-based approach are high traffic load and failure to update DNS [48]. Essentially, this approach is made possible due to dynamic DNS update [62].

The link layer approach [63] is proposed to reduce MIP handoff latency by noting that it is composed of movement detection and registration. Although [63] reduces registration delay, it fails to reduce movement detection delay. Another variant of the link layer approach is S-MIP [29], which reduces movement detection delays using the link layer information. S-MIP is a cross-layer approach to reduce handoff latency by tracking mobiles in the network layer and the link layer. S-MIP tightly couples the link layer and the network layer to reduce handoff latency, requiring IP stack changes.

Host Identifier Protocol (HIP) [37, 27] is different from other approaches as it adds an additional layer to the IP stack, leading to IP stack changes.

HIP uses a public key name space for global identifications and implementation complexity, but computational overheads are significant due to cryptographic functions. HIP guarantees security due to cryptographic functions, but only supports for macro mobility.

3 Motivation, Design Principle and Deployment Model

Most mobility protocols are based on MIP solutions and 3G and 4G adopt MIP as an IP mobility solution in their interworking architectures. The IP address problems of MIP as a dual functionality for location and identification are well resolved by using home addresses and care of addresses. Although the routing anomalies by triangle routing are resolved by route optimization [42], triangle routing is not totally addressed since correspondents still need to contact home agents first. Registration delays and packet loss by unnecessary routing were forgivable in the past since it was inevitable. However, it is not clear whether it is still inevitable since environments have been changed.

Here is a meaningful question: *Is MIP a definite solution in the interworking architecture between cellular networks and IP networks? Is there an alternative solution other than MIP in the interworking architecture?*

Although a lot of micro mobility protocols have been proposed, most of the protocols are short of supporting seamless mobility. Most mobility protocols solve only micro mobility problems. Yet, they depend on MIP for global mobility. Thus, the problems of MIP are inherent. Therefore, we take another approach to rethink mobility support in the interworking architecture between cellular networks and WLAN such that we design the interworking architecture without MIP.

3.1 Motivation

Our approach is motivated by the following aspects.

(M1) Design mobility support without MIP. Although MIP is advocated largely in research communities, it is meaningful to think about mobility protocols without MIP in the interworking architecture between cellular networks and WLAN. Since cellular networks support best for mobility, we will leverage the mobility management of cellular networks and we can reduce the redundant mobility functionalities in the Internet.

(M2) Incentives for ISPs. Importantly, we need to consider incentives for service providers. The deployment of any new technology requires a lot of investment for service providers. The costs should not exceed the benefits and the costs should promise the incentives for service quality and advantages over other service providers. A new technology is meaningless if the investment outweighs its gains. Service providers should leverage existing infrastructures to satisfy customers. Deploying the new technology becomes easier if the new technology does not require a whole change of networks. Our approach reuses

existing infrastructures and does not require a lot of changes in current networks such that service providers will deploy easily and satisfy their customers.

(M3) Evolvable Internet. We have seen that an evolvable approach is more applicable and better deployable than a revolutionary approach. Revolutionary approaches for the Internet architecture are proposed as in I^3 [56] and Active Networks [60]. Compared to these approaches, evolutionary approaches are considered in [47]. Although IP multicast [45] and IPv6 [19] were regarded as promising technologies in the past, they have not been fully deployed until now, since they require a lot of changes in the current Internet. On the other hand, in the past few years, overlay networks [7, 51, 1, 31, 57] have been widely accepted in diverse network areas and are deployed quickly since they do not require a fundamental change of the Internet. Our approach is evolvable rather than revolutionary and thus more practical and easier to deploy.

3.2 Design Principle

Based on our motivations, our design principles are as follows.

(P1) Unbounded seamless mobility. Our approach must ensure unbounded seamless mobility while most mobility protocols do not support mobility in micro, macro, and global areas. Seamless mobility can be realized without the area boundaries so that our approach supports mobility in small, middle, and large range.

(P2) Incorporation of existing architectures. In order to give incentives for service providers, our approach must incorporate current architectures. Service providers are not likely to build an interworking architecture from scratch. We will take this opportunity to use current architectures without dramatic changes. Our approach leverages existing infrastructure, and thus requires only a small change.

(P3) Easy, partial, and independent deployment. In order to be evolvable, our approach must be deployed easily, partially, and independently. Our approach must be easy to deploy and not require many entities like servers, router changes, and IP stack changes. Since our approach will not introduce foreign networks as in MIP, it can be partially deployed and easily tested. A service provider may deploy our approach without waiting for others to do so.

3.3 Deployment Model

In deploying the interworking architecture between cellular networks and WLAN, we can think of three deployment models as follows.

