Ubiquitous Communications for Wireless Personal Area Networks in a Heterogeneous Environment

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Abstract

The widespread use of wireless technologies has led to a tremendous development in wireless communication systems. Currently, an individual mobile user may carry multiple personal devices with multiple wireless interfaces, which can interconnect with each other to form a Wireless Personal Area Network (WPAN) which moves with this user. These devices exist in a heterogeneous environment which is composed of various wireless networks with differing coverage and access technologies and also the topology, device conditions and wireless connections in the WPAN may be dynamically changing. Such individual mobile users require ubiquitous communications anytime, anywhere, with any device and wish content to be efficiently and continuously transferred across the various wireless networks both outside and inside WPANs, wherever they move.

This thesis presents research carried out into how to implement ubiquitous communications for WPANs in such an environment. Two main issues are considered. The first is how to initiate content transfer and keep it continuous, no matter which wireless network is used as a user moves or how the WPAN changes dynamically. The second is how to implement this transfer in the most efficient way: selecting the most suitable transfer mode for a WPAN according to the user's and application's requirements. User-centric (personal-area-centric) and content-centric mechanisms are proposed in this thesis to address these issues. A scheme based on a Personal Distributed Environment (PDE) concept and designed as a logical user-based management entity is presented. This is based on three mechanisms which are proposed to overcome the technical problems in practical scenarios, which cannot be solved by existing approaches.

A novel mechanism is proposed to combine local direct and global mobile communications, in order to implement ubiquitous communications in both infrastructure-less and infrastructure-based networks. This enables an individual user's ubiquitous communications to be initiated in an infrastructure-less network environment and kept continuous when they move across infrastructure-based networks. Its advantages are evaluated by a performance analysis model and compared to existing solutions and verified by experiments. A cooperation and management scheme is also proposed for dynamic changes of multiple mobile routers and flexible switching of personal device roles in a WPAN while keeping ongoing ubiquitous communications continuous. This adopts a novel view of WPANs which solves the addressing problems caused by changes of mobile routers and makes these transparent to personal devices in the WPAN and external content sources. It provides an efficient method for changing the mobile router of a single WPAN or a WPAN merging with another moving network. Its benefits are demonstrated through performance analysis models. Finally, a novel user-centric and content-centric mechanism for decision making, to select the most appropriate mobile router in a dynamically changing WPAN environment is proposed. This selects the most suitable content transfer mode for the WPAN to fulfil an individual user's various requirements. It has different strategies to suit various types of applications. Selection results are demonstrated to verify the proposed mechanism in multiple scenarios of changing user requirements, applications and WPAN conditions.

Declaration of originality

I hereby declare that the research recorded in this thesis and the thesis itself was composed and originated entirely by myself in the Institute for Digital Communications at the School of Engineering at The University of Edinburgh.

Junkang Ma

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Contents

List of figures

List of tables

Acronyms and abbreviations

3GPP	The 3rd Generation Partner Project
ABC	Always Best Connected
ACK	Acknowledgement
AHP	Analytic Hierarchy Process
AP	Access Point
CMR	Current MR
CN	Correspondent Node
CoA	Care-of Address
CoT	CoA Test
CoTI	CoA Test Init
BA (BACK)	Binding Update Acknowledgement
BCE	Binding Cache Entry
BS	Base Station
BU	Binding Update
DAD	Duplicate Address Detection
DHCP	Dynamic Host Configuration Protocol
DID	Domain ID
DME	Device Management Entity
DNS	Domain Name System
GRA	Grey Relation Analysis
HA	Home Agent
HMIP	Hierarchical Mobile IP
HoA	Home Address
HoT	Home Test
HoTI	Home Test Init
IEEE	Institute of Electrical & Electronics Engineers
IETF	Internet Engineering Task Force
IP	Internet Protocol
IPv4	Internet Protocol version 4

IPv6	Internet Protocol version 6
LAN	Local Area Network
LCoA	On-Link Care-of-Address
LFN	Local Fixed Node
MADM	Multiple Attribute Decision Making
MANET	Mobile Ad hoc Networks
MAP	Mobility Anchor Point
MAC	Media Access Control
MH	Mobile Host
MIP	Mobile IP
MIPv4	Mobile IP version 4
MIPv6	Mobile IP version 6
MN	Mobile Node
MNN	Mobile Network Node
MNP	Mobile Network Prefix
MR	Mobile Router
NEMO	Network Mobility
NEMOBS	Network Mobility Basic Support
PAA	Personal Assistant Agent
PAN	Personal Area Network
PDA	Personal Digital Assistant
PDE	Personal Distributed Environment
PCM	Personal Content Management
PMR	Potential MR
QoS	Quality of Service
RA	Router Advertisement
RCoA	Regional Care-of-Address
RO	Routing Optimization
RR	return rentability
SP	System Standby Power
TCP	Transmission Control Protocol
UMNP	Unique Mobile Network Prefix
UMTS	Universal Mobile Telecommunications System

URI	Unique Resource Identifier
VMN	Visiting Mobile Node
VoIP	Voice-over-IP
WiFi	Wireless Fidelity (IEEE 802.11)
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WVN	Wireless Vehicle Network

Chapter 1
Introduction

Wireless technologies continue to develop rapidly and have led to the widespread use of wireless communication systems. These systems are now enabling the delivery of multimedia experiences that provide rich content to individual users. Content is the information required by or related to an individual user. Lots of different types of content are transferred with current wireless technologies, such as peer-to-peer file streaming, audio/video-on-demand or online gaming. Users can employ content for work, enjoy content for entertainment or share content for convenience.

Currently, an individual user is likely to be a mobile user who often possesses multiple wireless personal devices. These users require high-quality ubiquitous communications, giving the ability to move seamlessly within different wireless networks while receiving services (i.e. content) anytime, anywhere and with any terminal device [3]. For example, a user is watching a football match online with a laptop at home connecting to a household network, and then this user may leave home taking a bus and continue watching this match with the laptop connecting to a network provided by this bus or cellular providers.

In the future, such ubiquitous and pervasive services could produce increased revenue for service providers, telecommunication operators and technology manufacturers. The Virtual Centre of Excellence in Mobile & Personal Communications (Mobile VCE) [4], which aims to solve technical problems facing the industry for the future wireless era, has started a project - Ubiquitous Service [4]. This project aims to accelerate commercialisation of ubiquitous services with targeted innovations aimed at removing the barriers to deployment and adoption [4].

Two major challenges for ubiquitous communications of individual users exist. Currently, various wireless technologies have been deployed or are under development for personal communications, such as Bluetooth [5] for short-range and personal area communications, WiFi [6] for local areas and Universal Mobile Telecommunications System (UMTS) [7] for cellular networks. The coexistence of these wireless networks implies a heterogeneous environment with differing network coverage and access technologies. Ubiquitous communications in such a heterogeneous environment require that mobile users can adopt any available network to start content transfer and keep an ongoing transfer continuous when they change to use another network. Also, individual users increasingly own several personal devices, such as mobile phones, laptops and personal digital assistants (PDAs), each of which may have multiple wireless interfaces and different capacities. A number of such devices owned by a user can interconnect with each other to form a wireless personal area network (WPAN). Ubiquitous communications for a user's WPAN require efficient transfer of content from providers outside the WPAN to a suitable personal device inside the WPAN and free exchange of content among personal devices inside the WPAN. Therefore, an individual mobile user's environment is a heterogenous environment composed not only of multiple wireless networks but also a mix of wireless personal devices, which will lead to a considerable level of complexity.

1.1 Heterogeneous Environment: Multiple Wireless Networks

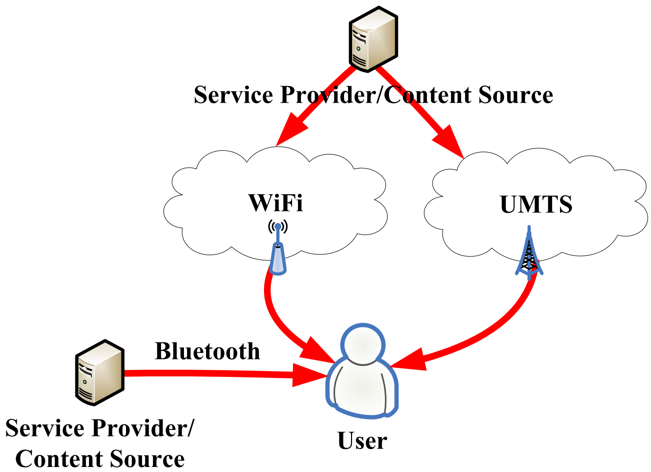


Figure 1.1: *Heterogeneous Environment: Multiple Wireless Networks*

A heterogeneous environment formed by the coexistence of multiple wireless networks is shown in Fig. 1.1. Two cases exist in this environment. Firstly, different wireless networks exist at the same time but not at the same place or at the same place but not at the same time, and thus their coverage may not overlap. An individual user accesses different network coverage when his/her physical location changes or when one wireless network disappears and then another becomes available. For example, a user can connect to UMTS on streets, and after this user moves to tube, UMTS becomes un-available but WiFi may be provided by tube. Another case is that different wireless networks exist not only at the same time but also at the same place, and thus their coverage may overlap. An individual user can select or change to use any available wireless network when this user is in the coverage of multiple networks. For example, when a user is in an office, WiFi provided by this office and UMTS from cellular providers are both available for this user to connect.

In order to implement ubiquitous communications in such an environment, a basic solution is interworking of multiple wireless networks that can provide a universal access (physical or virtual) to individual users (to be further discussed in Chapter 2), by which the users can simultaneously use these wireless networks. Two issues need to be researched: how to initiate and establish content transfer and how to keep this transfer continuous no matter which case discussed above an individual user will be in. The first issue is basically solved by the universal access, and the second issue is related to vertical handoff management of mobility support discussed in Section 1.3.

1.2 Heterogeneous Environment: WPAN

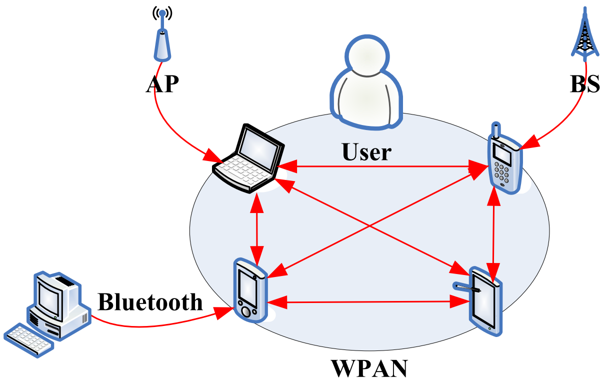


Figure 1.2: *Heterogeneous Environment: WPAN*

The original concept of a personal area network (PAN) considered fixed devices connected by wire, e.g. desktop computers connected via a local area network (LAN) at a user's home. The tremendous development in wireless communications has extended it to the WPAN that results in a heterogeneous environment, as shown in Fig. 1.2. An individual user should not be represented by a single mobile terminal, but by a WPAN owned by this user and moving like a bubble around the user, i.e. a moving sub-network. Content may be transferred to the user's WPAN via different interfaces and personal devices, not just directly to the end device. Therefore, ubiquitous communications with WPANs have two major characteristics - multiple wireless interfaces and communication modes.

A WPAN may have multiple wireless interfaces because it is composed of multiple personal devices with differing capabilities. For example, it can use a laptop's WiFi interface to connect to access points (AP), or use a mobile phone's UMTS interface to connect to base stations (BS), or connect to other devices outside but physically close to this WPAN with Bluetooth. On the other hand, inside a WPAN, all personal devices can interconnect with each other in LAN mode or ad hoc network mode using short-range wireless interfaces.

Given these interfaces, three kinds of communication modes exist for a WPAN. The first one is intra-WPAN communications among personal devices inside this WPAN. In the second mode, a personal device can directly receive content with its own wireless interface from sources outside the WPAN. The third one is multi-hop communications: content is transferred from sources outside this WPAN to a personal device that then acts as a router or gateway to relay this content to another personal device by intra-WPAN communication.

Currently, no existing wireless technology can simultaneously satisfy all the requirements of individual users. For example, Bluetooth consumes very little power but has a very short signal range; WiFi provides high bandwidth but only in a local area; UMTS supports mobility in wide geographic areas but can not provide very high bandwidth. Users may have to change to use different wireless networks when their requirements change. Therefore, network selection should be considered to adopt the most suitable ubiquitous communication mode for users.

1.3 Mobility Support

Mobility support is a major requirement for ubiquitous communications, which aims to keep a mobile terminal's connection active when it moves from one access point to another [8]. It is provided by handoff management. The handoff process can be intra-system (horizontal) or inter-system (vertical) [8].

Horizontal handoff means that every AP/BS belongs to the same administration domain, and handoff normally arises when the signal strength of the serving AP/BS deteriorates. Therefore, horizontal handoff is mainly used in a single wireless network. For example, in current cellular network, the change of BS for a mobile phone is horizontal handoff.

However, in a heterogeneous environment, an individual user may move across different types of wireless networks, and thus vertical handoff management should be focused on. Vertical handoff mainly arises when this user changes connections from one type of network to another type (shown in Fig. 1.3), which may be caused by accessing different coverage when the user's physical location changes or selecting to use another network if the user is in the coverage of multiple networks. Vertical handoff management can keep ongoing content transfer continuous in such a heterogeneous environment.

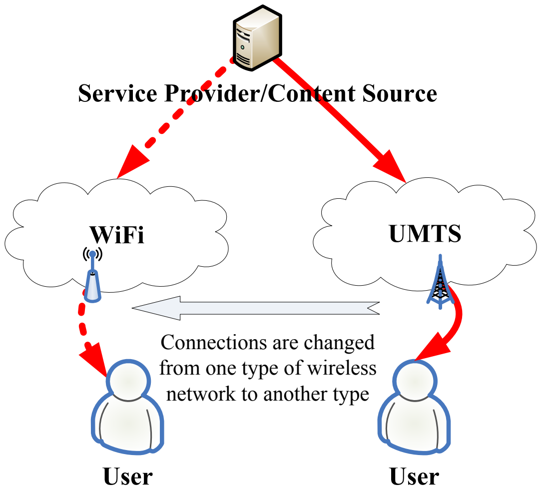


Figure 1.3: *Mobility: Vertical Handoff*

Mobility support can be implemented in different network layers, which will be further discussed in Chapter 2.

1.4 Motivations and Contributions of the Work

The motivation of the work presented in this thesis is to allow individual users to efficiently obtain required content anytime and anywhere, i.e. ubiquitous communications, using their WPAN in a heterogeneous environment. Technical barriers to achieving this are seldom considered in current research. The contributions of this thesis can be summarized as follows:

- A dynamic framework for a ubiquitous communication system for individual users is proposed. This framework extends the traditional view of a mobile user from a single terminal to a dynamically changing WPAN composed of multiple personal devices, always changing topology and with different capabilities and wireless interfaces. A new heterogeneous environment formed by various wireless access networks and dynamically changing WPANs, is included in this framework.

- A novel personal management system is designed to control the above framework. This management system's extended architecture is proposed to implement ubiquitous communications in such a heterogeneous environment.

- In order to implement ubiquitous communications in both infrastructure-less and infrastructure-based networks, a novel mechanism based on the proposed personal management system is designed. This mechanism can combine local direct and global mobile communications, so that communications can be initiated in infrastructure-less networks and kept continuous when users move between infrastructure-based networks.

- A novel cooperation and management scheme is proposed for dynamic changes of multiple mobile routers and flexible switching of personal devices' roles in a WPAN while keeping ongoing communications continuous. It solves addressing problems caused by changes of mobile routers which therefore can be made transparent to personal devices in the WPAN and the content sources. It provides an efficient method to change the mobile router of a single WPAN or a WPAN merged into another moving network. It implements a dynamic change in states for personal devices.

- A novel user-centric and content-centric mechanism for decision making is proposed to select the most appropriate mobile router in a dynamically changing WPAN. It can select the most suitable content transfer mode for the WPAN to fulfil an individual user's requirements from the aspects of financial cost, network speed and power consumption. It has different strategies to suit various types of applications such as real-time and non-real-time.

1.5 Organization of this Thesis

The remainder of this thesis consists of the following chapters:

Chapter 2 summarises the background to research in this thesis. These include relevant protocols in the network layer, the design of related mobile communication systems based on WPANs and Wireless Vehicle Networks (WVNs) and related research on network selection.

Chapter 3 proposes a framework for a ubiquitous communication system in the heterogeneous environment introduced in Chapter 1. A WPAN management system, the Personal Distributed

Environment (PDE) is described.

Chapter 4 first analyzes two scenarios for local direct communications and their existing solutions. A PDE-based scheme is then proposed to combine local direct (infrastructure-less) and global mobile (infrastructure-based) communications. Its advantages are evaluated by a performance analysis model and compared to existing solutions and verified by experiments.

Chapter 5 proposes another PDE-based scheme to solve problems of how to keep ubiquitous communications continuous in a WPAN with multiple dynamically changing mobile routers. It includes two mechanisms - an addressing mechanism and mobile router role management. Two scenarios are implemented using this scheme. The benefits of the proposed scheme in these scenarios are demonstrated through performance analysis models.

Chapter 6 presents a decision making mechanism for dynamically changing mobile router selection in a WPAN. It uses weighted cost functions to represent the different requirements of users and applications. Selection results are demonstrated to verify the proposed mechanism in scenarios with changing user and application requirements, and WPAN conditions (especially the available power of personal devices).

Chapter 7 contains the conclusions of this thesis and discusses its limitations as well as presenting proposed future work.

Chapter 2
Background

In this chapter, the background to research in this thesis is summarized and discussed. Relevant protocols in the network layer, the design of related mobile communication systems based on Wireless Personal Area Networks (WPANs) and Wireless Vehicle Networks (WVNs) and related research on network selection are considered.

2.1 Interworking of Networks

Interworking of networks is the basic solution for multiple wireless networks as discussed in Chapter 1. Two main methods for interworking of networks are used by current research, analyzed as follows.

The first one is tight integration that aims to integrate multiple access networks as a core radio access network [9], which is an access-network-based method. Using this method, the 3rd Generation Partner Project (3GPP) proposes an interworking system for 3G cellular systems and WLANs, in order to provide a fixed infrastructure connecting these two networks for the subscribers (i.e. users) of 3G operators [10, 11]. In this infrastructure, an individual user has an unchanged address and account obtained from a 3G operator no matter whether 3G or WLAN is used. Such a method needs lots of modifications to access networks, especially in the data-link layer, and deployment of a new infrastructure. Thus, most research adopts another method - loose integration which is user-based and needs no modifications to access networks. Currently, almost all wireless networks, each of which can be viewed as a sub-network with the same architecture in the network layer, support the Internet Protocol (IP). All these sub-networks form a uniform all-IP network [12] and differentiate from each other only by different IP addresses. Content can be transferred to an individual user with an IP address regardless of which wireless network the user is connected to. Therefore, IP is used as a "glue" to integrate multiple wireless networks. When a user changes a connection from one wireless network to another, the user only needs to change the IP address, and from the point of view of the network layer, the user moves across different sub-networks of this all-IP network (i.e. mobility in the network layer). How to keep communications continuous during such mobility is related to mobility support in the network layer discussed in Section 2.4. With the loose integration method, a new wireless network, supporting IP, can be easily integrated into users' heterogeneous environment and used for ubiquitous communications. However, it is hard to use this approach if the tight integration method is adopted because a new infrastructure needs to be designed to integrate it.