(M1) Individual deployment model. If a company owns cellular networks and IP networks, this company individually can deploy the interworking architecture between them. Thus, such a company has an edge over other companies with only cellular networks or IP networks.

(M2) Cooperative deployment model. A company that owns either cellular networks or IP networks is not competitive with the company in the first deployment model. In this case, such a company will try to find a way to cooperate

with another company that has a complementary network. In our approach, we provide a way for those companies to work together for a mutual benefit.

(M3) Third party deployment model. Finally, a third party can deploy the system to link cellular networks and IP networks. With this approach, the third party will be in charge of integrating multiple cellular network providers and ISPs. Furthermore, the third party can efficiently manage the system for interworking cellular networks and WLAN. Additionally, it will be easier for late starters to join quickly in the market. Our approach enables the third parties to deploy the interworking architecture on behalf of cellular network providers and ISPs. Thus, this approach provides a new business model for the third parties.

As a result, our approach benefits service providers and customers. Our approach enables service providers to deploy with a small investment and they will earn revenues quickly. Most companies would like to own both cellular networks and IP networks but most of them do not. Our approach will give a way for companies to cooperate with each other easily and ensure competitive markets. Meanwhile, at the same time, services for customers will be maximized with large range and high bandwidth, with minimum cost for the interworking architecture.

4 ABC^2: Overview

4.1 GLUE

IP addresses are tightly coupled with the locations of nodes in the Internet. Although IP addresses are well designed for routing, it is not suitable for identifying mobiles in the Internet. Since IP addresses are dependent on the topology of networks, MIP is proposed for forwarding packets to mobiles via home agents. Global identification is required for mobility support. HIP [37] uses a public key as a global identification while SIP [39] uses email addresses. HIP requires IP stack changes since the HIP layer is added between the transport layer and the network layer. SIP is not suitable for micro and macro mobility since it takes more time to handle messages in the application layer. As a global identification, telephone numbers provide an existing infrastructure for communication in telephone networks. We propose using telephone numbers as a global identification in the interworking architecture since they are widely used and familiar to many people.

Recently, Electronic Number (ENUM) [22] has been proposed to translate E.164 telephone numbers [30] for diverse purposes. ENUM is based on DNS and thus entirely not satisfactory for mobility; it requires the propagation of information globally and has scalability issues. In order to support mobility in the interworking architecture, it is sufficient to provide mapping between IP addresses and electronic IDs.

Compared to ENUM, our approach is called Global Location by Unique EID (GLUE) and we provide a way to map directly between IP addresses and telephone numbers. We do not restrict electronic IDs to E.164 telephone numbers and it can include private numbering plans since it is sufficient to have the unique ID in a Local Area. Thus, GLUE is a way to “glue” IP addresses and telephone numbers that subsumes E.164 telephone numbers in ENUM as a special case. In our approach, we don’t require a global propagation and there are no scalability issues. By locating users in cellular networks, we do not need to transfer mapping information. Instead, we use a direct mapping between IP addresses and telephone numbers in a Location Area (LA) of cellular networks.

E.164 telephone numbers are organized globally with country codes, local codes, and local telephone numbers. ENUM is an IETF standard to find services on the Internet by E.164 telephone number. For ENUM service, e164.arpa domain is added in DNS. Naming Authority Pointer (NAPTR) [35] resource records (RR) are added to associate with resources, services, and applications as DNS extensions for ENUM services. The algorithm to convert E.164 telephone numbers to a unique key in ENUM is straightforward. First, E.164 telephone number is reversed. Second, each digit is separated with “.”. Finally, e164.arpa is added at the end of the string.

Although GLUE and ENUM are both designed to leverage telephone numbers, there are several differences between these two approaches. GLUE directly maps between IP addresses and telephone numbers while ENUM is a generalized mapping service for SIP [43], H.323 [34], web and file transfer [9], voice [10], and messages [11]. ENUM adds DNS extensions as the number of services increases. Furthermore, the propagation time adds additional delays to handoff latency. GLUE assumes location management in cellular networks such that it does not have to propagate mapping information to the entire Internet and thus better for mobility support.

4.2 $\mathbf{ABC^2}$ Architecture

ABC^2 architecture is shown in Figure 1. Although ABC^2 can be deployed in both loosely and tightly coupled interworking architecture, we advocate loosely coupled interworking architecture [12] for our approach. Conceptually, the Internet is superimposed on top of cellular networks in our approach. ABC^2 can be applied to any cellular networks such as 3G, 4G, and Next Generation cellular networks. In our example, we focus our architecture on 3G cellular networks. We divide ABC^2 into two planes – IP networks and cellular networks – such that circuit switching of cellular networks is in charge of signaling traffic and packet switching of the Internet is in charge of data packets. With this approach, ABC^2 leverages the broad range of cellular networks and the high bandwidth of the Internet.

In our example, the GLUE system is attached to Gateway GPRS Support Node (GGSN) in 3GPP and Packet Data Serving Node (PDSN) in 3GPP2. GGSN and PDSN are the attachment points where cellular networks and IP networks meet, such that the GLUE system can be easily connected to GGSN and PDSN. Multiple Access Routers (ARs) are associated with the GLUE system and the addresses of ARs are assigned as Global CoAs (GCoAs) to mobiles while the addresses of mobiles are Local CoAs (LCoAs). GCoAs indicate the

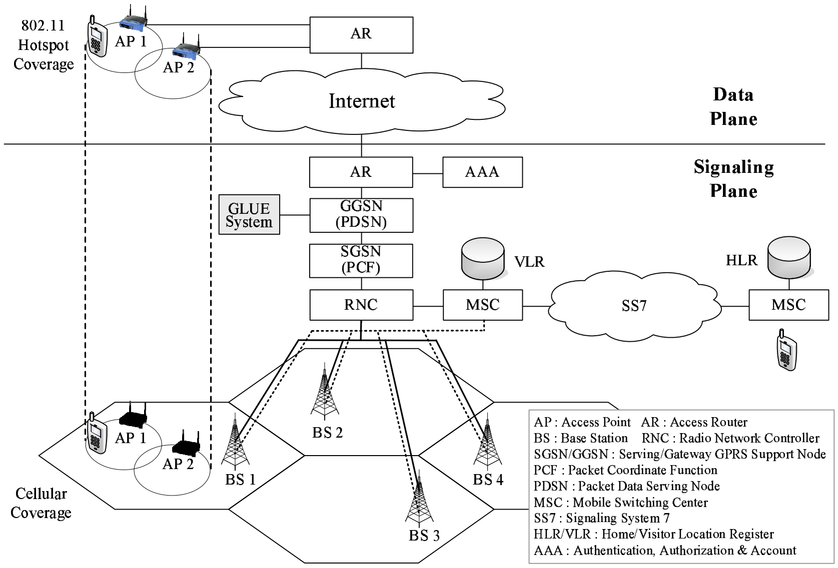

Figure 1: ABC^2 Architecture for 3G and WLAN interworking

location of mobiles up to domain level granularity while LCoAs are dynamically assigned to mobiles whenever mobiles move from one subnet to another.

4.3 Basic Operations

4.3.1 Registration

Two kinds of registrations are introduced in ABC^2: global and local. When a mobile moves from one domain to another, global registration is required. The mobile is assigned a GCoA and a LCoA and updates both to the GLUE system. In global registration, both are newly assigned while only LCoAs are assigned for local registration. When a mobile moves from one subnet to another, a LCoA is assigned and the mobile registers its LCoA to the GLUE system.

4.3.2 Handoff

IP mobility protocols require handoff procedures when a mobile moves from one subnet to another. Since IP addresses are dependent on the topology of networks, mobiles need to change their IP addresses. Depending on the movement of mobiles, two kinds of handoffs are required: intra-domain and inter-domain. When a mobile moves from one subnet to another in one domain, intra-domain handoff is performed. A mobile requests a new IP address to a DHCP server in its proximate area. After being assigned a new IP address, the mobile registers its new IP address to the GLUE system and deregisters its old mapping in the last visited subnet. On the other hand, when a mobile moves from one domain to another, inter-domain handoff is performed. The mobile performs cellular network handoff between one cellular domain and another. After the handoff, the mobile registers its GCoA to a new GLUE system with an IP address of ARs in a new cellular domain.

4.3.3 Signaling

A Correspondent Node (CN) must locate the mobile before they communicate with each other. In cellular networks, locating the mobile can be easily done by telephone numbers. The CN dials the phone number of the mobile. The Mobile Switching Center (MSC) for the CN sends an IP query request to a Home Location Register (HLR). The HLR looks up whether or not the mobile exists in the HLR. If the mobile is not in the HLR, the HLR forwards the signal to a Visitor Location Register (VLR). After confirming the location of the mobile, the MSC forwards the IP query request to the MSC in the mobile's location. The IP query message is forwarded to the mobile's GLUE system via GGSN or PDSN. The GLUE system searches the mapping of the mobile's GCoA and LCoA with the mobile's telephone number. The GLUE system responds to the CN with its GCoA and its LCoA. After receiving a reply from the GLUE system, the CN starts to send packets to the LCoA (the address of the mobile) via the GCoA (the address of an AR).