This thesis therefore adopts the loose integration method and assumes that all communications are IP-based. IP is the most well-known protocol in the network layer, and some of its issues related to this thesis are summarized in the following section.

2.2 IP

Internet Protocol version 4 (IPv4) [13] is the first widely-used fundamental protocol in the network layer, which has been used for about thirty years. Internet Protocol version 6 (IPv6) [14] is the next-generation Internet Protocol version designated as the successor to IPv4. A major drawback of IPv4 is address exhaustion due to its 32-bit address (e.g. 200.1.2.3 is an IPv4 address), which can only provide a 2^{32} address space. To overcome this problem which is becoming more urgent in current fast-developmenting networks, IPv6 uses a 128-bit address, which can support a 2^{128} address space that is much larger than IPv4. IPv6 introduces a new concept in address notation - prefix. IPv6 addresses are typically composed of two logical parts: a 64-bit network prefix and a 64-bit host part, e.g. a:b:c:0:0:1:2:3 (simplified as a:b:c::1:2:3) is an IPv6 address with a prefix "a:b:c:0" (separately denoted as a:b:c::/64 where "64" represents the bits of this prefix).

Besides the larger address space, the main difference between IPv6 and IPv4 is address autoconfiguration. IPv4 mainly uses a stateful method - Dynamic Host Configuration Protocol (DHCP) [15], which adopts a client/server model. With signalling messages defined by DHCP, a client node can discover and select a DHCP server that can reply and allocate an address to this client node. However, IPv6 improves address autoconfiguration - it uses IPv6 Stateless Address Autoconfiguration [16], with which nodes can automatically configure their IP addresses and other parameters without the need for a server.

When a node joins in an IPv6 network, it generates a link-local address that is only for local communication on a particular physical network segment (i.e. local link), especially for address resolution and neighbour discovery, and can not be used by routers to forward datagrams. A link-local address combines a prefix FE80::/10 (it presents that this prefix has 10 bits), which is specifically defined as the link-local address prefix by IPv6, and this node's interface identifier that is derived from its Media Access Control (MAC) address. This node then verifies the uniqueness of this link-local address in a given link by using a Duplicate Address Detection (DAD) procedure. DAD uses signalling messages defined by Neighbor Discovery Protocol (NDP) [17] to enquire and listen to other nodes that also have IPv6 addresses and connect to the same link as this node. After DAD is successful, this node listens for Router Advertisement (RA) messages sent periodically by routers, which is also defined by NDP. A global network prefix is included in a RA message, by which this node generates a globally-unique Internet address combined with the node's interface identifier. IPv6 Stateless Autoconfiguration is particularly suitable for nodes' mobility because they can obtain a valid global address without any knowledge of local servers or network prefixes when joining in a new network. Therefore, IPv6 is mainly considered in this thesis.

2.3 Mobility Support

Mobility support has been introduced in Chapter 1, which requires handoff management to keep a mobile terminal's connection active when it moves. Current research implements handoff in different layers, analyzed as follows.

Mobility support in the physical and data-link layers is suitable for horizontal handoff but not feasible for larger movement across domains [8] because different domains are likely to have completely different physical and data-link layers. Therefore, vertical handoff management is designed mainly in the network, transport and application layers. Mobile IP [1, 18] is used in the network layer to provide transparent mobility support to applications by tunnelling traffic. It can keep IP communications to a mobile node continuous when this node's IP address changes due to mobility. As for transport layer solutions, TCP-Migrate [19] is proposed to keep opened sockets unchanged when TCP sessions break as a result of users moving. In the application layer, the Session Initiation Protocol (SIP) [20] is proposed to allocate users uniform identifiers used by applications regardless of which network is used.

In this thesis, vertical handoff and mobility support in the network layer are mainly considered, which are analyzed in the following section.

2.4 Mobility Support in the Network Layer

An IP address does not only denote a node's location in the network layer but also is used by upper layers. Popular transport protocols such as Transmission Control Protocol (TCP) [21] keep track of their internal session state between the communicating endpoints by using the IP addresses of these two endpoints, stored along with a demultiplexing selectors for each session, i.e. the port number. [22] If a node moves in the network layer and connects to a different sub-network so as to obtain a new IP address, its existing TCP sessions will collapse because these sessions are maintained with this node's previous address that has become unavailable. Therefore, the major problem for mobility support in the network layer is how to keep a node's IP address used by upper layers unchanged but at the same time change its IP address in the network layer due to mobility, which results in a contradiction. Current research has proposed some approaches to solve this contradiction, analyzed in the following sections.

2.4.1 MIP

In order to provide continuous communication to a single mobile node during its moves across different subnetworks of the Internet (i.e. the network layer), Mobile IP (MIP) was designed based on IP. The Internet Engineering Task Force (IETF) has proposed two basic implementation protocols - Mobile IP version 4 (MIPv4) [18] and version 6 (MIPv6) [1] respectively for IPv4 and IPv6, and an extension of MIPv6 - Hierarchical Mobile IP version 6 (HMIPv6) [23].

2.4.1.1 MIPv4 and MIPv6

Every mobile node (MN) that supports MIP has two global-routable addresses. One is the Home Address (HoA), which is permanently allocated to the MN and kept unchanged regardless of where it moves. The HoA is provided to upper layers, like TCP sessions, so that all sessions to the MN can be maintained with this unchanged IP address. A HoA is initially assigned when the MN is in its home network (the MN's home link, maintaining its home subnet prefix) and thus the HoA has the same prefix as the home network. Another one is the Care-of Address (CoA), which is assigned to a MN when it moves into a foreign network that is a subnetwork of the Internet away from the home network. A CoA is generated according to the prefix of this foreign network, and thus packets addressed to this CoA are routed to the MN's current location in this foreign network. The MN obtains a new CoA when it changes its point of attachment to the Internet. Therefore, the CoA is used to represent the actual location of the MN in the network layer, the change of which represents the MN's mobility in the network layer. With the HoA and CoA, the contradiction of mobility support discussed above can be solved. How MIP works is summarized as follows.

MIP uses a special router called the home agent (HA) located in the home network. A MN registers its current CoA to the HA after it moves away from the home network. The HA maintains a "Binding Cache" storing an association between this MN's HoA and CoA. When the MN changes its CoA, it performs a procedure of binding update (BU) to inform the HA of its new CoA.

When a sender node, named as the correspondent node (CN) by MIP, sends data packets to a MN, it obtains this MN's HoA from the Domain Name System (DNS) and uses it as the packets' destination address. These packets are routed to this MN's home network, where the HA intercepts them and then tunnels them to the MN's CoA according to the binding cache. Tunneling is a method of encapsulating original packets with MIP headers in an IP-within-IP format where the CoA is used as the destination address. After receiving these tunneled packets, the MN de-capsulates them to obtain the original packets. Therefore, wherever the MN moves, packets from a CN can be routed to this MN via the HA, which is called triangle routing shown in Fig. 2.1. This kind of triangle routing is a basic operation mode of MIPv4 [18] and MIPv6 [1], but it is inefficient due to the high overhead cost and delay produced by relaying and tunneling of the HA.

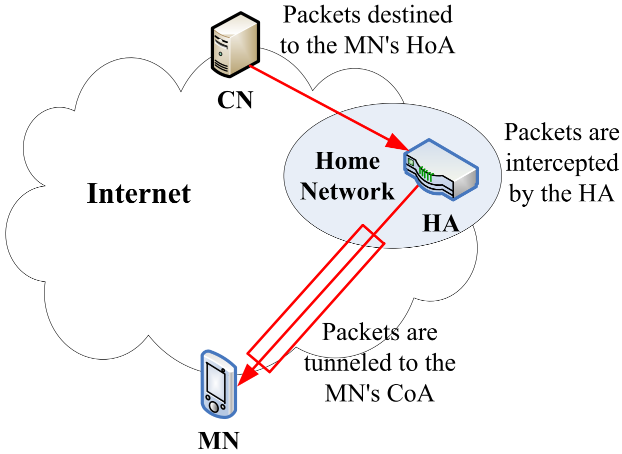


Figure 2.1: *Triangle routing of MIP*

MIPv6 [1] improves MIPv4 with an extended operation mode - routing optimization (RO) to avoid triangle routing. After receiving packets tunneled from the HA, the MN performs procedures of return routability (RR) and BU to initiate RO. RR aims to verify that a MN's HoA and CoA are addressable. Two kinds of signalling messages are used: Home Test Init (HoTI)/Home Test (HoT) are transferred between a MN and its CN routed via and tunneled by its HA; Care-of Test Init (CoTI)/Care-of Test (CoT) are directly transferred between a MN and its CN. After RR, The MN sends a BU message including its current CoA to the CN that replies with a Binding Acknowledgement (BA) message. In this way, a binding cache is established in the CN, which stores the binding of the MN's HoA and CoA. Therefore, with MIPv6, when the MN changes its CoA, it performs BU procedures with both the HA and the CN. After this binding is setup in the CN, which means that RO is established successfully, the CN sends packets directly to the MN not via the HA. This is implemented by adding an IPv6 routing header in a packet, which uses the MN's CoA as the destination address, not by encapsulating IP-within-IP packets. The operation procedures of MIPv6 are shown in Fig. 2.2.

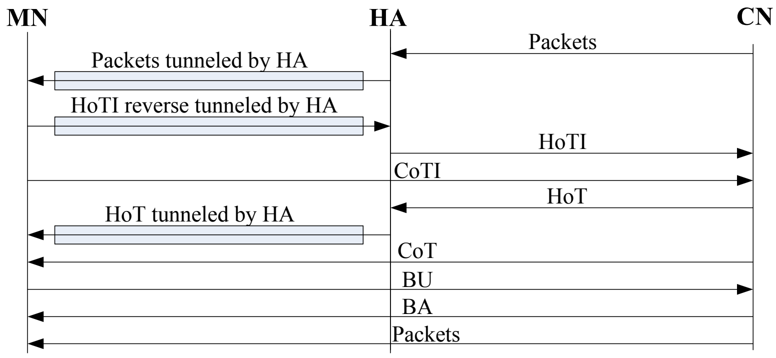


Figure 2.2: *Operation procedures of MIPv6*

2.4.1.2 HMIPv6

MIPv4 and MIPv6 are called macro-mobility protocols, which means that a MN may move across the whole Internet. However, there is often a situation where a MN may move frequently among subnets of a domain, which is called micro-mobility. Some micro-mobility protocols are extensions of MIPv6 which are designed to reduce signalling load and delay in this situation, among which HMIPv6 [23] is the most widely used one.

A new entity, a Mobility Anchor Point (MAP) [23] is introduced in HMIPv6. A MAP is located in a domain of the access network and handles mobility of MNs that move only inside this domain and functions like a HA. A MAP intercepts packets sent from the CN outwith a domain to a MN inside this domain, and then tunnels them to this MN. A MN has two CoAs: An On-Link Care-of-Address (LCoA) [23] and a Regional Care-of-Address (RCoA) [23]. A MN's RCoA is obtained on behalf of this MAP's domain and sent to the CN as this MN's binding. The RCoA is kept unchanged unless the MN moves to a new MAP's domain. When the MN moves across subnets within this domain, it only sends its new CoA obtained in a subnet, i.e. LCoA, to the MAP to update its local binding that is maintained and used inside this domain by the MAP. With HMIPv6, signalling messages are only exchanged inside a domain between MNs and a MAP, and none is sent to CNs. Therefore, a MN's micro-mobility is transparent to its CN, and, in this way, signalling cost and delay are reduced.

This thesis only considers MIPv6, so the term "MIP" used in the rest of the thesis refers to MIPv6. More of the operation of these technologies and further work on MIPv6 and its extensions, such as HMIPv6, will be discussed further in Chapter 4 and 5.

2.4.2 Network Mobility

MIP can support a single node's mobility, but it does not consider a moving network's mobility. A moving network, also called a mobile network, is an IP subnetwork formed by nodes moving together and changing the point of attachment to the Internet as a unit. The aim of mobility support for a mobile network is to keep communications destined to nodes inside it continuous as it moves. A working group "Network Mobility (NEMO)" [24] was established by IETF in Oct. 2002 for this research area. The IETF has proposed a Network Mobility Basic Support Protocol (NEMOBS protocol) [2], but lots of technical problems and extensions are still under development, which are analyzed as follows.

2.4.2.1 NEMOBS protocol

The NEMOBS protocol is an extension to MIPv6 and is also backward compatible with MIPv6. A new entity is introduced to NEMO - a Mobile Router (MR). A MR is a router located in a mobile network and capable of changing its point of attachment to the Internet. It acts as a gateway between an entire mobile network and the Internet using two kinds of interfaces - egress and ingress interfaces [2]. The MR uses its egress interface to connect to the Internet, and uses its ingress interface to connect all nodes inside this mobile network, which are called Mobile Network Nodes (MNNs). Therefore, with the MR forwarding packets into or out of this mobile network, MNNs can obtain connectivity to the Internet.

The MR supports MIPv6. Therefore, when a MR moves away from the home network, based on MIPv6, it binds its CoA, which is obtained by the egress interface from a foreign network, with its HoA to its HA, and establishes a bidirectional tunnel with the HA. The NEMOBS protocol, as an extension to MIPv6, proposes a new concept - a Mobile Network Prefix (MNP) [2]. A MNP is an IPv6 prefix delegated to a MR specifically for this MR's mobile network. The MR uses its ingress interface to advertise this MNP inside the mobile network. MNNs can obtain their addresses according to the MNP. Therefore, in NEMO, the MR binds both the CoA and the MNP with its HoA to the HA, which is different from the binding designed by MIPv6, as shown in Fig. 2.3. Generally, a MNP is pre-assigned to a MR by its HA when the mobile network is established in the home network [25], and thus this MNP belongs to and is managed by the HA. Packets destined to addresses that are generated from the MNP (i.e. sent to MNNs) are intercepted by the HA. By checking the binding cache, the HA obtains the CoA of the MR that is using this MNP, and then encapsulates and forwards packets to this MR by the bidirectional tunnel. After receiving these packets, the MR decapsulates and relays them to MNNs. When the mobile network moves across subnetworks of the Internet, the MR changes its point of attachment to the Internet and obtains new CoA. The MR performs a BU procedure to its HA to bind its new CoA as MIPv6 defines, but the MNP is kept unchanged and being advertised inside this mobile network, which allows MNNs' addresses to remain unchanged. Therefore, a mobile network can actually be viewed as a normal IPv6 link so that MNNs inside it are not aware of mobility.

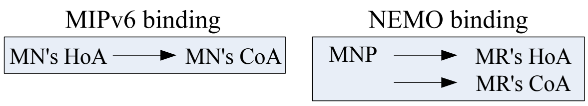


Figure 2.3: *Different binding of MIPv6 and NEMO*

Two kinds of MNNs are mainly used. A Local Fixed Node (LFN) [2] is a node fixed in a mobile network and unable to change its point of attachment while maintaining ongoing communications [26]. Therefore, a LFN is not a MN, and it has only one address generated from the MNP. Another kind is the Visiting Mobile Node (VMN) [2] which does not belong to any mobile network and can change its point of attachment [26]. A VMN is actually a MN supporting MIPv6, and it temporarily attaches to a mobile network and generates a CoA according to the MNP. NEMO operations for LFNs and VMNs are different. The NEMO operation for a LFN is shown in Fig. 2.4. All packets destined to the LFN must go through the bidirectional tunnel between the MR and its HA. The NEMO operation for a VMN is shown in Fig. 2.5. Before the VMN's BU procedure with its CN is finished, all packets destined to this VMN must be tunneled respectively by its HA and the MR's HA, which means that a double-level tunnel is used between the MR and the MR's HA. All Signalling messages between this VMN and its CN, such as BU and BA (signalling of RR procedure is not illustrated in Fig. 2.5), and packets after RO is established also must go through the tunnel between the MR and its HA.

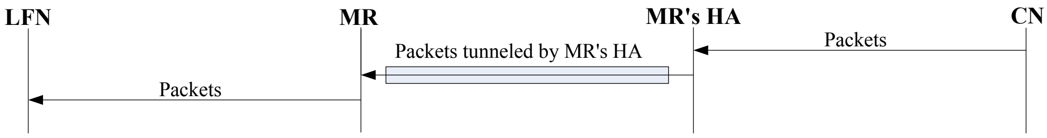


Figure 2.4: *The NEMO operation for a LFN*

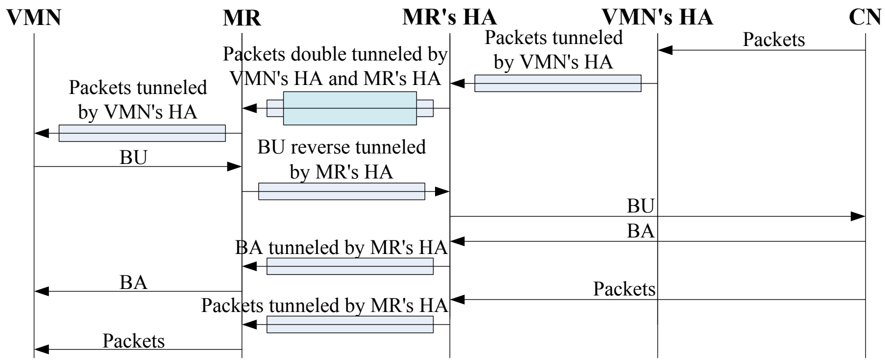


Figure 2.5: *The NEMO operation for a VMN*

The NEMOBS protocol does not provide RO for the MR, and thus all packets sent to a mobile network must be transferred through a tunnel between a MR and its HA, shown in Fig. 2.4 and 2.5. RO for a MR aims to establish a direct path from the CN to the MR, bypassing the MR's HA, similar to MIPv6 RO. This kind of RO is referred to as "Non-Nested NEMO RO" by an IETF document [27], which summaries this problem and proposes requirements for solutions. Different Non-Nested NEMO RO mechanisms are under development, among which Mobile IPv6 Route Optimization for NEMO (MIRON) protocol [28], Global HA to HA protocol and specification [29, 30] and Optimized Route Cache protocol (ORC) [31] are typical solutions. However, these solutions can not fulfill all the requirements of RO, and thus none has support from IETF for standardization. Therefore, no standard for extending the NEMOBS protocol to support RO has been proposed. In this thesis, only the NEMOBS protocol is used, so the term "NEMO protocol" used in the rest of the thesis to refer to the NEMOBS protocol. These protocols and more related work will be discussed further in Chapter 4 and 5.

2.4.2.2 Multihoming and Nested-NEMO

Multihoming of NEMO is different from that of MIP. Multihoming of MIP describes a scenario where a MN may have multiple interfaces, from which it can get multiple CoAs. Multihoming of NEMO has a larger scope: multiple egress interfaces of a MR, or multiple MRs in one mobile network, or multiple HAs for one mobile network can all be defined as multihoming of NEMO. These scenarios were first illustrated in an IETF document [32], and further analyzed in a later IETF document [33] which classifies and proposes research requirements for different configurations. Among these scenarios, "Multiple MRs" have been most widely researched because, in real life, it is very likely that multiple MR devices will be deployed in a mobile network, such as a train. Therefore, solutions to handle multiple MRs need to be designed. An IETF document [34] first summarized a rudimentary problem statement for "Multiple MRs". Technical problems in this area and current research on mechanisms controlling multiple MRs are further analyzed in Chapter 5.