5 Protocol Detail

5.1 Private IP in IP Encapsulation

In ABC^2, IP addresses are dynamically assigned to mobiles and the connectivity of traffic is not ensured since transport layer protocol is tightly coupled with network layer protocol with IP addresses and port numbers. This coupling problem is resolved by decoupling those two relations with the HIP layer and the daemon in HIP [37]. However, HIP requires IP stack changes for mobiles. In MIP, IP Encapsulation within IP [38] is used for decoupling the coupled relationship. IP Encapsulation within IP is a way to change the normal routing for datagrams by delivering packets to an intermediate node. In ABC^2, we use IP Encapsulation within IP in both ends of communication such that mobiles send and receive packets using dynamic IP addresses in the Internet while applications in mobiles use static IP addresses. Thus, applications in mobiles are not disrupted by the change of IP addresses since they use static private IP addresses. Although IP Encapsulation within IP incurs packet overheads, it does not require modifications on IP stacks and it is more applicable to practical situations. Additionally, considering the increase of bandwidth by ABC^2, IP Encapsulation within IP is a small amount of overhead. Clearly, if we use IP Encapsulation within IP in ABC^2, we run out of IP addresses. In order to get around the shortage of public IP addresses, we use private IP addresses[49] for applications in mobiles. Private IP Encapsulation within IP (PIPE) [44] is a way to encapsulate private IP addresses in public IP addresses.

ABC^2 uses the IPinIP Encapsulator like MIP but a difference exists in applying the IPinIP Encapsulator. MIP requires two public IP addresses such as a home addresses and a CoA but ABC^2 requires one dynamically assigned public address and uses a private IP address to ensure network connectivity. This is a huge difference since ABC^2 does not run out of IP addresses, which are a limited resource on the Internet. In MIP, the IPinIP Encapsulator can be used with colocated CoAs and home addresses in IPv6. With this approach, mobiles can directly register to their home agents without being directed via foreign agents. This process removes the uses of foreign agents and it reduces registration delays. However, it is only deployable with IPv6 due to the lack of IP addresses. Additionally, mobiles are still required to register all the way back to home agents when they move to foreign networks.

5.2 GLUE packet format

In Figure 2, we show the packet format for GLUE registration. ENUM is based on DNS and ENUM uses the Naming Authority Pointer (NAPTR) [35] to identify available services connected to an E.164 number. NAPTR is a type of RDATA defined in Resource Records (RR), which is the DNS data records. Although ENUM supports for diverse applications, adding numerous records to the DNS could have a significant performance impact on the processing and storage requirements. In addition, translating to a URI entails resolving the URI in order to route the call. Thus, a direct mapping between IP addresses and telephone numbers is practical in mobile environments where delays are critical for seamless mobility.

In contrast to NAPTR in ENUM for the mapping between telephone numbers and diverse applications, we propose an IP Authority Pointer (IPAPTR) as a way to provide a direct mapping between IP addresses and telephone numbers. The field definitions of IPAPTR are as follows.

- Version
  Version field indicates IP version. The length of IPv4 addresses is 32 bits and that of IPv6 addresses is 128 bits such that the packet length is variable depending on the IP version.

- Timestamp
  Timestamp field records the time that mobiles register their IP addresses

```
                     1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-------+-------------------------------------------------------+
|VERSION|                       TIMESTAMP                       |
+-------+-------------------------------------------------------+
/                  ADDRESS OF AN ACCESS ROUTER                  /
+---------------------------------------------------------------+
|                      ADDRESS OF A MOBILE                      |
+---------------------------------------------------------------+
```

Figure 2: Packet Format for IPAPTR RR of GLUE

to the GLUE systems. Timestamp is used for the expiration of old records.

- Address of an access router
  The IP address of an AR is used for a GCoA. The GCoA changes when mobiles move from one domain to another.

- Address of a mobile
  The IP address of a mobile is used for a LCoA. The LCoA changes when mobiles move from one subnet to another.

5.3 Message Flow Details

We describe message flow details based on 3GPP2 cellular networks [4]. However, it will be applicable to most cellular networks such as 2.5G, 3GPP, and 4G. In our example, we focus on registration, handoff, and signaling. In the following examples, we assume that PCF 1 is associated with PDSN 1 in domain 1 and PCF 2 is associated with PDSN 2 in domain 2. MSC 1 is located in domain 1 and MSC 2 is located in domain 2.