A special configuration of "Multiple MRs" is Nested NEMO which describes a mobile network (sub-NEMO) connecting to a MR of another mobile network (parent-NEMO) to access the Internet [26, 35]. Multiple MRs connecting in this configuration form a multiple-level hierarchy for a nested mobile network. According to the NEMOBS protocol, each sub-MR uses its egress interface to connect to a parent-MR's ingress interface, so as to obtain a CoA generated from the MNP of this parent-MR. Therefore, packets destined to MNNs attaching to the sub-MR must be multi-level tunneled by both HAs of the sub-MR and the parent-MR, as shown in Fig. 2.6.

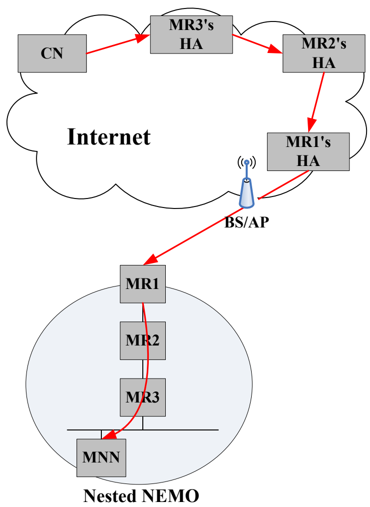


Figure 2.6: *Packet transfer in Nested NEMO*

The advantage of Nested NEMO is that without any extra signalling and controlling protocol, MNPs of MRs can all be kept unchanged and the nested configuration is transparent to MNNs. However, the route via every MR's HA causes problems of Pinball Routing [26, 35] (shown in Fig. 2.6) and multiple NEMO headers added in each packet. The NEMOBS protocol does not consider "Nested NEMO RO" which is defined by [27]. Nested NEMO RO aims to reduce the number of HAs and MRs through which packets must be tunneled. Different mechanisms are under development to solve this kind of RO, which are summarized in [36]. However, none of these mechanisms has been standardized by IETF to extend the NEMOBS protocol to support Nested NEMO RO because they all introduce many extra controlling entities and protocols and cannot fulfill all requirements of RO. Current research adopting Nested NEMO as solutions (e.g. vehicle communications and multiple MR mechanisms to be discussed in Chapter 5) almost all directly uses it without RO to eliminate the influence of these immature RO mechanisms. More of the operation of these technologies and related work on Nested NEMO will be discussed further in Chapter 5.

2.4.2.3 Mobile Ad-hoc Networks and MANET-NEMO

The Mobile Ad-hoc Network (MANET) is one kind of wireless ad hoc network. It is an independent and self-configuring sub-network of mobile devices connected by wireless links without the use of fixed infrastructure-based access networks (i.e. the IP backbone/the Internet). Mobile devices can join or leave a MANET flexibly, and, therefore, research on MANETs aims to design autonomous routing mechanisms for its dynamic topologies in an infrastructure-less environment. The IETF first described the MANET in [37] and then established a MANET working group [38] focusing on routing research. Optimized Link State Routing Protocol (OLSR) [39] and Ad hoc On-Demand Distance Vector (AODV) Routing [40] are proposed by this working group to be the baseline protocols. Support for a MANET to connect to the IP backbone is also required, which is discussed further in Chapter 4.

MANET-NEMO (MANEMO) is a research topic first proposed in 2007 and introduced in [41, 42]. When mobile networks get physically close, their MRs can connect in an ad-hoc fashion, and thus they converge to form a single network and are able to provide Internet connectivity to one another, as shown in Fig. 2.7. The advantage of MANEMO is that MRs of different mobile networks can communicate directly in ad-hoc mode, and thus local communications among these mobile networks can be implemented. MANEMO can be viewed as a combination of

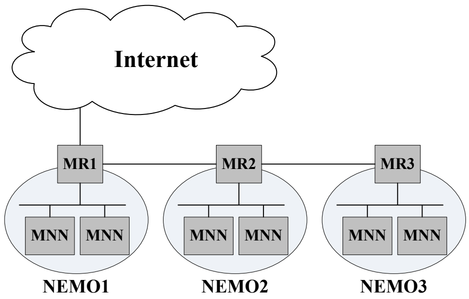


Figure 2.7: *The configuration of MANEMO*

MANET and NEMO (especially multiple MRs and Nested NEMO), but has not received much consideration as such a configuration. MANEMO is under development, and two kinds of possible solutions are proposed by [43]. If two MRs are connected by 1-hop, they can advertise their respective MNPs directly using IPv6 Neighbor Discovery Protocol [17]. If two MRs are connected by multiple-hops, they must use MANET routing technologies. In this way, every MR can be aware of other MRs' MNPs from its ad-hoc interface, and routing to these MNPs can be established. More of the operation of MANEMO technologies will be discussed further in Chapter 4.

2.5 Related User-based Mobile Communication Systems

Recently more research has begun to focus on end users (user-based), which had previously mainly considered fixed access networks (access-network-based). This is because technologies for mobile devices have been improved a lot and they can now be provided with more applications and functions. Two kinds of user-based mobile communication systems are mainly designed: Wireless Personal Area Network (WPAN) and Wireless Vehicle Network (WVN).

2.5.1 WPAN

The concept of WPANs has been introduced in Chapter 1 as one aspect of the heterogenous environment for individual users. More technical details will be analyzed in this section.

A WPAN is a sub-network of interconnecting devices centred around and belonging to an individual person, the connections between which are short-range wireless. These devices are referred to as wireless personal devices or mobile personal devices if mobility is supported, e.g. mobile phones, PDAs and laptops. Personal devices can join or leave a WPAN flexibly, and a WPAN can also interconnect ordinary communication devices, e.g. desktop computers or fixed wireless access points. No matter how the topology of a WPAN alters, content can be transferred directly among personal devices. On the other hand, a WPAN can be mobile, accompanying the individual user as they move. During the moving, communications between entities outside and inside the WPAN should be kept continuous and seamless. A WPAN may also be able to use different wireless technologies to connect in the heterogeneous environment that is composed by various types of access networks.

This concept of a WPAN has existed for quite a while, but it has not been researched systematically and thoroughly and no organization has yet proposed mature and widely-supported standards. This is because personal devices, especially mobile personal devices, have had lots of limitations in their hardware and functions due to the implementation technologies. For example, a mobile phone, as the most common mobile personal device, could not obtain high speed wireless communication until 3G was widely deployed as is now happening. In addition there are problems of limited working time due to low-capacity batteries. These types of limitations have seriously affected the designs of WPANs. Most current research on WPANs has focused on the physical and MAC layers with little consideration of the network layer.

In the physical and MAC layers, several enabling technologies are proposed to interconnect personal devices to form a WPAN. Bluetooth (IEEE 802.15.1) [5] is most often used in current research because it is widely installed in personal devices for low-rate and energy-saving communications. Bluetooth designs a specific sub-layer and adopts a master-slave mode for communications, which can be up to 3Mbps based on the current version. Another widely used technology is WiFi (IEEE 802.11) [6]. WiFi is designed for wireless local area networks, but it has an ad hoc mode, with which devices can communicate with each other directly. WiFi provides high-speed communications up to 54Mbps but needs much higher energy consumption than Bluetooth. Other technologies, e.g. IEEE 802.15.3 [44] for high data rate WPANs, are still under development.

Because few studies have been done on the network layer for WPANs, most of the current research assumes that only traditional IP is used or directly adopts protocols from other areas, e.g. MANET. However, these protocols are not fully suitable for WPANs because scenarios and requirements are different (as will be further discussed in Chapter 4). Considering mobility support for WPANs, NEMO protocols should be more suitable. The IETF NEMO working group is the principal organization planning to design a widely supported standard for the network layer for WPANs. It has included the WPAN as one of its practical deployment scenarios, and recently proposed an IETF document [45] that explores NEMO scenarios from a WPAN aspect and proposes research requirements. However, no further research has been proposed since then. Technical issues in the design of NEMO-based WPANs are discussed further in Chapters 4 and 5.

Some WPAN projects in progress have tried to propose their own system for a WPAN. For example, My Personal Adaptive Global Network and Beyond (MAGNET Beyond) [46] is funded by the Information Society Technologies (IST). It proposes a new concept named "personal network", which can be viewed as a sub-layer, to solve addressing and routing problems. MAGNET requires much modification to access networks in order to deploy its modules. A subproject for WPANs is in the Ambient Network [47] that is also an IST project. The Ambient Network proposes a new network framework between users and access networks to hide the heterogeneity from users [48]. A Personal Mobile Hub [49] was proposed by IBM. It is a fixed gateway between a WPAN and the Internet, but it is more suitable for wearable devices, such as medical sensors.

2.5.2 WVN

A WVN is a sub-network formed by communication devices mounted in a car. These devices may interconnect with wireless or wired technologies. A WVN can communicate with entities outside it with wireless technologies. WVNs are more focused on by researchers than WPANs because much more powerful devices can be installed in a car, e.g. a large vehicle computer with high-capacity batteries, with which more functions and applications can easily be implemented in a WVN than a WPAN. The main difference of configuration between WVNs and WPANs is that, generally, vehicle devices are mainly fixed in a car, e.g. a GPS or a web-TV set, with wired connections to another fixed vehicle device that is specifically used for wireless communications into or forwarding outside this car, e.g. a vehicle gateway or router with UMTS or WiFi interfaces. It means that a WVN mainly has a relative fixed configuration and topology. Therefore, most research focuses on communications between a WVN and entities outside it.

The NEMO working group has much interest in WVNs because one of the original objectives for NEMO design was for cars or trains. Most research on NEMO focuses on car/train scenarios. This working group also includes the WVN as one of its practical deployment scenarios.

However, the NEMOBS protocol can not fulfill all the requirements of WVNs, and thus more mechanisms should be studied. An IETF document [50] was recently proposed to specify scenarios and research requirements for WVNs.

Some projects on WVNs are in work funded by a European framework project for vehicular communications - Intelligent Transportation Systems (ITS). The Car 2 Car Communication Consortium (C2CCC) [51] is a project in Germany, which is mainly organized by NEC and started in 2005. A general architecture and research requirements for C2CCC were proposed in [52, 53]. Its technical details and experimental evaluation were presented recently in [54]. Informatique Mathematiques et Automatique pour la Route Automatisee (IMARA) [55] is a large project in France, whose methods and architecture are proposed in [56]. Some Japanese projects are cooperating with IMARA, which is mainly organized by Keio University. The Widely Integrated Distributed Environment (WIDE) [57] revised and implemented NEMO and MANET Protocols in WVNs, as is summarized and evaluated in [58].

These projects consider similar scenarios. The first scenario is communications from vehicles to the infrastructure (V2I). One vehicle can communicate with the CN in the IP backbone or another vehicle through the IP backbone (V2I2V). In this scenario, MIP/NEMO is mainly adopted. When one vehicle is out of the range of access routers, other vehicles should relay the communication to access routers by multiple hops (i.e. in an ad hoc mode), where MAENT is mainly used. The second scenario is direct communications among vehicles closely located (V2V), where MANET directly works. More of the operation of these technologies and related work on WVNs will be discussed further in Chapter 4.

2.6 Related Research on Network Selection

The concept of interworking of different networks leads to a crucial question: which network should be used. A lot of study has been done on this issue.

In 3GPP-WLAN interworking architecture [10, 11], a basic method is adopted. The system provides several preferred lists for the service. During network selection, the WLAN device goes through these lists in a priority order until an available service is found. However, there is no model or algorithm to represent the user preferences about the networks which may change dynamically.

In a heterogeneous network architecture, what users require is not only connecting to the IP backbone, but also connecting through the best available device and access technology, namely "Always Best Connected (ABC)" [59]. It means that the system should guarantee the user to access the network which is the most suitable for the user's experience. The most important issue in network selection (i.e. ABC) is how to make the decision according to a number of conditions or parameters that can represent the users' needs. Algorithms, mathematic models and mechanisms have been researched in this area.

For ABC, "Terminal-based selection" and "Network-based selection" have been proposed [59], which respectively consider the selection from the mobile device aspect and the access network/service provider aspect. In this thesis, we consider the problem from the terminal-based selection because the mobile user and WPAN are being focused on. A lot of research on ABC has been proposed, and can be classified into three kinds: weighted cost function, multiple attribute decision making (MADM) and utility function.

2.6.1 Weighted Cost Function

In this method, weights are assigned to the factors that are considered in the network selection. Scores are computed as a weighted sum of all the normalized factor values to evaluate the performance, from which network interfaces are ranked for the user to select according to the requirements.

Earlier studies proposing and developing this kind of method are reported in [3, 60, 61]. In [60], a policy-enabled handoff system is presented. The sum of weighted cost functions of bandwidth, power consumption and network cost are computed, and the network with the minimum cost is selected as the "best" one. A similar smart decision model [61] is proposed, using a score function that is well-tuned according to usage expense, link capacity, and power consumption. Also using a weighted cost function, a dynamic vertical handoff algorithm [3] is proposed involving QoS factors, weighting factors, and network elimination factors in the optimization by considering the features of individual services. Based on these earlier studies [3, 60, 61], later research also uses the concept of weighted cost functions but involves further considerations. Concentrating on the user's needs, dynamic weights [62] are defined to accord with the variation of user requirements. Theoretical analysis models by using Markov chains to evaluate the cost function are proposed in [63]. In [64] a weighted cost function is also used with the addition of a utility function to solve the problem.

2.6.2 Multiple Attribute Decision Making

Multiple Attribute Decision Making (MADM) based approaches treat the handoff decision making as a MADM problem. Classical MADM methods includes Analytic Hierarchy Process (AHP) and Grey Relation Analysis(GRA). MADM can be combined with weighted cost function, fuzzy logic and game theory. A representative study using MADM is [65]. It comprises two components, with the first applying an AHP to decide the relative weights of evaluative criteria set according to user preferences and service applications, while the second adopts GRA to rank the network alternatives. QoS parameters considered in the scheme include throughput, timeliness, reliability, security, and cost.

2.6.3 Utility Function

Utility is a concept from microeconomic theory. It is a continuous function representation of the consumer's preference relations over a set of commodities. With proposed utility functions representing the different needs of users and applications, the network that can maximize the utility is selected as the most preferred one. A representative study using utility function for the network selection problem is [66, 67]. It proposes an ABC model and analyzes it with utility functions combining Knapsack problems, focusing on QoS factors. Huang et al [68] calculate the cost of QoS and evaluate its mechanism with a utility function to show that it can get a higher overall utility than others. In this kind of method, the selection is often only based on one aspect of a user's consideration. This is because the utility function may be completely different when different preferences of a user are considered. For example, a special utility function is used to represent a user's consideration on network speed, but another different special utility function should be adopted to represent his/her consideration on power consumption. This is different from the weighted cost function, which often has a similar format including different aspects of a user's consideration.

Network selection will be discussed further in Chapter 6.

2.7 Summary

IPv6 provides a promising future for the Internet due to its large address space. Besides the addressing problem, another issue in the network layer gathering much interest from researchers is mobility support. Wireless networks have become a very important access technology for the Internet, via which mobility of wireless devices is easy to be implemented. How to provide continuous communications for mobile devices when they move across different subnetworks of the Internet is a challenging problem. MIP and NEMO have been proposed to support the mobility of a signal node and a mobile network. MIPv6 is more efficient because it can solve the triangle routing problem. Although the NEMOBS protocol still can not support routing optimization for a mobile network, researchers have proposed NEMO multihoming (multiple Mobile Routers), Nested-NEMO and MANET-NEMO (MANEMO) as extensions of NEMO to support more functions.

Two main networking applications using mobile devices are WPANs and WVNs, which are both user-based. A WPAN is used for an individual user's mobile communications. Because of its dynamic topology and high requirements for flexibility, most research on WPANs only focuses on the physical and MAC layer to interconnect devices in a WPAN, and few studies have been done in the network layer to provide mobile communications for WPANs. WVNs are used in cars or trains. WVNs are researched more than WPANs because a WVN basically has a fixed topology and configuration.

Moreover, during a device or a mobile network's movement, it may be able to connect to different access networks via the same interface or its multiple interfaces. Therefore, the ABC problem is proposed to select the most suitable network for connecting. Three main kinds of methods for ABC have been discussed in this Chapter.

The WPAN considered in this thesis is NEMO-based. Chapters 4 and 5 will further discuss the mobility support including standard MIP/NEMO, multiple Mobile Routers for NEMO, Nested-NEMO, MANEMO, WPANs and WVNs. Chapter 6 will further discuss the network selection used in NEMO.

Chapter 3
The Personal Distributed Environment

The framework for a ubiquitous communication system and a WPAN management system, the Personal Distributed Environment (PDE), used in this thesis, are discussed in this Chapter.

3.1 A Framework for a Ubiquitous Communication System

The widespread usage of wireless communications has led to many developments in mobile communication systems. New types of wireless personal devices have been developed in addition to the immensely popular mobile phone. An individual user can no longer be assumed to possess only a single wireless device (terminal) as in most traditional research. A user may have several wireless capable devices which may form a dynamically changing WPAN. The framework for an individual users' ubiquitous communications used in this thesis, is shown in Fig. 3.1.

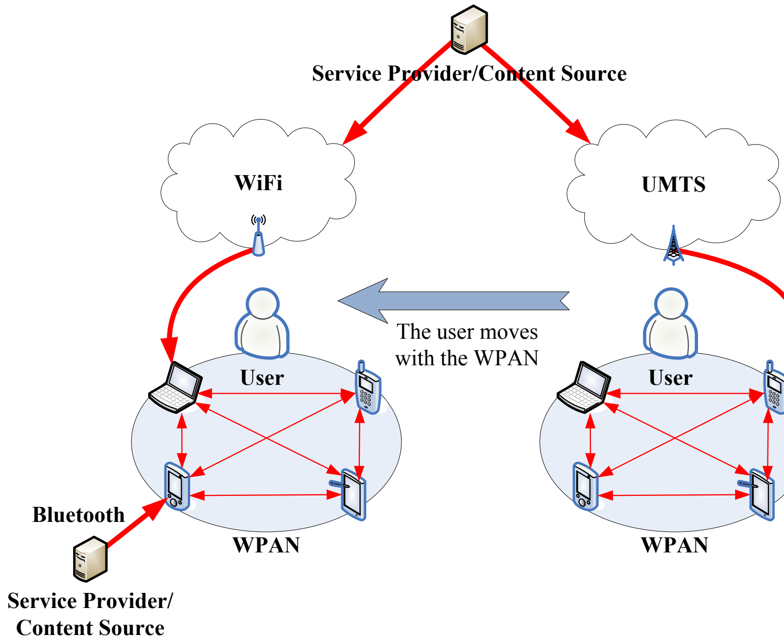


Figure 3.1: *A Framework for a Ubiquitous Communication System*

The heterogeneous environment summarized in Chapter 1 is incorporated in this framework. The various wireless networks with differing coverage and access technologies form a heterogeneous environment for individual users to access networks (as discussed in Chapter 1). Also, personal devices may have diverse capabilities, such as different screen size and resolution, support for audio and video, and be able to connect to the Internet and interact with each other using multiple wireless interfaces. They form a WPAN that accompanies an individual moving user and can dynamically change its topology and wireless connections (as discussed in Chapters 1 and 2). No matter how the user accesses different networks or the WPAN dynamically alters, required content should be transferred, in the most suitable and efficient way, to the user anywhere and anytime and kept continuous as they move. This framework is personal-area-centric and content-centric, and thus the design of mechanisms for it should be based on WPANs and also fulfil the users' requirements for obtaining content.

3.2 The Personal Distributed Environment (PDE) concept

This framework presents a heterogeneous and dynamic networking and application environment for individual users. The Virtual Centre of Excellence in Mobile & Personal Communications (Mobile VCE) [4] has proposed a Personal Distributed Environment (PDE) concept [69] to provide this kind of framework. The PDE is a personal networking solution aimed at providing access to a diverse range of services over multifaceted terminals, by which content from services can be delivered to users over heterogeneous networks to these terminals [70]. The PDE is a user-centric approach, which means that users manage and control their sub-networks and content delivery.

An individual user may require to access services at particular locations, such as at home, in the office, in a car or a WPAN that moves accompanying this user. The cluster of personal devices belonging to this user at each location forms a PDE sub-network. The PDE uses a two-level architecture: local management entities in PDE sub-networks and root management entities in the fixed network (e.g. a service provider). The PDE's management entities include: the Device Management Entity (DME), Personal Content Management (PCM) and Personal Assistant Agent (PAA), which are shown in Fig. 3.2.

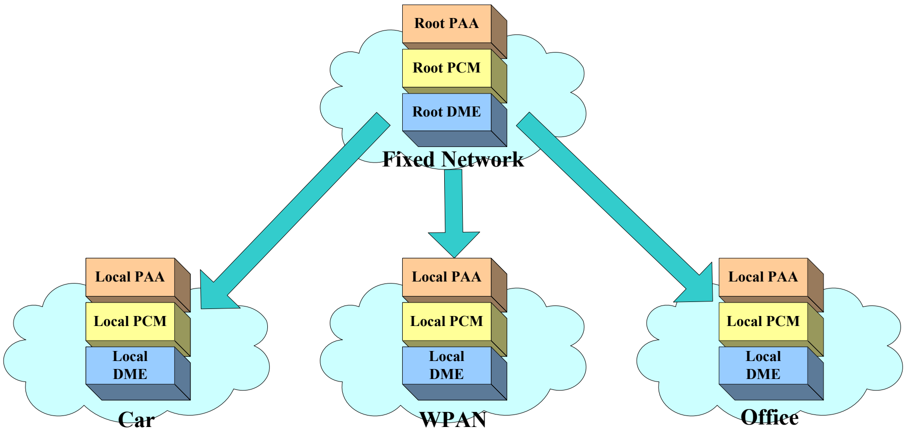


Figure 3.2: *The Personal Distributed Environment (PDE) structure*

3.3 The Device Management Entity (DME)

3.3.1 The DME concept

Because the PDE embraces a user-centric view of communications and users may have access to a number of disparate devices attached to heterogeneous networks, a network identity is required to set up a network link to a user. Therefore, there is a requirement for incoming services to communicate initially with a single nominated entity within the PDE. Based on communications with this entity, content delivery can then be established across an appropriate network with an appropriate personal device. This entity is the DME. Every user is provided with a unique person-based Unique Resource Identifier (URI), which is mapped to the IP address of the DME belonging to this user's PDE [70]. All sessions destined for this user send setup requests to this URI, i.e. this user's DME. The DME, cooperating with the PCM and PAA, performs endpoint determination to select the most appropriate personal device for each service. The DME is a distributed logical entity in every PDE sub-network with a root located at a predefined Internet location such that it can be contacted by outside agencies [69]. The DME was the first management entity proposed and researched for the PDE concept by Core 3 of Mobile VCE from 2002, and thus its basic architecture and mechanisms have been investigated.

There are two issues central to the operation of the PDE. Firstly, it is required to determine which devices are accessible to the user. In addition, characteristics and capabilities of these devices should also be determined to set up sessions to them. In order to implement these functions, some registers are designed. The first one is "Equipment Register" [70], through which, devices' capabilities can be ascertained and recorded, such as wireless interfaces, power level and storage status. These capabilities will be used to make decisions about which device content should be transferred to and stored in. The second one is the “Location Register” [70] to get devices’ reachability information. In all-IP-based communication systems, this information is the current IP addresses of these devices. The last one is “Security Register” [70], which assures encryption keys and policies to guarantee that the un-authorised devices and servers cannot link to devices inside the PDE. When a personal device switches on, it registers this information to the DME, and thus becomes a device managed by the user’s PDE. The DME periodically checks its stored register information from personal devices. When any condition of a personal device changes, it updates the last information to the DME.

3.3.2 The Root DME and Local DME

The Root DME is located in the fixed network, while the Local DME is located in every PDE subnetwork but may dynamically change its physical location among the devices in this subnetwork based on considerations such as power level [70]. The register information obtained in a PDE subnetwork is also cached in the Root DME. The periodically updated information of all devices in this PDE subnetwork can be aggregated and sent as a single signalling message by the Local DME to the Root DME.

This partition of the DME gives rise to a hierarchical and distributed control architecture. If communications only happen inside or local to a PDE subnetwork, only the Local DME will be involved. For example, when a user wishes to determine capabilities of devices in a PDE subnetwork where they are currently located (like a WPAN), the Local DME is checked; when a content source is inside or in the vicinity of this WPAN, named as a local service provider, the Local DME will manage this local content transfer. However, if this PDE network contacts remote service providers or other remote PDE subnetworks, communications, whether signalling or content transfer, should be redirected by the Local DME to the Root DME which then contacts other corresponding Local DMEs [70]

3.4 The Personal Content Manager (PCM) and Personal Assistant Agent (PAA)

The PCM and PAA, as extensions of the DME, are novel management entities proposed by Core 4 of Mobile VCE in 2005, and are still under development. The research on the PCM and PAA aims to hide the complexity associated with pervasive technologies away from users making their experience easier to manage. It focuses on simplifying the usage of users' devices and wireless communications through the heterogeneous networks. The users can concentrate on what they want to do and the experience they can enjoy, without considering the details of the technologies, such as networking parameter settings and device configurations [71].

The PAA is used to manage the way that content is presented to users, and simplify the content management by hiding terminal configurations from users [72]. It simultaneously observes and senses users' behaviour, and enhances user experience by providing more simple and relevant choices, in order to help users to get the content more effectively and rapidly, or even forecast the content that the users will need in future.

The PCM is designed to define mechanisms and tools used by the PAA to achieve its tasks. It can ensure that users' required content is accessible at the right time, through the right device and via the right route, based on information provided by the DME [72]. Therefore, the PCM can make the content more readily available for a user in a PDE environment where multiple devices with multiple interfaces are interconnecting. The PCM is an important tool of the PAA and has the closest relationship with the DME, because the PCM and DME will cooperate to determine networking configurations of PDE subnetworks (e.g. a WPAN) and implement content delivery in the most suitable and efficient way.

3.5 Summary

The PDE concept has been proposed by Mobile VCE for an individual user's content delivery in a heterogeneous environment that is composed not only of diverse personal devices but also by various access networks and dynamic networking configurations. The WPAN is considered as one of the PDE subnetworks. The DME was the first proposed PDE management entity, and its basic architecture and mechanisms have been researched in some detail. The DME registers and records personal devices' condition information, and works as a low-level networking support for the whole PDE architecture. The PCM and PAA are two new PDE management entities currently being investigated to implement more functions for the PDE. The PCM co-operates with the DME to handle the networking issues for content delivery. Based on device information provided by the DME and transfer request from the PAA, the PCM will decide where and how to delivery the required content.

A framework for individual users' ubiquitous communications was proposed in this chapter. As discussed in Chapter 2, the basic mobile communications of a WPAN can be implemented by MIP and NEMO, but many scenarios of ubiquitous communications in this proposed framework, which will be analyzed in Chapters 4 to 6, cannot be supported by existing research. The DME and PCM will be further researched in this thesis to design PDE-based schemes to support ubiquitous communications of WPANs in the heterogeneous environment. In chapter 4, a mechanism based on the PCM and the DME with an extended architecture is proposed to combine local direct and global mobile communications of WPANs. In Chapter 5, a mechanism based on the DME is proposed to manage addressing problems and multiple mobile routers in WPANs. In Chapter 6, a decision making mechanism of mobile router selection is designed, which will be used by the PCM to decide the content delivery route.

Chapter 4
Ubiquitous Communications: Combining Local Direct and Global Mobile Communications

One of the problems for ubiquitous communications is that individual users often use both infrastructure-based and infrastructure-less communications during content transfer. A novel scheme is proposed in this chapter to combine local direct and global mobile communications.

4.1 Introduction

The environment for individual users' communications is composed not only of multiple wireless networks with differing coverage and access technologies, but also a mix of personal devices in a WPAN, which are mobile and have multiple wireless interfaces. In such a heterogeneous environment, the basic technologies adopted for ubiquitous communications are likely to be derived from work on infrastructure-based networks. Mobile IP (MIP) is widely used for the mobility of a single device. Network Mobility (NEMO) is under development to support the mobility of moving networks with WPANs considered as one practical case. This kind of content transfer is based on the IP backbone and can maintain continuous global mobile communications. This thesis refers to it as "standard MIP/NEMO mode".

For individual users, local personal and trusted content transfer will often happen among personal devices in close vicinity. Although the standard MIP/NEMO mode can support ubiquitous content transfer, it has extra signalling communications with high overhead and so low performance in local content transfer. Thus individual users will usually prefer to use infrastructure-less communications to transfer local content since it can immediately initiate direct communications among physically close devices with short range technologies. This mainly uses mobile ad hoc networks (MANET) and does not depend on the IP backbone. This thesis refers to it as ”pure ad hoc mode”. However, in this mode content transfer can not be kept continuous when the devices move out of the range of their short range wireless interfaces (like Bluetooth), because the current local transfer would have to be disconnected and then a new global connection through the IP backbone (e.g. via 3G) established.

Such a coexistence of infrastructure-based and infrastructure-less communication leads to a hybrid networking environment for ubiquitous content transfer. How to keep communication continuous in this environment and also keep high performance for local content transfer provides a challenge for research. The aim of the work in this chapter is to design a scheme for ubiquitous communications, which can combine local direct and global mobile communications. In this chapter, a scheme based on a Personal Distributed Environment (PDE) is proposed which combines pure ad hoc mode and standard MIP/NEMO mode and takes advantages from both of them. It can support ubiquitous personal content transfer and have low transfer delay and cost.

The rest of this chapter is structured as follows. Section 4.2 analyzes related research and discusses relevant issues. Existing approaches to local direct communication are analyzed in Section 4.3. In Section 4.4, a PDE-based scheme combining local direct and global mobile communications is proposed considering two scenarios. The performance of the proposed scheme is evaluated and demonstrated in Section 4.5 and 4.6 with numerical analysis and networking experiments.

4.2 Related Work and Research Issues

4.2.1 Related Protocols

4.2.1.1 MIP and NEMO

In this thesis, the standard MIP/NEMO mode also includes the extensions and enhancements of MIP and NEMO.

The MIP protocol [1] does not consider local direct content transfer, nor do its extensions. In order to reduce signalling traffic of a Binding Update (BU) when a Mobile Node (MN) changes its Care-of Address (CoA) during ongoing communication, Hierarchical Mobile IP (HMIP) [23] is designed for micro-mobility (a MN often moves in one domain) introducing a new entity - a Mobility Anchor Point (MAP) that is responsible for this domain. However, the MAP is still located in the access networks (just nearer to the MN than the Home Agent (HA)), thus it still does not consider local direct content transfer.

The NEMO protocol [2] also does not consider local direct content transfer, and its problems and drawbacks are analyzed in an IETF document [73]. Its enhancements - Nested NEMO and MANET-NEMO (MANEMO) have been summarized in Chpater 2. Nested NEMO is a new configuration for a moving network where multiple MRs are connected in a nested formation. New routing protocols are proposed in [74, 75] to get Routing Optimization (RO) for intra communications of a Nested NEMO network that happen among Mobile Network Nodes (MNNs) inside it. MANEMO can be viewed as a sub-area of Nested NEMO: MRs of different NEMO networks connect via a MANET to provide infrastructure-based connectivity to each other [41, 42]. An IETF document [27] proposes that MANETs can be considered to be used to get RO for intra communication of Nested NEMO. One solution is to inform every MR of the Mobile Network Prefixes (MNPs) of other NEMO networks via the MANET [76].

Although current research on NEMO enhancements can provide local direct communications inside a Nested NEMO network, they assume that the destination node's ingress interface address (the address obtained inside the NEMO network) is known by the source node before communication starts. This means that they only consider Local Fixed Nodes (LFNs) that are fixed in a NEMO network and so have fixed addresses, or Visiting Mobile Nodes (VMNs) that have established RO and so have informed the CNs of their CoAs (i.e. ingress interface addresses). The procedures of RO establishment and BU are not considered in current research. However, in a WPAN, personal devices may be all VMNs that could join in or leave this WPAN anytime. Therefore, RO establishment and BU must be considered when WPANs are researched.

4.2.1.2 MANET

MANETs have been summarized in Chapter 2. They are designed for areas without any preexisting infrastructure. The major task of research on MANETs is to design IP routing protocols in such an infrastructure-less environment because there is no traditional fixed access router. Therefore, a MANET does not consider a mobile node's globe mobile communications. In order to enhance a MANET, Internet connectivity is proposed [77], which assumes that one node in a MANET can connect to the IP backbone and provide the Internet connection for other nodes in this MANET. It aims to solve routing and addressing problems caused by the differences between a MANET and the traditional IP backbone. From this concept, [77] also proposes that it is possible to make MIP work in a MANET. It views a MANET as an extension of the IP backbone, and MIP logically works on top of this combination of the MANET and IP backbone. MIP only requires an Internet connection, and thus the combination of a MANET and the IP backbone can be viewed as transparent to MIP. Therefore, MIP does not care or even does not know whether a MANET is used, and the MIP protocol [1] still runs in its traditional mode in every node in this MANET, which means that MIP's problems and drawbacks in local direct communication still exist.

4.2.2 Related Research Projects

Some research projects on Wireless Vehicle Networks (WVNs) consider a similar scenario. The work of the Car-to-car Communication Consortium (C2CCC) [51], IMARA [55] and WIDE [57] are summarized in Chapter 2. These are all based on a European framework project for vehicular communications: Intelligent Transportation Systems (ITS). A scenario proposed by them is Vehicle to Vehicle (V2V) communication [52, 53, 78]. In V2V, the MRs of vehicles that are closely located can directly communicate with each other. This scenario is similar to the work in this chapter. These projects only consider the direct communication among MRs because they only focus on a car not the devices inside this car. However, when WPANs are researched, the direct communication between personal devices inside a WPAN and between two WPANs should both be considered. Therefore, the work in this chapter considers both MNNs and MRs, while other projects only consider MRs.

Two kinds of approaches are proposed [52]: a MANET-Centric and a NEMO-Centric approach. In the MANET-Centric approach, MANET routing protocols are used to connect nodes, and NEMO runs on top of it. In the NEMO-Centric approach, NEMO provides routing of infrastructure connectivity for a moving network, whereas the MANET deals with routing issues inside this moving network. These projects all adopt a MANET-Centric approach because they only consider communications between two cars. C2CCC has designed a special sub-network layer - C2C Network Layer [52, 54]. It's not an IP-address compatible sub-layer, and uses link local identifiers, generated from geographical information (like GPS), in a MANET that adopts a geographic routing protocol, and not traditional IP routing protocols. NEMO runs on top of this C2C Network Layer which is transparent to NEMO. IMARA and WIDE adopt a MANEMO solution that connects the MRs of two cars via a MANET and uses traditional IP routing in this MANET [56, 58, 79, 80]. They propose that MRs can use their addresses obtained from the corresponding MNPs in this MANET, i.e. a MR can use one address in this

MANEMO. In the work described in this chapter, a NEMO-Centric approach is used when the local direct communication inside a WPAN is considered, while a MANET-Centric approach is adopted when direct inter-WPANs communication is required.

These WVN projects all only consider LFNs to simplify their design. They all consider vehicle scenarios where communication devices may often be fixed in a car, e.g. a GPS or a Web-TV set, so they can assume that all nodes in this WVN are LFNs. However, when a WPAN is considered, personal devices may all be VMNs that could join or leave this WPAN.

4.3 Analysis of Local Direct Communication

In this section, local direct communication is analyzed with different approaches in two scenarios: Intra-WPAN and Inter-WPANs. It is assume that every personal device in a WPAN is a VMN with multiple wireless interfaces.

4.3.1 Scenario A: Intra-WPAN

Two personal devices in a WPAN, shown in Fig. 4.1, initiate direct content transfer without contacting the remote entities in the IP backbone (i.e. local direct communication). Subsequently, the receiver device moves away from this WPAN (i.e. change from local direct to global mobile communication) while keeping this content transfer continuous.

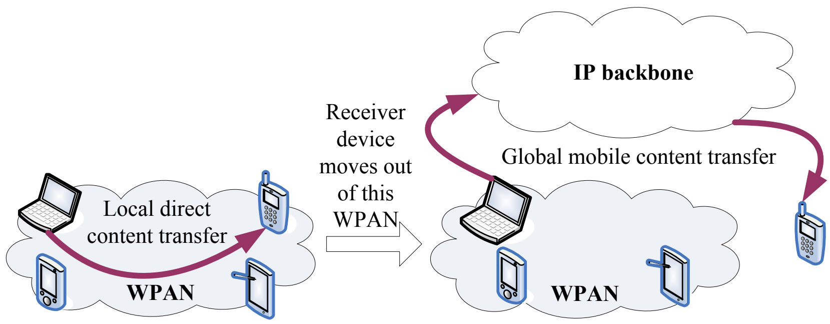


Figure 4.1: *Scenario A: Intra-WPAN*

4.3.1.1 Pure Ad Hoc Mode

The pure ad hoc mode can establish a direct communication between these two personal devices immediately. The addresses used by them are MANET link-local addresses that can not be global routable. This ongoing transfer is disconnected when the receiver device moves out of this WPAN due to loss of wireless signal. Therefore, this mode's drawback is that it can not support a personal device's mobility from inside to outside a WPAN and its ubiquitous content transfer, and thus it is unacceptable for global mobile communication.

4.3.1.2 Standard MIP/NEMO Mode

Procedures for the standard MIP/NEMO mode are shown in Fig. 4.2 where the steps are numbered. According to the MIP protocol [1], when a CN (i.e. sender device) contacts a MN (i.e. receiver device) for the first time, it gets the MN's Home Address (HoA) via the Domain Name System (DNS) and sends data packets to this HoA. Data packets are tunnelled via the MR, the MR's HA and the MN's HA respectively according to the NEMO protocol [2]. After these data packets are received, the MN sends a BU including its Care-of Address (CoA) to the CN to establish RO. After RO is set up, subsequent data packets can be transferred directly between these two devices. When the MN moves out of this WPAN, it sends a BU including its new CoA to the CN, so data packets are then sent to the MN according to this new CoA.