5.3.1 Registration

In Figure 3, we illustrate the registration procedures. Mobiles are required to register their current IP addresses to their GLUE systems when they move from one location to another. When a mobile moves from one subnet to another, the mobile is required to register its LCoA to its GLUE system. Similarly, when a mobile moves from one domain to another, the mobile is required to register its LCoA and GCoA to its GLUE system. Before a mobile registers to its GLUE system, its IP address must be configured with DHCP [20], DHCPv6 [21], or Stateless IP auto-configuration in IPv6 [61]. In 3GPP2, an IP Control Protocol (IPCP) message is used for assigning a new IP address to a mobile and it is generally an IP address request message to a DHCP server. The newly assigned

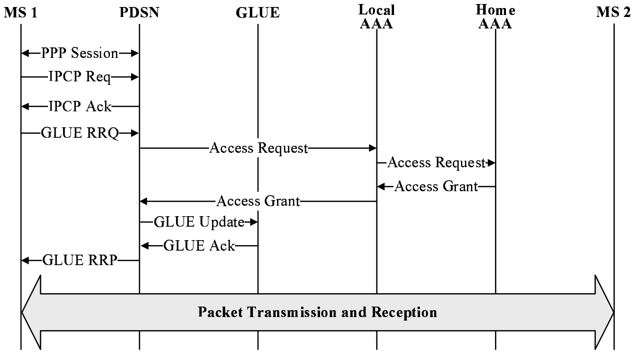

Figure 3: Registration

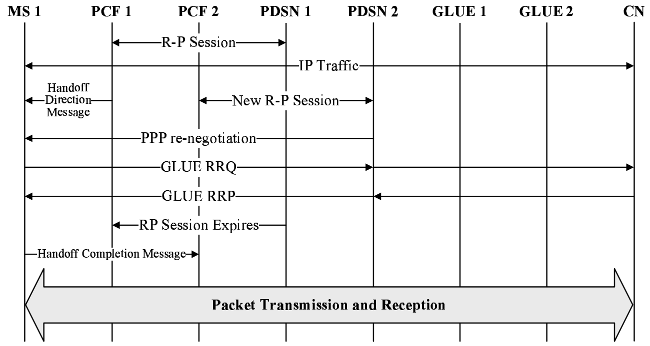

Figure 4: Inter-domain Handoff

IP address is regarded as a LCoA and it is the point of attachment in a subnet. Similarly, when a mobile performs global registration, it is assigned an IP address of an AR as a GCoA and it is the point of attachment in a domain.

When a mobile, Mobile Station (MS) 1, moves from one domain to another, global registration occurs. MS 1 sends an IPCP request message to a Packet Data Serving Node (PDSN) in its cellular domain and MS 1 is assigned dynamically with a new IP address. After receiving an IPCP ack from the PDSN, MS 1 sends a GLUE Registration Request (RRQ) message to the PDSN. The PDSN sends an access request message to the Local Authentication, Authorization, and Accounting (AAA). After the PDSN is granted access, the PDSN sends a GLUE update message to the GLUE system. The GLUE system picks an access router for the mobile and the GLUE system updates its database with the new IP address as a LCoA and the IP address of an AR as a GCoA. After the PDSN receives an ack for a GLUE update, the PDSN sends a GLUE Registration Reply (RRP) message to MS 1. Similarly, when a mobile moves from one subnet to another, local registration is performed. The mobile updates its new IP address but it does not have to change its GCoA.

5.3.2 Handoff

We illustrate inter-domain handoff in Figure 4. MS 1 registers its current IP address to GLUE 1 via PDSN 1. When MS 1 moves from domain 1 to domain 2, MS 1 receives a handoff direction message from PCF 1. MS 1 sends an IPCP request message to PDSN 2 and MS 1 is assigned with a new IP address. MS 1 registers the new IP address to GLUE 2 and GLUE 2 picks an AR for MS 1 and updates the database with the new IP address for a LCoA and the IP address of an AR for a GCoA. MS 1 deregisters the old mapping from GLUE 1. If the old mappings are not explicitly deregistered by mobiles, the GLUE system periodically checks mapping information and causes to expire old mappings by time stamp. MS 1 finishes the handoff by sending a handoff completion message to PCF 2.

In intra-domain handoff, when a mobile moves from one subnet to another,

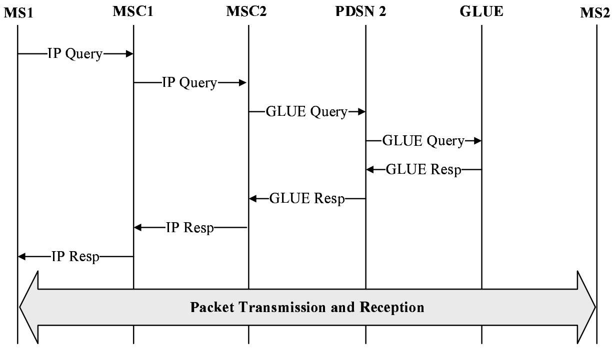

Figure 5: Data Communication

the mobile sends an IPCP request message to the PDSN. After being assigned with a new IP address, the mobile registers its new IP address to its GLUE system. After registering in a new subnet, the mobile deregisters its old mapping in the old subnet.