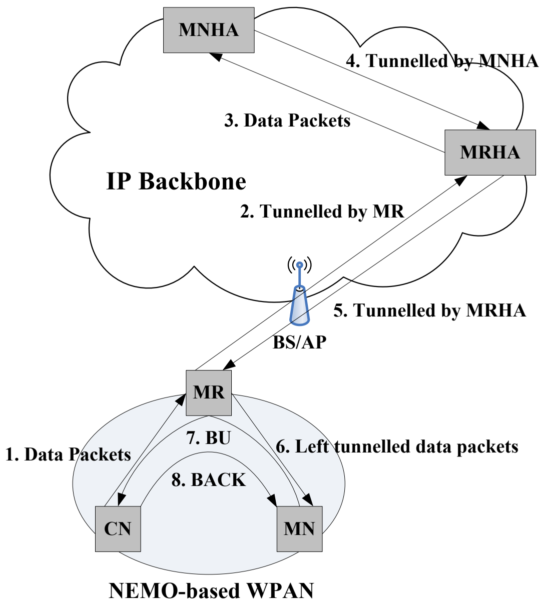


Figure 4.2: *Standard MIP/NEMO mode in Scenario A*

The standard MIP/NEMO mode can keep content transfer continuous when the MN moves out of the WPAN. However, some data packets have to be sent to the MN's HA to get RO initialization, which leads to the following disadvantages:

- ***HA dependency***: The CN has to depend on a remotely located entity to get the MN's CoA, although the CN and MN may be physically close to each other.

- ***High delay and cost***: The data packets sent to the MN's HA lead to a much higher delay and cost than for a MANET. Also, the signalling procedures of RO establishment increase delay and cost. Furthermore, the delay and cost will increase when the distance from the MR to the HA increases and the speed of the wireless channel to the Access Point/Base Station decreases. (The distance is represented by hops that a packet must be transferred in the network layer. The path from one router to the next router is one hop.)

- ***MR connectivity***: The standard MIP/NEMO mode requires that the MR must connect to the IP backbone. However, a moving WPAN may lead to a dynamic change of wireless network quality for the MR, and highly mobile personal devices (like mobile phones) are more likely to lose wireless signal than fixed devices in a car. If the MR is disconnected from the IP backbone (i.e. in an infrastructure-less environment) while data and signalling packets are being routed, the CN and the MN can not communicate even though they are connected to the same link [73]. This is related to an important research issue - "Optimization for a stand-alone mobile network" [81], which aims to support VMNs when a mobile network is in an infrastructure-less environment. Current research almost all assumes an infrastructure-based environment, and thus very few studies have been done on stand-alone mobile networks.

If HMIP [23] is used, since the MAP does not hold the complete binding cache of a MN and can not replace its HA, packets also need to be sent to this MN's HA first to get RO initialization, so it also has the same drawbacks as MIP/NEMO. If MIP runs on a combination of the MANET and IP backbone as discussed in Section 4.2.1.2, since the MIP protocol [1] still works traditionally in every device, the same disadvantages exist. Therefore, the standard MIP/NEMO mode (including the enhancements of MIP/NEMO) has low performance in local direct communications, and thus is unsuitable.

4.3.2 Scenario B: Inter-WPANs

Personal devices in two physically closely located WPANs may wish to directly communicate with each other through the MRs of these two WPANs without contacting remote entities (i.e. local direct communication). Personal devices' mobility out of WPANs and continuous content transfer (i.e. change from local direct to global mobile communication) should be supported. This scenario is shown in Fig. 4.3.

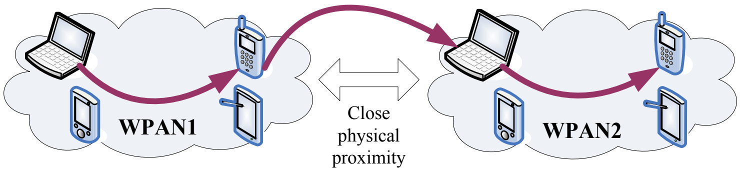


Figure 4.3: *Scenario B: Inter-WPANs*

Pure ad hoc mode is unacceptable in this scenario due to the same reasons discussed in Scenario A. On the other hand, Fig. 4.4 shows the standard MIP/NEMO mode, which uses MANEMO after RO is established. MANEMO can connect the MRs of these two WPANs in a MANET for direct content transfer when receiver devices' CoAs have been obtained. The standard MIP/NEMO mode is also unsuitable for local direct communication as was discussed in Scenario A, although it can adopt MANEMO.

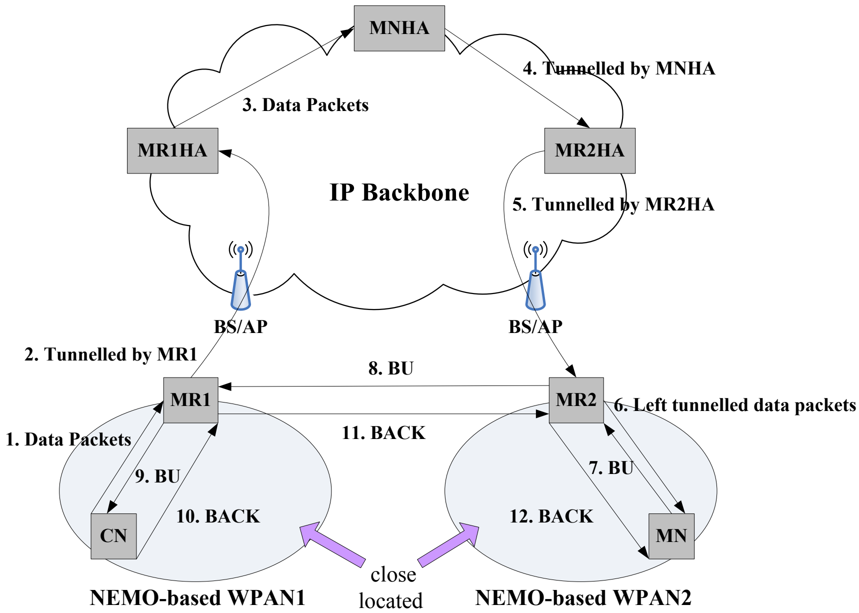


Figure 4.4: *Standard MIP/NEMO mode in Scenario B*

4.3.3 Summary

Based on the above analysis, no existing scheme can fully satisfy the requirements of ubiquitous content transfer combining local direct and global mobile communications. Their characteristics are summarized in Table 4.1.

Schemes	Support "Continuous Communications with Mobility"	"HA Dependency" not required	Delay and Cost	"MR Connectivity" not required
Pure Ad hoc Mode	No	Yes	Low	Yes
Standard MIP/NEMO Mode	Yes	No	High	No
Standard MIP/NEMO Mode (MANEMO)	Yes	No	High	No

Table 4.1: *Summary of existing schemes in ubiquitous communications*

4.4 PDE-based Scheme for Combining Local Direct and Global Mobile Communications

In this section, a PDE-based scheme is proposed for ubiquitous content transfer combining local direct and global mobile communications.

4.4.1 Topology and Addressing

The topology of a WPAN is that all personal devices in the WPAN are VMNs supporting MIP, and connect to each other in a MANET via short range wireless interfaces, e.g. Bluetooth, but also have other wide area wireless interfaces, such as WiFi and 3G. Also, they all connect to a personal device working as a MR of this WPAN via, say, Bluetooth, and this MR aggregates them moving as an entity as defined in NEMO. It is assumed that local logical entities of the PDE are located in the MR of a WPAN. When personal devices join the WPAN, they register to the local Device Management Entity (DME) of this WPAN.

When Scenario A is considered, the NEMO-centric approach is used for addressing. MNs (personal devices) generate CoAs using the MNP advertised by the MR with the NEMO protocol [2]. These CoAs are also used by the MANET inside this WPAN. If a MN's CoA has the same prefix as a CN's CoA, it means that they are part of the same NEMO network, and thus content is transferred with their short range wireless interfaces via MANET. If their address prefixes are different, the CN and the MN may not be in the same NEMO network.

When Scenario B is considered, the MANET-centric approach is used for addressing. In practice, MANEMO is implied to use a MANET to connect two WPANs' MRs directly via short range wireless interfaces, where every MR uses an address generated from its own MNP. In this way, the MR of one WPAN can be aware of other physically closely located WPANs' network address prefixes (i.e. MNPs advertised by MRs in other WPANs) [76]. Therefore, content from a CN in one WPAN to MNs in other WPANs that use CoAs generated from these MNPs is sent via this MANET between MRs using their short range wireless interfaces.

4.4.2 Extended Functions of the DME

The DME has been discussed in Chapter 3. The location register and URI mapping are two of its proposed functions [70]. In this section, these functions are extended to support more applications.

The location register of the DME stores "location" information of every personal device. In an all-IP-based communication system, this information is the current IP address of a device [69]. A personal device may have multiple CoAs obtained from its multiple wireless interfaces. Here, it is proposed that a personal device registers all its active CoAs to the DME's location register as well as its HoA.

A personal-based URI, e.g. John@ABC.com, used by applications to denote an individual user is mapped to the IP address of this user's DME in a DNS-like procedure [70]. Here, it is proposed that this URI is extended to two kinds: a personal-device-based URI and a personal-area-based URI, whose mappings are shown in Fig. 4.5. A personal-device-based URI represents a personal device, which is mapped to this device's HoA and CoAs that can be obtained from the location register. A personal-area-based URI represents a subnetwork owned by an individual user (e.g. a WPAN or a WVN), which is mapped to the device where the local DME resides and then to its HoA and CoAs. For example, WPAN.John@ABC.com is the URI of a WPAN owned by John, and is mapped to a mobile phone where this WPAN's local DME resides, whose URI is mobilephone.John@ABC.com.

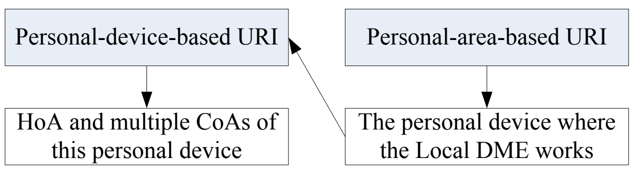


Figure 4.5: *Extended URI mappings of the DME*

The logical architecture of the DME is shown in Fig. 4.6. The personal-device-based URI and personal-area-based URI also act as logical interfaces. The local DME can send corresponding information of IP addresses to communication entities that can also query the local DME using these URIs.

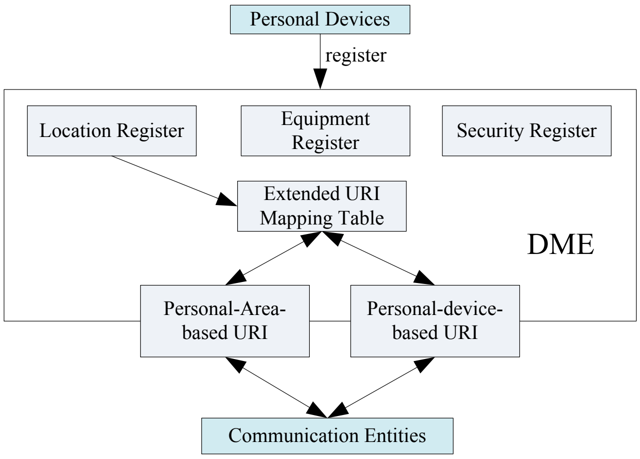


Figure 4.6: *The logical architecture of the DME*

4.4.3 Procedures of the PDE-based Scheme

The Personal Assistant Agent (PAA) decides source and destination devices for a required content transfer, and informs the Personal Content Manager (PCM) of these devices' URIs [72]. The PCM queries the DME with these URIs. The DME checks its URI mapping table and sends these devices' HoAs and CoAs to the PCM. In this way, the DME can implement multi-homing binding of personal devices (similar to the HA) in the local personal area. The PCM decides suitable interfaces and routes, and sends initiation instruction messages including an Initial BU (IBU) to start this content transfer. These process are shown in Fig. 4.7.

The IBU binds one of the MN's CoAs, whose corresponding interface is selected by the PCM, to its HoA. The IBU includes this CoA, the MN's HoA and the CN's HoA with the BU format as defined by MIP. After receiving the IBU, the MN and CN can establish binding cache entries for this content transfer. Then, the CN sends data packets directly to the MN's CoA according to MIP. Scenario A and B are analyzed for the PDE-based scheme as follows.

- **Scenario A: Intra-WPAN**

The procedure of the PDE-based scheme for Scenario A is shown in Fig. 4.8. IBACK is the

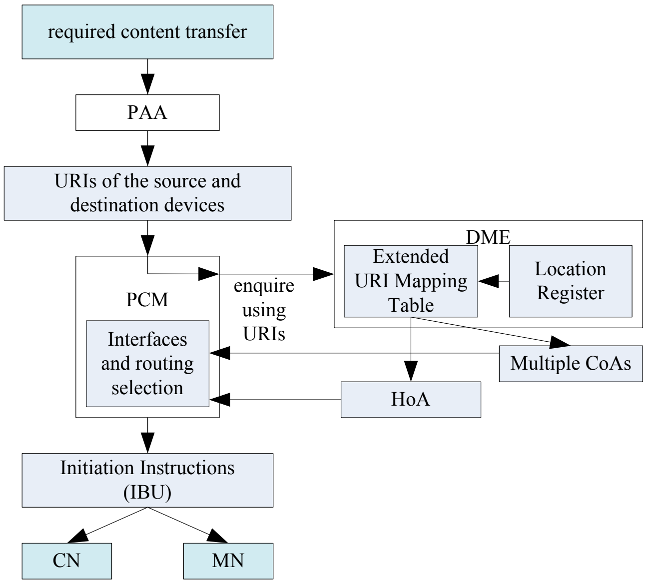


Figure 4.7: *PDE-based Scheme process*

initiation binding acknowledgment used by MNs and CNs to inform the Local PCM/DME of successful establishments of binding cache entry. If the MN's CoA is from its short range wireless interface inside this WPAN (which means this is a local content transfer), the CN can immediately start to send data packets using local direct communication. With the standard MIP/NEMO mode (Fig. 4.2), a CN needs eight steps to obtain the MN's CoA, and the PDE-based scheme only two steps. After this transfer is initiated, MIP/NEMO runs traditionally so this transfer can be kept continuous when the MN moves out of this WPAN because a standard BU mechanism will work.

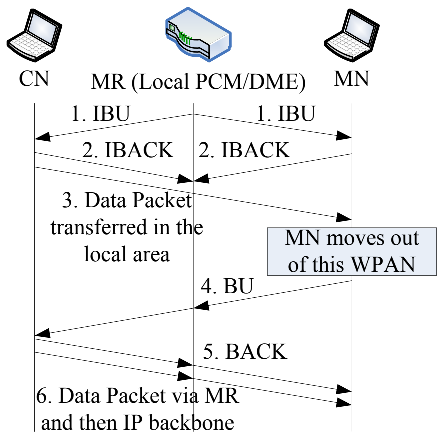


Figure 4.8: *PDE-based scheme in Scenario A*

- **Scenario B: Inter-WPANs**

The procedure of the PDE-based scheme for Scenario B is shown in Fig. 4.9. The CN is in WPAN1, and the MN is in WPAN2. The Local PCM1 in WPAN1 requests the Local DME2 in WPAN2 for IP address mapping information of the MN with its URI. If the MN's CoA is from its short range wireless interface inside WPAN2 (which means this is local content transfer in MANEMO), the CN can immediately start this transfer with local direct communications via a MANET between MR1 and MR2. All signalling is in the local area, and the MN's mobility is supported as well.

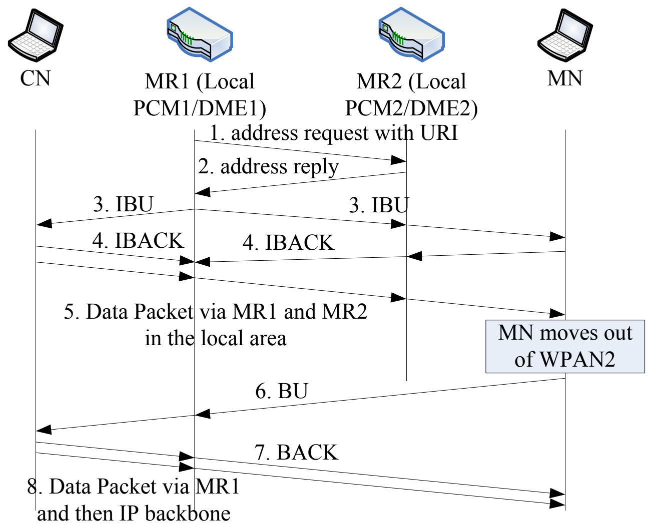


Figure 4.9: *PDE-based scheme in Scenario B*

4.4.4 Summary

This PDE-based scheme has a number of advantages:

- ***Continuous Communications with Mobility:*** Because the proposed scheme is based on NEMO/MIP, the mobility of a personal device or a WPAN is supported, which can keep ongoing communications continuous when this personal device or this WPAN moves away. This property is demonstrated in Section 4.6.

- ***HA independency:*** Because mapping is maintained by the local DME and binding is produced by the local PCM, a CN need not contact a MN's HA to obtain its CoA. This property is demonstrated in Section 4.6.

- ***Low delay and cost:*** Although the delay and cost in the PDE-based scheme is higher than that of the pure ad hoc mode due to initiation instruction messages, they are lower than that of the standard MIP/NEMO mode. This is demonstrated in section 4.5 through a numerical analysis.

- ***MR connectivity not required (Stand-alone mobile networks supported):*** No MR connectivity with the IP backbone is needed for local content transfer. Therefore, if it is a stand-alone WPAN without Internet connectivity (i.e. in an infrastructure-less environment), local content can still be transferred directly. Also, local direct communication can be maintained because binding cache entries of personal devices can be controlled by the Local DME/PCM (e.g. re-send IBU to the MN and CN) without the HA. When this WPAN connects to the Internet, it can change to the standard MIP/NEMO mode seamlessly and keep transfer continuous, supporting devices' mobility. This is demonstrated experimentally in Section 4.6.

- ***Selection of transfer modes:*** The PCM implements the selection and change of transfer modes by different pre-set bindings of CoAs in the IBU.

4.5 Numerical Performance Evaluation

In this section, the performance of the PDE-based scheme is analyzed in terms of overhead cost (C_{oh}), RO establishment delay (t_{et}) and RO establishment cost (C_{et}) in Scenarios A and B, compared to the pure ad hoc mode and standard MIP/NEMO mode.

4.5.1 Performance Analysis Model

The symbols used in this section are listed in Table 4.2.

Processes of the pure ad hoc mode used for content transfer in Scenarios A and B are shown in Fig. 4.10, where this transfer can be started immediately and no signalling is needed.

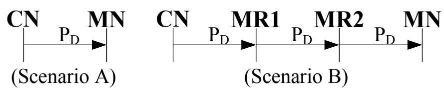


Figure 4.10: *Processes of the pure ad hoc mode for Scenarios A and B*

Processes of the standard MIP/NEMO mode used for content transfer in Scenario A and B are respectively shown in Fig. 4.11 and Fig. 4.12. The first data packet must be sent from the CN to the MN's HA that will tunnel this packet to the MN. After the first data packet is received,

P_D	Size of an original data packet sent by CN including a IPv6 header
P_S	Size of signalling packets including BU, BA, HoTI, HoT, CoTI, CoT and $P_{S(PDE)}$ (signalling between PDE entities)
t_D	Transmission delay for the first data packet from CN to MN without RO before RO is established
t_S	Transmission delay for signalling packets
H	Size of headers: H_{NEMO} (NEMO header), $H_{MIP(noRO)}$ (MIP header before RO is established), $H_{MIP(RO)}$ (MIP header after RO is established), H_{IPv6} (IPv6 header)
B	Bandwidth of links
L	Latency of links
d	Hops of communication
n	Number of data packets having been sent from CN to MN before RO is established
$E(S)$	Average session length in the number of packets
λ	Average session generation rate of CN

Table 4.2: *Parameters for Performance Analysis*

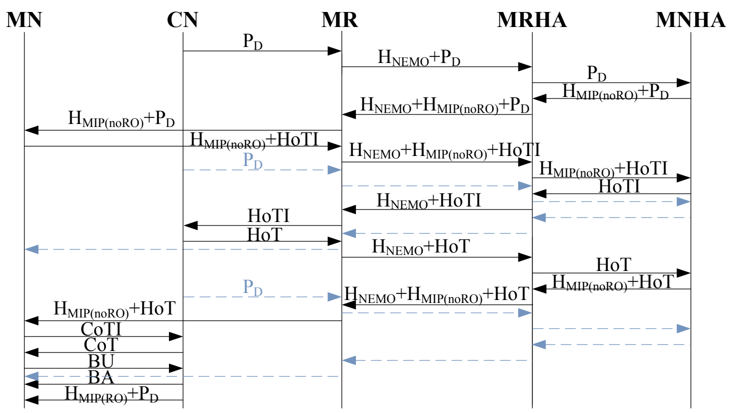


Figure 4.11: *Processes of the standard MIP/NEMO mode for Scenario A*

the MN can start RO initiation. According to the MIP protocol [1], Home Test Init (HoTI), Home Test (HoT), CoA Test Init (CoTI) and CoA Test (CoT) must be performed between this MN and its CN before BU and Binding Update Acknowledgment (BA), and HoTI and HoT must be tunneled via the MN's HA that adds $H_{MIP(noRO)}$ in these signalling packets. Before RO is established, as well as the first data packet, all subsequent data packets must be still sent to and tunneled by the MN's HA that adds a $H_{MIP(noRO)}$ into every data packet, which is shown by dotted lines in Fig. 4.11 and Fig. 4.12. After RO is established, data packets can be transferred between the CN and MN directly, which add $H_{MIP(RO)}$ onto data packets. On the other hand, according to the NEMO protocol [2], any packet transferred between inside and outside a moving network must be tunneled by its MR and this MR's HA, and thus H_{NEMO} is added to packets for tunneling.

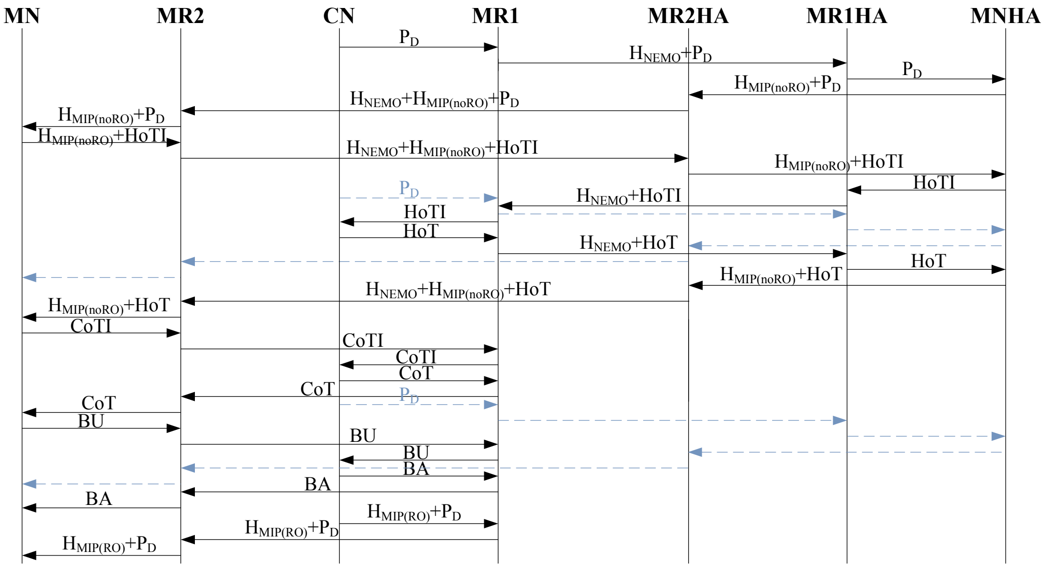


Figure 4.12: *Processes of the standard MIP/NEMO mode for Scenario B*

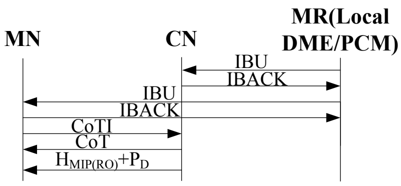


Figure 4.13: *Processes of the PDE-based scheme for Scenario A*

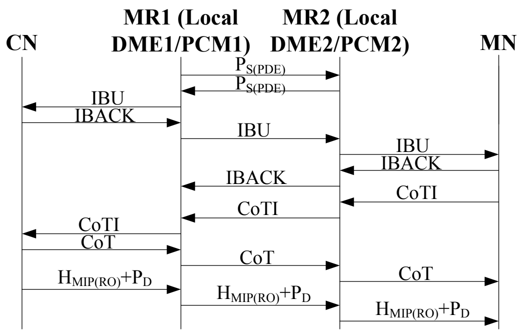


Figure 4.14: *Processes of the PDE-based scheme for Scenario B*

Processes of the PDE-based scheme used for content transfer in Scenarios A and B respectively are shown in Fig. 4.13 and Fig. 4.14. The binding cache entries of the CN and MN are established after IBUs are received which contain the MN's binding selected by the Local PCM. The CN generates a home keygen token and a home nonce index defined by the MIP protocol [1] for future BU. They are first included in the CN's IBACK sent to the Local PCM that then includes them in IBU sent to the MN. After IBU and IBACK, the MN and CN perform CoTI and CoT to generate a care-of keygen token and a care-of nonce index defined by the MIP protocol [1] also for future BU. Because RO is established by the Local DME/PCM, all data packets are transferred directly between the CN and MN, which adds $H_{MIP(RO)}$ to every data packet. The periodically updating signalling of the PDE environment is assumed to be included in the periodic MIP BU that is also used by MIP/NEMO. Therefore, the periodic BU is not considered in this section.

(A) Overhead Cost (C_{oh})

The overhead of a scheme for content transfer includes two parts: all signalling packets used by this scheme to start this transfer and headers added in data packets during this transfer. Two kinds of C_{oh} are analyzed by this model: the signalling overhead cost ($C_{oh(S)}$) and the per-data-packet overhead cost ($C_{oh(D)}$). Their cumulative value ($C_{oh(cum)}$) is also used for evaluation. In network performance evaluation, cost is calculated by the product of the number of hops and packet size [82].

(A.1) Signalling Overhead Cost ($C_{oh(S)}$)

$C_{oh(S)}$ is the cost produced by all signalling packets that are used to start content transfer, which is calculated as follows:

$$C_{oh(S)} = \sum_{k} \left(\left(P_{S(k)} + H_k \right) \cdot d_k \right) \tag{4.1}$$

where

$$H_k = H_{IPv6} + H_{MIP} + H_{NEMO} \tag{4.2}$$

$P_{S(k)}$, H_k and d_k respectively denote P_S, H and d in the k-th step of the processes where signalling packets are used. For signalling packets defined by MIP/NEMO, P_S already includes H_{IPv6} and H_{MIP}. Therefore, if P_S is not tunneled by the MN's HA, only H_{NEMO} should be considered in equation 4.2, otherwise, an extra H_{MIP} is added to the calculation.

(A.2) Per-data-packet Overhead Cost ($C_{oh(D)}$)

$C_{oh(D)}$ is the cost produced by headers in a data packet during its transfer from the CN to the

MN, which is calculated as follows.

$$C_{oh(D)} = \sum_{j} (H_j \cdot d_j) \tag{4.3}$$

H_j and d_j respectively denote H and d in the j-th step of the processes that transfer this data packet. H_j is calculated by equation 4.2.

(A.3) Cumulative Overhead Cost ($C_{oh(cum)}$)

$C_{oh(cum)}(t)$ is the average cumulative cost produced by overhead from the beginning of content transfer (0 second) to a particular time (t seconds), which is calculated as follows. It is assumed that m data packets have been sent out from the CN in the interval that is in the range $(0, t)$ s. $C_{oh(S)}(t)$ and $C^{(m)}_{oh(D)}(t)$ respectively denote $C_{oh(S)}$ and the m-th data packet's $C_{oh(D)}$ in $(0, t)$ s, which respectively use equation 4.1 and 4.3 according to the steps of content transfer processes that are performed in $(0, t)$ s.

$$C_{oh(cum)}(t) = C_{oh(S)}(t) + (m-1) \cdot C_{oh(D)} + C^{(m)}_{oh(D)}(t) \tag{4.4}$$

(B) RO Establishment

Although pure ad hoc mode can start local direct communication immediately, it is unacceptable for global mobile communication. The standard MIP/NEMO mode and the PDE-based scheme are preferred by mobile individual users, and thus compared in this sub-section. RO is vital for these two schemes because local direct communication can be initiated after RO is established. Therefore, the performance of RO establishment processes is analyzed with the following models.

(B.1) RO Establishment Delay (t_{et})

t_{et} denotes the delay for a scheme to establish RO. For the standard MIP/NEMO mode, it is the sum of t_D and t_S that are calculated as follows:

$$t_D = \sum_{j} \left(\frac{P_D + H_j}{B_j} + L_j \right) \cdot d_j \tag{4.5}$$

$$t_S = \sum_k \left(\frac{P_{S(k)} + H_k}{B_k} + L_k \right) \cdot d_k \tag{4.6}$$

B_k and L_k respectively denote B and L in the k-th step of the processes where signalling packets are used. B_j and L_j respectively denote B and L in the j-th step of the processes that transfer the first data packet. The calculation of H_k is the same as that in equation 4.1. However, because P_D already includes H_{IPv6}, only H_{MIP} and H_{NEMO} should be considered in H_j of equation 4.5 that uses equation 4.2. Therefore:

$$t_{et(MIP/NEMO)} = t_D + t_S = \sum_j \left(\frac{P_D + H_j}{B_j} + L_j \right) \cdot d_j + \sum_k \left(\frac{P_{S(k)} + H_k}{B_k} + L_k \right) \cdot d_k \tag{4.7}$$

For the PDE-based scheme, no data packet needs to be sent before RO is established, therefore:

$$t_{et(PDE)} = t_S = \sum_k \left(\frac{P_{S(k)} + H_k}{B_k} + L_k \right) \cdot d_k \tag{4.8}$$

(B.2) RO Establishment Cost (C_{et})

C_{et} denotes the average total cost produced by a scheme to establish RO. For the standard MIP/NEMO mode, it is the sum of multiple $C_{et(D)}$ and $C_{et(S)}$, which respectively denote the cost produced by one data packet and all signalling packets that are transferred before RO is established. Therefore:

$$C_{et} = n \cdot C_{et(D)} + C_{et(S)} \tag{4.9}$$

$\lambda \cdot E(S)$ can obtain the average generation rate of data packets sent from CN in numbers [83]. Therefore:

$$n = 1 + \lambda \cdot E(S) \cdot (t_D + t_S) \tag{4.10}$$

$C_{et(D)}$ and $C_{et(S)}$ are respectively calculated as follows, where H_j and H_k are calculated in the same way as those in equation 4.5 and 4.6.

$$C_{et(D)} = \sum_{j} ((P_D + H_j) \cdot d_j) \tag{4.11}$$

$$C_{et(S)} = C_{oh(S)} = \sum_{k} \left(\left(P_{S(k)} + H_k\right) \cdot d_k\right) \tag{4.12}$$

Therefore:

$$\begin{aligned} & C_{et(MIP/NEMO)} = n \cdot C_{oh(D)} + C_{oh(S)} \qquad (4.13) \\ = \quad & (1 + \lambda \cdot E(S) \cdot (t_D + t_S)) \cdot \sum_{j} ((P_D + H_j) \cdot d_j) + \sum_{k} \left(\left(P_{S(k)} + H_k\right) \cdot d_k\right) \end{aligned}$$

For the PDE-based scheme:

$$C_{et(PDE)} = C_{oh(S)} = \sum_{k} \left(\left(P_{S(k)} + H_k\right) \cdot d_k\right) \tag{4.14}$$

4.5.2 Numerical Simulation Results

4.5.2.1 Parameter Settings

Parameter	Value	Parameter	Value
P_D	0∼1400 Bytes	$H_{MIP(RO)}$	24 Bytes [1]
B (MR egress interfaces)	3 Mbps	H_{NEMO}	40 Bytes [2]
B (inside a WPAN)	50 Mbps	d (MR to MNN)	1
B (inside the IP backbone)	100 Mbps	d (MR to MR's HA)	10
L (wireless link)	2 ms	d (between HAs)	1
L (wired link)	0.5 ms	d (between MNNs)	1
$P_{S(PDE)}$	1000 Bytes	$E(S)$	20
H_{IPv6}	40 Bytes [1]	λ	2
$H_{MIP(noRO)}$	40 Bytes [1]	IBU	120 Bytes
		$IBACK$	120 Bytes

Table 4.3: *Common Parameter Settings*

Table 4.3 shows the common parameter settings used in numerical simulation, where H_{IPv6},

H_{MIP} and H_{NEMO} are defined by MIP/NEMO. P_S is different in different steps of communications according to the definition of the MIP protocol [1]. The size of different signalling messages are listed in Table 4.4.

Signalling Message	Size	Signalling Message	Size
BU (MN to CN)	96 Bytes	HoTI	56 Bytes
BA (CN to MN)	96 Bytes	HoT	64 Bytes
CoTI	56 Bytes		
CoT	64 Bytes		

Table 4.4: *Signalling messages defined by MIP/NEMO [1, 2]*

4.5.2.2 Discussion of Results

The performance analysis model was calculated for the pure ad hoc mode, the standard MIP/NEMO mode and the PDE-based scheme according to their communication processes described in Fig. 4.10, 4.11, 4.12, 4.13 and 4.14 for Scenarios A and B.

	Per-data-packet Overhead Cost ($C_{oh(D)}$)	Signalling Overhead Cost ($C_{oh(S)}$)
Pure Ad hoc Mode	40 Bytes	0
Standard MIP/NEMO Mode (before RO is established)	2240 Bytes	5752 Bytes
Standard MIP/NEMO Mode (after RO is established)	64 Bytes	0
PDE-based Scheme	64 Bytes	792 Bytes

Table 4.5: *Overhead Cost in Scenario A*

	Per-data-packet Overhead Cost ($C_{oh(D)}$)	Signalling Overhead Cost ($C_{oh(S)}$)
Pure Ad hoc Mode	120 Bytes	0
Standard MIP/NEMO Mode (before RO is established)	2240 Bytes	6376 Bytes
Standard MIP/NEMO Mode (after RO is established)	192 Bytes	0
PDE-based Scheme	192 Bytes	1656 Bytes

Table 4.6: *Overhead Cost in Scenario B*

Tables 4.5 and 4.6 list the overhead cost (C_{oh}) of these three schemes in Scenarios A and B. The pure ad hoc mode has the least C_{oh} without any signalling overhead cost because it only considers local direct communications. The standard MIP/NEMO mode (after RO is established) has a similar C_{oh} to the PDE-based scheme, but before RO is established, it has a much higher C_{oh} than the PDE-based scheme. Therefore, when local direct and global mobile communications are both considered, the PDE-based scheme has the best performance in C_{oh}.

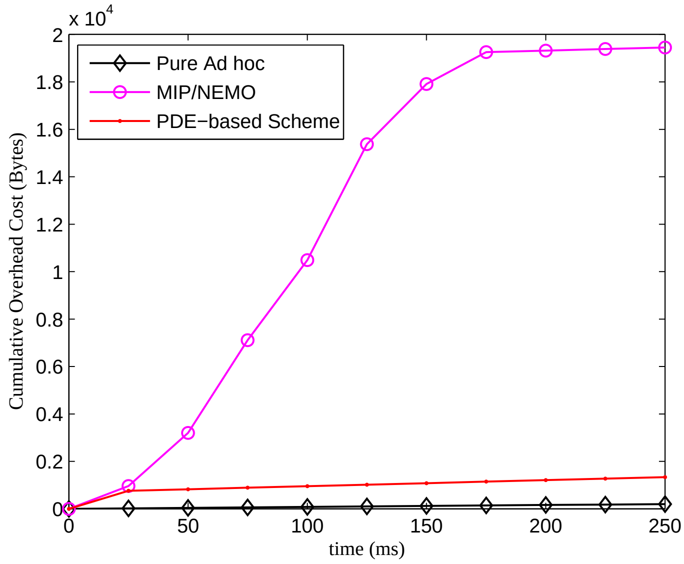


Figure 4.15: *The cumulative overhead cost for Scenario A*

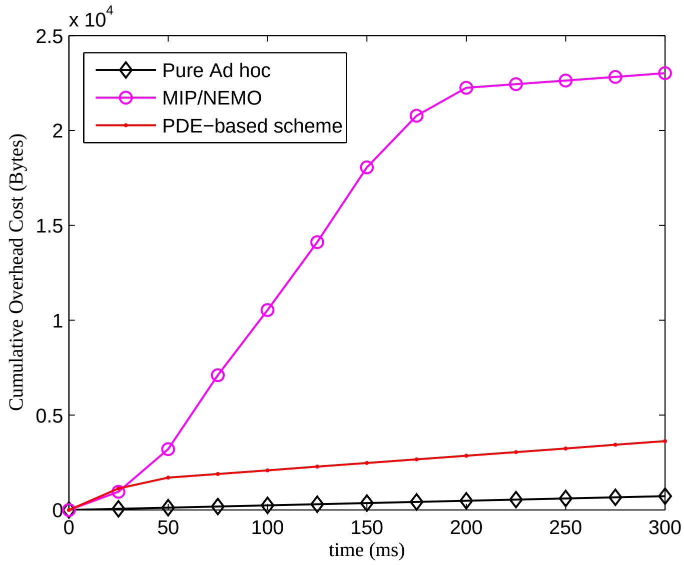


Figure 4.16: *The cumulative overhead cost for Scenario B*

The cumulative overhead cost ($C_{oh(cum)}$) for Scenario A and B is shown in Fig. 4.15 and 4.16, where P_D is set to 800 Bytes. The pure ad hoc mode still has the least $C_{oh(cum)}$ because it only has $C_{oh(D)}$ without any signalling. The PDE-based scheme has higher $C_{oh(cum)}$ than the pure ad hoc mode but much smaller than the standard MIP/NEMO mode because it needs several signalling processes to establish RO but these processes are only inside the WPAN and no data packet is sent before RO is established. The standard MIP/NEMO mode's $C_{oh(cum)}$ increases sharply because it needs to communicate with HAs in the IP backbone with lots of signalling and before RO is established, all data packets must be sent outside this WPAN and tunneled back via HAs, which significantly increases $C_{oh(cum)}$.