5.3.3 Signaling

In ABC^2, data communication is started in the Internet after mobiles are located by signaling in cellular networks. Before a mobile starts to communicate with its counterpart, the mobile is required to find its counterpart. In Figure 5, we explain how the mobile searches its counterpart. MS 1 starts to communicate with MS 2. MS 1 sends an IP query message to MSC 1 with MS 2's telephone number. MSC 1 searches its subscribers' database, an HLR and if MS 2 is not found in the HLR of MSC 1, MSC 1 forwards an IP query message to MSC 2. MSC 2 forwards an IP query message to PDSN 2. PDSN 2 sends a GLUE query message to GLUE 2. GLUE 2 searches its mapping database and replies to PDSN 2 with the IP address of MS 2 in a GLUE response message. PDSN 2 sends an IP response message to MSC 2 and MSC 2 forwards the IP response message to MSC 1. MSC 1 replies the IP response message to MS 1.

If MS 2 is in domain 1, MSC 1 forwards the IP query message to PDSN 1. PDSN 1 sends a GLUE query message to GLUE 1. GLUE 1 looks up its mapping table and replies to PDSN 1 with the IP address of MS 2 in a GLUE response message. PDSN 1 sends an IP response message to MSC 1 and MSC 1 forwards the IP response message to MS 1.

5.4 Scenarios

In Figure 6, we illustrate various scenarios using ABC^2. In Figure 6-(1), a mobile registers the IP address of its WLAN interface to the GLUE system located in the current serving cellular network via a cellular network interface. Figure 6-(2) shows that a mobile queries the IP address of a correspondent with the telephone number to start communication. Figure 6-(3) shows that a mobile

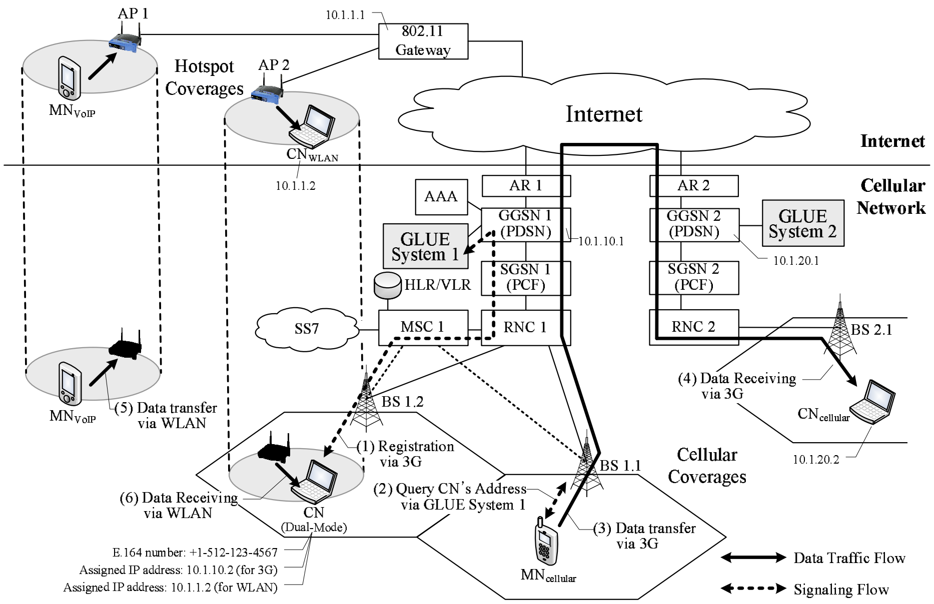

Figure 6: ABC^2 scenarios in interworking 3G and WLAN

sends packets to a correspondent. Figure 6-(4) shows that a correspondent receives packets from a mobile. In Figure 6-(5), a mobile starts to send VoIP traffic to a correspondent. In Figure 6-(6), a correspondent receives data or VoIP traffic from a mobile via its WLAN interface.

5.4.1 Mobiles to Mobiles

In Figure 6, the scenario of the communication between mobiles and mobiles is illustrated. Mobile 1 queries the IP address of mobile 2 with mobile 2's telephone number. The query message is sent to MSC 1 in its area and MSC 1 forwards the signaling message to MSC 2 in mobile 2's area. MSC 2 forwards the signaling message to GLUE system 2 and GLUE system 2 searches its local database and sends back the result to mobile 1. Mobile 1 starts to communicate with mobile 2 with the IP address of mobile 2. If mobile 2 in domain 2 moves to another subnet in domain 2, intra-domain handoff is performed. Mobile 2 is assigned a new IP address for a LCoA but it does not change its GCoA. After mobile 2 registers the new IP address of a new subnet, data packets are gracefully forwarded to mobile 2 without being disrupted since the data packets are forwarded via the AR. If mobile 2 in domain 2 moves to domain 3, inter-domain handoff is executed. Mobile 2 is assigned a new IP address for a LCoA and an IP address of an AR for a GCoA and registers the addresses to GLUE system 3. When mobile 2 deregisters the old mapping in GLUE system 2, GLUE system 2 notifies the movement of mobile 2 to mobile 1. Mobile 1 starts to communicate with mobile 2 with the new IP address of mobile 2. The AR in domain 2 buffers in-flight messages to mobile 2 in domain 2 and forwards the messages to mobile 2 in domain 3 when GLUE system 2 notifies the movement of mobile 2 to the AR.