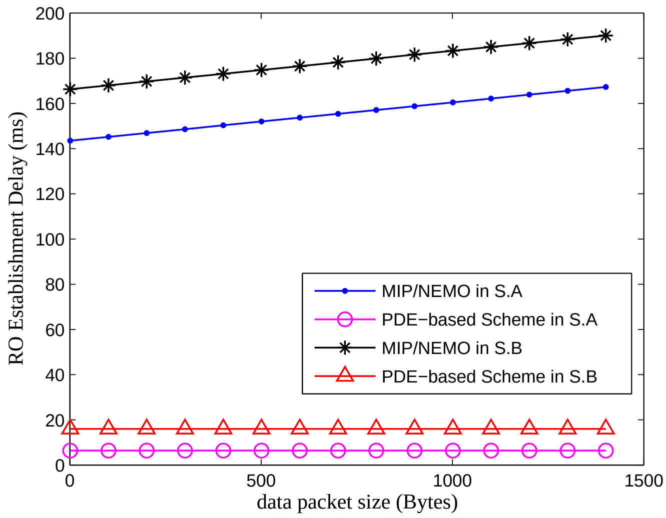


Figure 4.17: *The RO establishment delay*

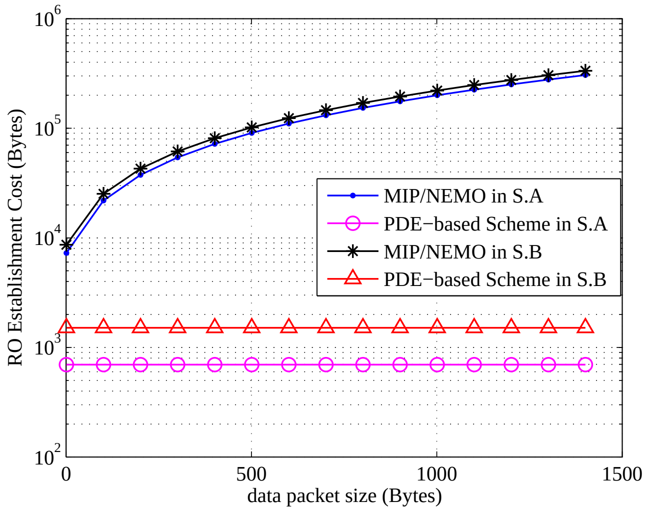


Figure 4.18: *The RO establishment cost*

Fig. 4.17 and 4.18 show the RO establishment delay (t_{et}) and RO establishment cost (C_{et}) in Scenario A and B (S.A and S.B for short in the figures) to compare the performance of RO establishment processes of the standard MIP/NEMO mode and the PDE-based scheme. t_{et} and C_{et} of the standard MIP/NEMO mode are always the largest and increase with increasing data packet size, because it has much more signalling than the PDE-based scheme and needs to transfer data packets outside and then back to this WPAN via tunnels with HAs before RO is established. t_{et} and C_{et} of the PDE-based scheme remain at a low value irrespective of the data packet size. It is true that a smaller packet size used during the RO establishment phase of MIP/NEMO can reduce delay and cost. However, this needs cross layer solutions to be implemented to control the packet size in the transport layer or extra control protocols in the network layer to generate small sized packets before large ones can be sent. The PDE-based scheme allows larger more efficient data packet sizes to be used immediately, with which the transport layer can send large packets immediately without any limitation from the network layer. Thus, in both scenarios, the PDE-based scheme has a better performance than the standard MIP/NEMO mode in RO establishment.

4.6 Experimental Evaluation

In this section, the performance of the PDE-based scheme is analyzed with experiments comparing it to the standard MIP/NEMO mode.

4.6.1 Experimental Scenarios

The technical aspects of the tested are described in detail in Appendix A. The objective of this experiment is to demonstrate the performance of these two schemes in terms of “Continuous Communications with Mobility”, “HA independency” and “MR connectivity not required”. Two experimental scenarios were used, which are respectively based on Scenarios A and B that were described in Section 4.3. One HA is used for all MRs in these experiments.

Fig. 4.19 shows Experiment Scenario A. In Case A.1, the MR does not connect to the HA, which represents this WPAN being a stand-alone moving network in an infrastructure-less environment. Case A.2 represents the MN moving out of this WPAN and every device being able to connect to the IP backbone. Content transfer starts in Case A.1, then changes to Case A.2, and finally back to Case A.1.

Fig. 4.20 shows Experiment Scenario B. In Case B.1, two MRs do not connect to the HA but

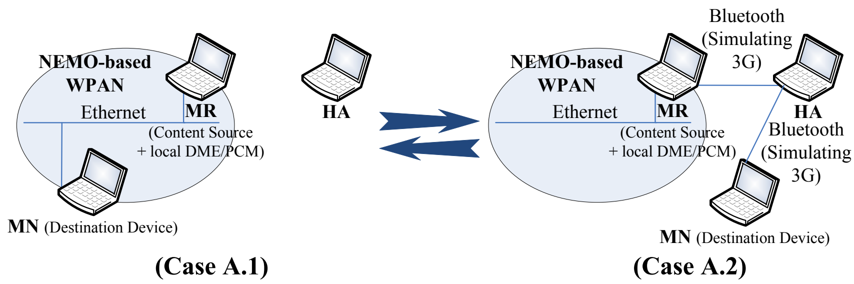


Figure 4.19: *Experiment Scenario A*

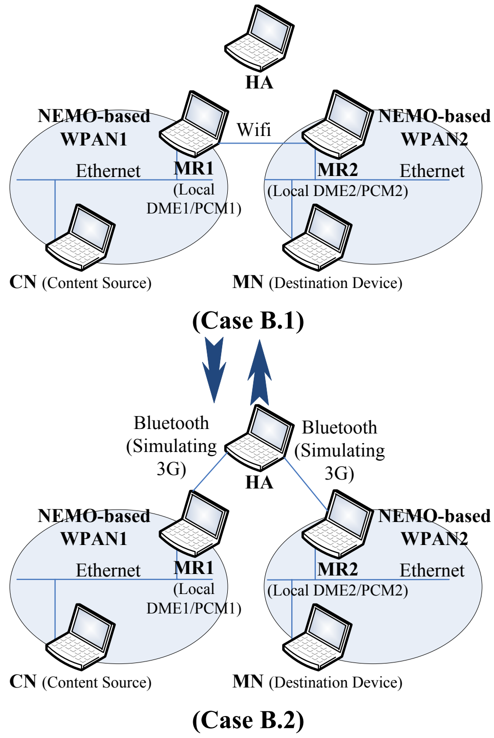


Figure 4.20: *Experiment Scenario B*

connect to each other using MANEMO, which represents these two WPANs being stand-alone moving networks in an infrastructure-less environment. Case B.2 represents these WPANs moving away from each other, with each being able to connect to the IP backbone. Content transfer starts in Case B.1, then changes to Case B.2, and finally back to Case B.1.

4.6.2 Experimental Results and Analysis

Delay of content transfer is measured by 56 Byte ICMP Echo Request packets (i.e. Ping). Bandwidth that content transfer can use is measured by TCP streams. Every experiment lasts for 100 seconds, with the changing of cases for a scenario being made at the 20th and 60th second.

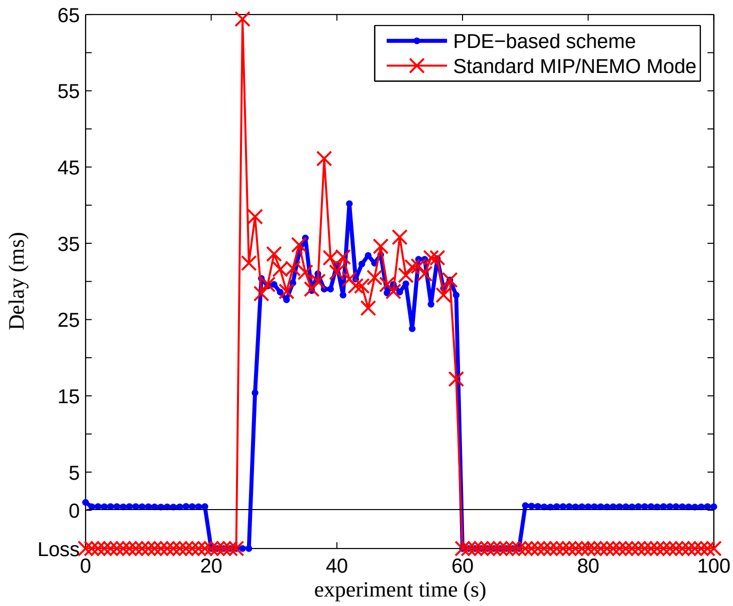


Figure 4.21: *Delay in Experiment Scenario A*

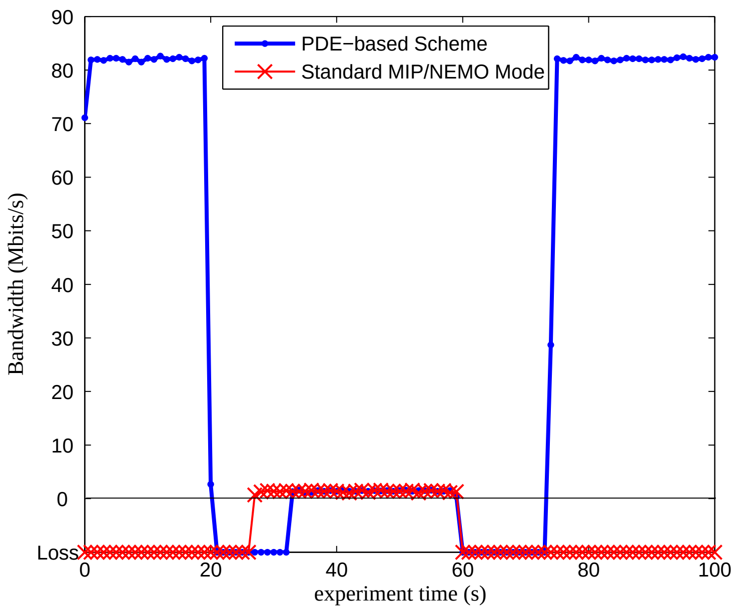


Figure 4.22: *Bandwidth in Experiment Scenario A*

Fig. 4.21 and 4.22 respectively show delay and bandwidth of these two schemes in Experiment

Scenario A. "Loss" used in these figures is a special axis to particularly represent loss of packets and differentiate it clearly from points whose values are very small. From 0 s to 20 s, no communication of the standard MIP/NEMO mode can be initiated because it requires MR's connectivity to the IP backbone and HA, but the PDE-based scheme can transfer content in such an infrastructure-less environment with low delay and high bandwidth due to local direct communications being immediately used. From 20 s to 60 s, the standard MIP/NEMO mode can start this transfer due to the connectivity to the IP backbone and HA, but it loses all packets again from 60 s to 100 s due to the infrastructure-less environment. On the other hand, the PDE-based scheme can keep this content transfer continuous after the MN moves out of this WPAN because it supports devices' mobility with global mobile communications, but with some packets lost during the handover.

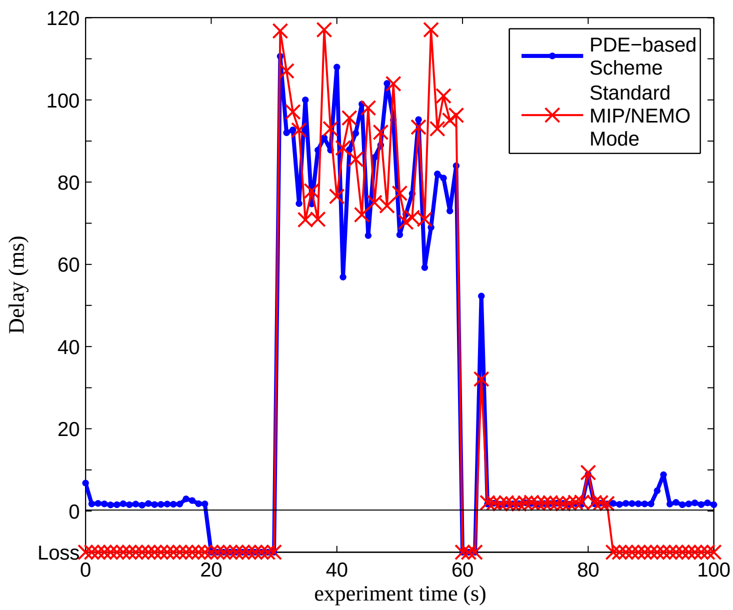


Figure 4.23: *Delay in Experiment Scenario B*

Fig. 4.23 and 4.24 respectively show delay and bandwidth of these two schemes in Experimental Scenario B. From 0 s to 20 s, no communication of the standard MIP/NEMO mode can be initiated due to the infrastructure-less environment, but the PDE-based scheme can start this content transfer immediately with local direct communications that have low delay and high bandwidth. From 60 s to 100 s, the standard MIP/NEMO mode can keep this transfer for several seconds because the MANEMO connection between these two MRs uses an ad hoc routing protocol to re-route this transfer replacing the NEMO routing, which is transparent to the CN

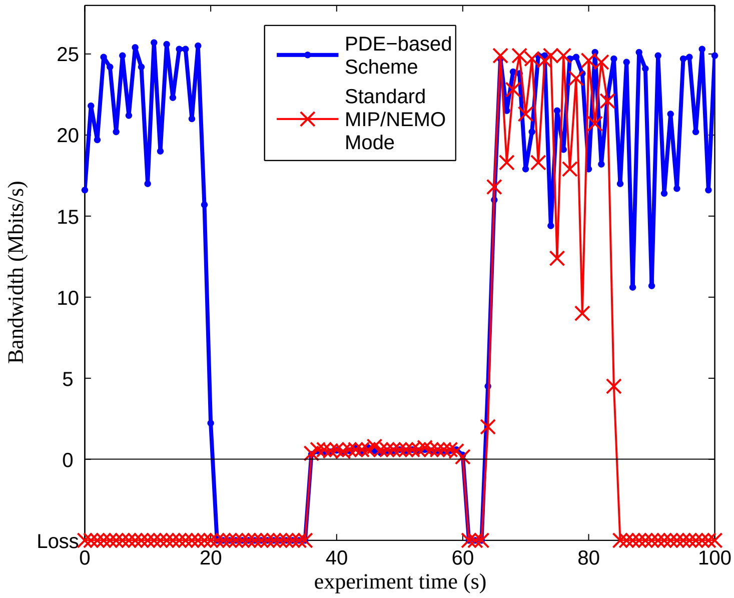


Figure 4.24: *Bandwidth in Experiment Scenario B*

and MN inside WPANs. However, after a while, when the CN, MN and MRs need to contact the HA required by MIP/NEMO, communication stops due to the infrastructure-less environment. The PDE-based scheme can keep this content transfer continuous after these two WPANs move away from each other or closer again to connect using MANEMO because it can use global mobile communications when WPANs are mobile while keeping local direct communications with the Local DME/PCM's control on binding cache entries of personal devices.

4.7 Conclusion

Local direct and global mobile communications are both often used by individual users, who are likely to be in a hybrid networking environment where infrastructure-based and infrastructure-less communications may coexist. Existing approaches, the pure ad hoc mode and the standard MIP/NEMO mode, are only suitable for one of these two kinds of communications. Therefore, a PDE-based scheme has been proposed to integrate both modes to obtain high-performance ubiquitous communications. It can start content transfer immediately with local direct communications while keeping this transfer continuous with global mobile communications, and thus combine advantages from both of them.

Extended functions of the DME and detailed signalling procedures of the scheme were also proposed in this chapter to implement two scenarios: intra-WPAN and inter-WPANs communications. Performance analysis models show that the PDE-based scheme has low delay and cost compared to existing approaches. Also, networking experiments demonstrate that the PDE-based scheme is better than others in terms of "Continuous Communications with Mobility", "HA independency" and "MR connectivity not required". Therefore, this scheme can support ubiquitous communications when WPANs' networking environment exchanges between infrastructure-less and infrastructure-based networks, where existing approaches can not work properly.

The proposed PDE-based scheme is particularly suitable for individual users. In real life, they often move into places where no wireless signal from access networks can be received, e.g. tube or basement, or they often prefer to only use short-range wireless technologies to directly transfer content from sources in close vicinity to them. Therefore, individual users may often need WPANs to work in such an infrastructure-less environment, i.e. stand-alone WPANs, and mobility support is also required by them. These requirements can all be implemented by the proposed scheme but can not supported by existing approaches.

Chapter 5
Ubiquitous Communications: Multiple Dynamically Changing MRs in a WPAN

Chapter 4 discusses the establishment of ubiquitous communications with WPANs. In this chapter, another problem is analyzed: how to keep these ongoing communications continuous in a WPAN with multiple dynamically changing MRs. A PDE-based scheme is proposed in this chapter.

5.1 Introduction

In a NEMO-based WPAN, many personal devices may be capable of working as a MR, e.g. a laptop, a mobile phone or a PDA. They may work as normal nodes (MNN) in this WPAN and only communicate via the current MR, or they may startup their own MR function, using necessary software and hardware to work as the MR for this WPAN, relaying communications for other MNNs. Normally, there is not a fixed MR in a WPAN, and the MR may be selected from all MR-capable personal devices, according to different access network coverage, device conditions, application types and user requirements. Thus, personal devices may dynamically change their roles between a MNN and a MR in this WPAN, according to decisions based on the desired requirements. This kind of MR is called a "dynamically changing MR" in this thesis. A scheme is needed to control the switch of roles of these personal devices.

When the MR of a WPAN changes, according to the NEMO protocol [2], the new MR device requests a MNP from its HA to start to work as the MR for this WPAN. A new MNP is generated or allocated by its HA. This leads to address changes, re-homing and ingress filtering problems for MNNs in this WPAN [33]. Generally, a MNN can be a Local Fixed Node (LFN) or a Visiting Mobile Node (VMN). A LFN has a fixed address generated from the MNP of this WPAN and will not move out of the WPAN. A VMN is a mobile node that supports Mobile IP (MIP) and can move into and leave the WPAN. When the MR changes, a LFN's address also changes due to the change of the MNP, which leads to ongoing communications between this LFN and sender nodes being interrupted. For a VMN, although it can theoretically send Binding Updates (BUs) to Correspondent Nodes (CNs) (if these sender nodes also support MIP) to update its new Care-of Address (CoA) that is generated from the new MNP, the CoA re-addressing, BU and re-tunneling process increase signalling, delay, cost and packet loss. The NEMO protocol does not explicitly consider dynamic MR changes, and thus can not solve these problems. A scheme to handle multiple dynamically changing MRs in a WPAN is needed.

The aim of this research is to propose a cooperation and management scheme for dynamic changes of multiple MRs and flexible switches of personal devices' roles in a WPAN. It provides a unique and unchanged MNP for a WPAN no matter how these dynamically changing MRs alter, so as to keep changes of MRs transparent to MNNs in this WPAN and their CNs.

The rest of this chapter is structured as follows. Section 5.2 analyzes related research and discusses relevant issues. Mechanisms for addressing and MR role management are respectively proposed in Section 5.3 and 5.4. In Section 5.5, a PDE-based scheme for multiple dynamically changing MRs are proposed considering two scenarios. The performance of proposed schemes is evaluated in Section 5.6.

5.2 Related Work and Research Issues Discussion

5.2.1 Wireless Vehicle Network (WVN) and WPAN

The NEMO protocol [2] assumes that a fixed MR is already placed in a moving network when this moving network is initialized in the Home Network and a MNP is pre-allocated as well in this Home Network. Thus, NEMO is suitable for WVN, where fixed MRs can be installed. Most projects using NEMO focus on scenarios of cars, coaches and planes, e.g. C2CCC [52], IMARA [84] and WIDE [85]. However, WPANs have a heterogeneous environment that is different from WVNs. Normally there is not a fixed MR in a WPAN and the MR may be selected from all MR-capable personal devices. Also, these personal devices may be dynamically changing MRs and can join or leave this WPAN at any time. A later IETF document [45] is the only one that explores scenarios of NEMO from a WPAN aspect and proposes research requirements, which differ from those used in current research focusing on a WVN. Therefore, although the NEMO Working Group [24] already includes both WVNs and WPANs as its practical deployment scenarios, current research about NEMO mainly considers WVNs and few studies have been done from a WPAN aspect. Furthermore, methods already proposed by these researchers are not suitable for WPANs because the environment and requirements are different.