5.4.2 Mobiles to Correspondents

In this scenario, the correspondents can be any fixed nodes in the Internet or any nodes without an interface of cellular networks. When a mobile communicates with a correspondent in the Internet, the mobile can communicate with the correspondent by the IP address of the correspondent. Thus the communication from mobiles to correspondents is not much different from the communication between two nodes in the Internet. However, the mobile change its IP address dynamically when it moves from one subnet to another. Thus, the connection can be disrupted by the change of IP addresses. If the correspondent uses the IPinIP Encapsulator, this problem can be resolved. Applications in the correspondent use the internal IP addresses and those internal IP addresses are fixed but the public IP address of the mobile is dynamically changed. Whenever the change of IP address is notified to the correspondent, the IPinIP Encapsulator of the correspondent encapsulates the packets with the new IP address of the mobile.

5.4.3 Correspondents to Mobiles

In order to locate a mobile, a correspondent needs to contact a GLUE system in its proximate area. The correspondent sends an IP Query message to the GLUE system with the telephone number of the mobile. The GLUE system searches its database and if the telephone number of the mobile is found in the database, the GLUE system will reply to the correspondent with the IP address of the mobile. If the telephone number is not found in the database of the GLUE system, the GLUE system forwards the IP query message to cellular networks via its PDSN. The PDSN forwards the IP query message to the MSC in its area and the MSC forwads the IP query message to the MSC in the mobile's area. The MSC forwards the IP query message to the GLUE system, which is associated with the MSC and the GLUE system looks up its database and sends back the IP address of the mobile to the correspondent. After the correspondent receives an IP response message from the GLUE system, the correspondent starts to communicate with the mobile with the IP address of the mobile. When a mobile moves from one subnet to another in one domain, intra-domain handoff is executed. Since correspondents sends messages through a GCoA, the IP address of an AR, messages are forwarded to the new IP address of the mobile without being disrupted. When a mobile moves from one domain to another, inter-domain handoff is performed. The mobile is assigned a new IP address for a LCoA and an IP address of an AR for a GCoA and registers the addresses to a new GLUE system. When a mobile deregisters the old mapping in the old GLUE system, the correspondent is notified of the new IP address of the mobile and the AR is requested to forward the in-flight messages to the new AR.

6 Analysis

We analyze ABC^2 regarding location update traffic, handoff latency, and signaling delay with other MIP variants. Our analysis is based on the methodology in [18, 50] and we use the same symbols for our analysis.

Symbols for traffic analysis are explained as follows.

- N : the number of subnets
- M : the number of mobility agents
- P : the number of mobiles
- R : the number of subnets handled by a mobility agent
- $\frac{N}{R} \approx M$: the number of mobility agents are approximately the same as the number of subnets divided by the number of subnets handled by a mobility agent
- L : the level of hierarchies in HMIP

Symbols for delay analysis are explained as follows.

- $\triangle_1$: time required for a registration message from a mobility agent to reach a home agent (∼200 ms)
- $\triangle_2$: time required for a registration message from a mobile to reach a mobility agent in a foreign network (∼10 ms)
- $\triangle_3$: time required for communication from a correspondence node to a home agent
- $\triangle_4$: typical cellular network signaling delay (∼90 ms) [58]

Table 3 shows that ABC^2 has the least location update traffic in micro, macro, and global location update. Since most micro mobility protocols assume MIP for global mobility, we assume MIP for global location update in Cellular IP, HAWAII, TIMIP, HMIP, and TeleMIP. Since ABC^2 uses cellular networks for location management, it maintains the consistent location update traffic in all kinds of mobility.

Table 4 shows that ABC^2 has the least handoff latency in micro, macro, and global mobility. In MIP variants, mobiles complete global handoff by registering their CoAs to their home agents, but ABC^2 does not differentiate home agents and foreign agents such that the handoff latency of ABC^2 is consistent for all kinds of mobility. Precisely, it is bounded by the handoff delay in cellular networks, which is better than that in the Internet.

Table 3: Comparisons of location updates

	Micro	Macro	Global
MIP	$P \times N$	$P \times N$	$P \times N$
Cellular IP (CIP)	P	P	$P \times N$
HAWAII	P	P	$P \times N$
TIMIP	P	P	$P \times N$
HMIP	P	$P \times \frac{N}{R} \times L$	$P \times N$
TeleMIP	P	$P \times \frac{N}{R}$	$P \times N$
ABC^2	P	P	P

Table 4 shows that ABC^2 not only has the least signaling delay but is also robust to the distance between correspondent nodes and home agents. Noticeably, $\triangle_3$ exists in MIP variants while it does not exist in ABC^2. $\triangle_3$ is variable and increases significantly if a mobile moves away from its home agent. While home agents must be involved to intercept a message from a correspondent node in MIP variants, ABC^2 does not require home agents such that it guarantees the average initiation delay regardless of the location of mobiles.

Table 4: Comparisons of handoff latency and signaling delay

	Handoff Latency		Signaling Delay
	Micro/Macro	Global	
MIP	$\triangle_1 + \triangle_2$	$2(\triangle_1 + \triangle_2)$	$\triangle_1 + \triangle_2 + \triangle_3$
CIP	$\triangle_2$	$\triangle_1 + \triangle_2$	$\triangle_1 + \triangle_2 + \triangle_3$
HAWAII	$2\triangle_2$	$\triangle_1 + 2\triangle_2$	$\triangle_1 + 2\triangle_2 + \triangle_3$
TIMIP	$2\triangle_2$	$\triangle_1 + 2\triangle_2$	$\triangle_1 + 2\triangle_2 + \triangle_3$
HMIP	$4\triangle_2$	$\triangle_1 + 4\triangle_2$	$\triangle_1 + 4\triangle_2 + \triangle_3$
TeleMIP	$\triangle_2$	$\triangle_1 + \triangle_2$	$\triangle_1 + \triangle_2 + \triangle_3$
ABC^2	$\triangle_2$	$\triangle_2$	$\triangle_2 + \triangle_4$

Based on our analysis, we show graphs in Figure 7 and Figure 8. With a slight increase of the number of mobiles in Figure 7, location update traffic in MIP and HMIP is significant while that in ABC^2 is not. Figure 8 shows that ABC^2 performs better than MIP variants in terms of handoff latency and signaling delay.

7 Conclusion and Discussion

In this paper, we have rigorously rethought the existing mobility solutions and have intentionally designed our approach without using MIP. We have proposed a practical and evolvable approach for mobility support in the interworking architecture between cellular networks and WLAN. Compared to most mobility protocols based on Mobile IP, our approach does not resolve the cur-

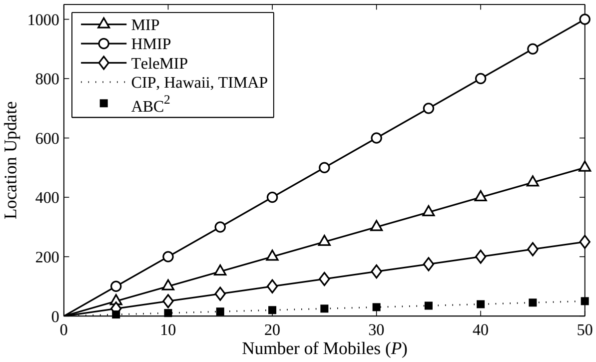

Figure 7: Comparison of location update traffic for macro mobility when R=2, N=10, and L=4

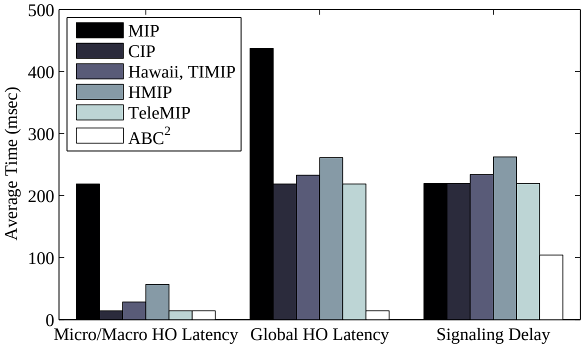

Figure 8: Comparison of handoff latency and signaling delay

rent location by home agents as in MIP such that our analysis shows that ABC^2 has the least location update traffic, handoff delay, and signaling delay.

In our approach, we assume that the Internet is operating on top of cellular networks. Since cellular networks are widely deployed in the world, we can reuse the current existing infrastructures. Thus, our approach does not require an enormous investment for operation.

Our approach is modular, flexible, and evolvable. With our approach, cellular networks and WLAN networks are modularly combined. Our approach is flexible since it is applicable to any cellular network. Our approach is evolvable since it is partially and independently deployable by service providers.

The future networks envisage mobile users experiencing the unbounded mobility with multimedia data. Our approach provides both with easy deployment and low costs and thus will benefit both service providers and subscribers.

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