5.2.2 MNP ownership

Current research on NEMO considers that the MNP of a moving network is owned by the MR of this moving network and the MR's HA [86]. This is because they all use an original assumption from the NEMO protocol [2]. The NEMO protocol assumes that a MR is fixed in a NEMO network and a MNP is pre-configured when this NEMO network is formed. From this aspect, since a MR is fixed and does not change in a NEMO network, it can represent this NEMO network, and thus the MNP owned by this MR or its HA can also represent this NEMO network. For example, a car network's MNP is owned by a fixed MR installed in this car and this MR's HA. This point of view about the MNP ownership has drawbacks that are discussed in the following sections.

5.2.3 Multiple MRs/Single MNP

"Multiple MRs" is a general research topic proposed by the NEMO working group [33]: multiple MRs are located in the same moving network and MR synchronization solutions should be used. One of the models proposed by [33] is "Multiple MRs/Single MNP", which assumes that these multiple MRs advertise a single MNP in this NEMO network. This model is used by most current research on "Multiple MRs". This is because with the same MNP, the MNNs' addresses will not change when the MR changes and thus ongoing communications can be kept continuous. This IETF document [33] only proposes general research topics and requirements and gives no solutions. Therefore, management schemes need to be designed to control the multiple MRs and keep the same MNP. The schemes proposed in current research on "Multiple MRs/Single MNP" can be divided into two types: "HA aspect" and "MR aspect", which accord with their points of view about the MNP ownership.

5.2.3.1 HA aspect

This type of scheme considers that the MNP is owned by the HA. Two methods are used: "Single HA" and "HA Synchronization".

Single HA: In this method, only one HA is used for all MRs, e.g. [87, 88]. "Single HA" is not suitable for a WPAN because in practice, different personal devices may have their own separate HAs. Requiring only one HA is a serious limitation for deployment of WPANs in real life.

HA Synchronization: In this method, each MR can have its own separate HA. These HAs must negotiate with each other to allocate a single MNP for multiple MRs. Few thorough studies have been done on this method but a basic approach has been suggested [89]. This allows a Mobile Node (MN) to use multiple HAs simultaneously, picking one as the primary HA, for the purpose of HA redundancy and load balancing. This approach, however, is not suitable for a WPAN because it only considers a MIP scenario and a single MN, not a NEMO scenario. When multiple MRs are used in a NEMO network, this approach's drawbacks are more serious.

If the approach in [89] is used for "Multiple MRs", a primary problem is that HAs will not be aware of each other because they are owned by different MRs not a single MN. A possible solution could be that each MR registers with every other MR's HA. However, if there are many MRs, much signalling will be required. In addition, this method will make the protocols complicated because each MR has to work not only with its own HA but also with every other MR's HA.

5.2.3.2 MR aspect

This type of scheme considers that the MNP is owned by the MR. Two methods are used: "Master/Slave MR Synchronization" and "Nested NEMO".

Master/Slave MR Synchronization: In this method, a master/slave mode for multiple MRs is adopted [88, 90–92]. Different names for Master/Slave MRs are used by researchers. They select a first MR as the Master MR (also named as the Owner/Primary/Former/Root MR), and a second MR as the Slave MR (also named as the Borrower/Peer/Neigbour MR). The Master MR owns and maintains the MNP for this NEMO network, and the Slave MR requests use of this MNP from the Master MR. In this way, the Master MR's MNP can be used by other MRs, and thus it can be considered as a single MNP for this WPAN.

Two ways are used to let Slave MRs obtain and use this MNP. The first [88] adopts a single HA for all MRs, but this is not suitable for WPANs as discussed above. The second [90–92] can support each MR having its own separate HA, but requires that Slave MRs must first register to and establish a tunnel with the Master MR's HA. This registration must be triggered or authorized by the Master MR. The Master MR's HA can then authorize Slave MRs to use the Master MR's MNP. During communications, Slave MRs must use the tunnel connected to the Master MR's HA to use this MNP. However, if the Master MR fails or disconnects before Slave MRs finish the registration, or the Master MR's HA fails or can not be connected to by Slave MRs during communications, or the Master MR can not refresh the MNP with its HA so that its binding times out, or the Master MR leaves this NEMO network, the Master MR's MNP can not be used by any other MR because this MNP is only owned by the Master MR not by any other MR, and thus the MNP must be changed in this NEMO network. Because most current research [90–92] is based on WVNs, fixed MRs in a WVN are less likely to fail or lose the wireless signal, e.g. high-power fixed routers installed in a car. However, in a WPAN, individual personal devices, e.g. a mobile phone, are more likely to lose signal and may leave the WPAN entirely. Therefore, MRs in a WPAN are much more likely to fail than fixed MRs in a WVN, and thus this method is not suitable for a WPAN.

Nested NEMO: Other researchers [87, 93] adopt Nested NEMO which has been discussed in Chapters 2 and 4. When a new MR is used in a Nested NEMO network, the MNNs still connect to their original MR which is still working as a MR with the same MNP. This original MR connects to the new MR and becomes a subordinate MR to this new MR, which forms a Nested NEMO network. In this way, MNNs connected to their original MR can keep addresses unchanged, but incoming communications must go through both the new MR and the original MR. Nested NEMO involves more encapsulated tunnels, and thus has a high overhead in signalling and delay. Furthermore, if more new MRs are used, the level of encapsulation in a Nested NEMO network also increases, which will seriously increase the signalling and delay overheads.

5.2.4 Summary

The "Multiple MRs/Single MNP" [33] is the most useful model to solve problems with "Multiple MRs", and thus it is adopted by most current research in this area. However, current research is mostly based on a WVN scenario, where fixed MRs are installed. The MNP is considered to be owned by the MR or its HA. This approach is not suitable for a WPAN, where personal devices are dynamically changing and where MRs are unlikely to be fixed. Therefore, these schemes are not suitable for a WPAN scenario. Thus a novel approach which regards the MNP as being owned by a particular WPAN (as represented by its Local DME) is proposed in this thesis. A PDE-based scheme to manage dynamically changing MRs is also proposed. This focuses on the two research issues: "Addressing Mechanisms" and "MR Role Management".

5.3 Addressing Mechanisms

This thesis adopts the "Multiple MRs/Single MNP" [33] model. Thus the communications of LFNs and VMNs located in a WPAN can be kept continuous, and additional processes, e.g. rehoming and BU, can be avoided. The proposed scheme allows each personal device in a WPAN to have its own separate HA. It is assumed that these HAs are all in the same Home Network because these personal devices belong to one individual user. The first research issue which arises is: ***In a WPAN, when different MR-capable devices register to their corresponding HAs to start to work as MRs for this WPAN, how can their corresponding HAs reply with the same MNP?*** An addressing mechanism for MNP initiation, acquisition and maintenance in different cases are now proposed.

5.3.1 Unique Mobile Network Prefix (UMNP) and Domain ID (DID)

As discussed above, if the MNP is owned by the MR or its HA all Slave MRs must register and connect to the Master MR's HA. However, logically, a certain MNP could be considered to be owned by a particular WPAN but not specifically by any personal device in this WPAN. In PDE based system implementations a logical entity - the Local DME - is located in every WPAN so can specifically represent this WPAN. Thus a certain MNP for a particular WPAN can be considered to be owned by the Local DME of this WPAN.

The novel concept of a Unique Mobile Network Prefix (UMNP) is proposed in this thesis. A UMNP is an unchanging MNP owned by a WPAN. It is only held by this WPAN and its Local DME, and will not be affected by any change of personal devices in this WPAN. Another novel concept, a Domain ID (DID) is also proposed. The DID is used to identify different WPANs of an individual user and also to identify their corresponding UMNPs. An encryption key and security information are attached to the DID. In the same way as the UMNP, a certain DID for a particular WPAN is owned by the Local DME of this WPAN. The security part in the DID will be updated during the DID and UMNP's usage, maintaining and refreshing, e.g. when the MR refreshes the UMNP and DID with the Root DME, or when the MR changes to another personal device.

Although the UMNP and the DID are owned by their corresponding Local DME, they are generated by the Root DME and given to the Local DME when this WPAN is established. A mapping table of DIDs and UMNPs is maintained in the Root DME. Therefore, by using a WPAN's DID, its UMNP can be checked out from this mapping table by the Root DME.

The lifetime of a DID is used in a way similar to a binding cache in MIP. According to the lifetime, the Root DME and Local DME periodically refresh the DID and update its associated encryption key. In this way, a MR capable device that leaves the WPAN can not indefinitely hold the latest correct DID and its security information.

5.3.2 Use cases for UMNP and DID

Five cases are discussed in this section to explain how the UMNP and the DID work. Cases A and B discuss initiation of the UMNP and the DID. Case C aims to maintain and refresh the DID when a WPAN disconnects from access networks. Case D and E present how to acquire the UMNP and maintain the DID when MRs change.

Case A: UMNP and DID initiation in an infrastructure-based environment

Description: A WPAN and its Local DME is established for the first time, and can connect to access networks via infrastructure-based technologies (e.g. UMTS or WiFi). Its UMNP and DID need to be initiated.

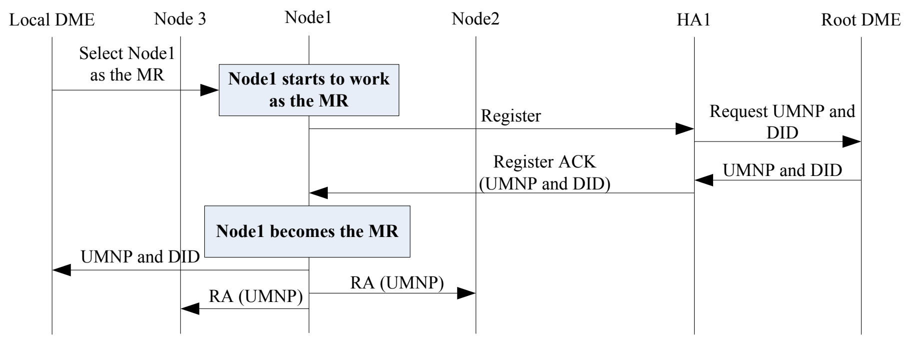


Figure 5.1: *Case A: UMNP and DID initiation in an infrastructure-based environment*

Case A is a basic use case in an infrastructure-based environment. The Local DME selects one personal device to work as the MR. This device registers to its HA for being a MR. Then, its HA requests the Root DME to apply for a UMNP and a DID. Because this WPAN is just established, there is not any information for it stored in the Root DME. The Root DME allocates a MNP for this WPAN as its UMNP, and generates a corresponding DID for this UMNP. This UMNP and DID pair is stored in the mapping table of the Root DME. The Root DME replies with the UMNP and the DID to the HA, and then the HA replies with them to the personal device working as the MR. The UMNP and the DID are now transferred to the Local DME of this WPAN. Finally, the MR advertises the UMNP in the WPAN. Every personal device in this WPAN can now generate a CoA according to this UMNP. The procedure is shown in Fig. 5.1, where three nodes in a WPAN are used as an example, and HA1 is Node1's HA. "RA" in the figure means the router advertisement.

Case B: UMNP and DID initiation in an infrastructure-less environment

Description: A WPAN and its Local DME is established for the first time, and it can not connect to access networks (i.e. it is a stand-alone WPAN in an infrastructure-less environment). However, after a while, this WPAN can connect to access networks (i.e. it gets into an infrastructure-based environment). Its UMNP and DID need to be initiated.

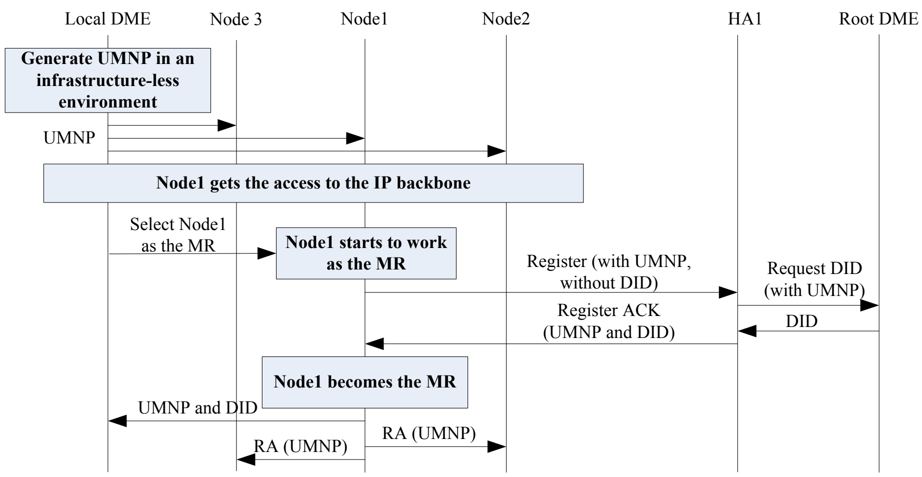


Figure 5.2: *Case B: UMNP and DID initiation in an infrastructure-less environment*

An individual user may often move into places where no wireless signal from access networks can be received, such as a basement or lift. Case B describes a stand-alone WPAN established in such a situation. However, after a while, this user may leave the basement or lift taking the WPAN. This WPAN needs to communicate with the IP backbone when it can receive wireless signal of access networks. Such an environment change is also included in Case B.

It is proposed that a pool of IP address prefixes for an individual user's WPANs is pre-allocated by their Root DME. This pool is a range of MNPs that can be used as UMNPs for WPANs. Notice that these MNPs have the same address prefix because they belong to the same home network for one individual user. This MNP pool is also pre-stored in every personal device of this individual user, in the same way as its pre-allocated Home Address (HoA).

When a WPAN is established in an infrastructure-less environment, it allocates a UMNP by itself. Its Local DME selects a UMNP from the MNP pool randomly. Because these MNPs have a same prefix, the Local DME only needs to select the subfix of the UMNP. For example, if the prefix of UMNPs in the pool is a:b:c::/48 and the subfix is from 1 to 255. If the Local DME randomly selects 1 as subfix, a:b:c:1::/64 becomes the UMNP for this WPAN. However, there is a problem that different WPANs of one individual user may select the same UMNP. The possibility of such overlapping UMNPs can be calculated. In practice, one individual user will not possess many WPANs. If the total number of separate WPANs owned by a user is 5 and the subfix is from 1 to 255, the probability that "every WPAN has a different UMNP" is 0.96, which means that overlapping seldom happens. Furthermore, this probability can be increased by enlarging the range of subfixes.

However, this self-allocated UMNP has not been authorized by the Root DME, and thus there is no DID for this WPAN. When infrastructure-based communications become available to this WPAN, the Local DME/PCM selects one personal device to work as the MR for this WPAN and to send the UMNP to the HA for registration. This personal device's HA sends the UMNP to the Root DME for authorization. The Root DME checks the MNP pool to see whether this UMNP has been used. If has not, and so is available, the Root DME generates a corresponding DID for this UMNP and replies with them to the HA which then sends them to this personal device and the Local DME. At the same time, this UMNP and DID pair is stored in the mapping table by the Root DME. If the requested UMNP is not available, the Root DME replies with an error message and allocates a new UMNP and DID pair (this means that nodes inside this WPAN have to change their CoAs according to the new MNP but this is unlikely to happen as discussed above). The procedure is shown in Fig. 5.2 where HA1 is Node1's HA.

Case C: UMNP and DID maintenance in an infrastructure-less environment

Description: After the UMNP and the DID are held by the Local DME (i.e. after Case A), the

WPAN disconnects from all access networks (i.e. in an infrastructure-less environment). After some time, this WPAN re-connects to an access network (i.e. it gets into an infrastructure-based environment). Its UMNP and DID need to be maintained and refreshed.

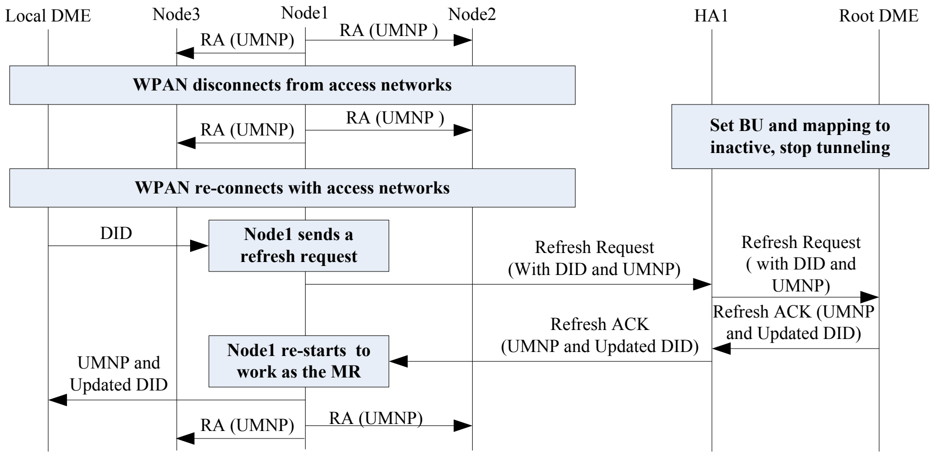


Figure 5.3: *Case C: UMNP and DID maintenance in an infrastructure-less environment*

An individual user may often spend some time with the WPAN in places without any wireless signal, e.g. they may enter a basement and stay there for one hour. If a WPAN disconnects from all access networks and the lifetime of its UMNP's binding expires, its corresponding UMNP-DID-mapping in the Root DME and its MR's Binding Cache Entry (BCE) in the HA will be deleted according to the MIP standard. A pre-set "Inactive Time" is proposed for this type of situation. When the lifetime of a UMNP's binding expires, the HA and the Root DME set the BCE and mapping to inactive and keep them for the duration of this inactive time. The HA stops intercepting and tunneling data packets to this WPAN's MR. At the same time, this WPAN becomes a stand-alone WPAN and its Local DME continues using the same UMNP. Generally, the inactive time will be much longer than the lifetime of a binding, e.g. 24 hours. When this WPAN re-connects to access networks, there are two possibilities.

- If its binding's lifetime has expired but its inactive time has not, this WPAN needs to refresh its UMNP and DID. After receiving a refresh request from this WPAN, the HA and Root DME set the corresponding BCE and mapping to active, and the HA begins to intercept and tunnel data packets to this WPAN's MR. The same UMNP is kept for use in this WPAN, and the DID's security part is updated (which is named as "Updated DID" shown in Fig. 5.3).

  If the CoA of this WPAN's MR changes (due to changes of wireless interfaces for different access networks) when re-connection occurs, the MR includes its new CoA in refresh request messages the same as the process of BU in MIP.

- If the duration of disconnection is greater than the inactive time, this WPAN's corresponding BCE and mapping will be deleted by the HA and Root DME. When this WPAN re-connects to an access network, it has to apply for a new UMNP and DID.

The procedure is shown in Fig. 5.3 where at the beginning, Node1 is working as the MR for this WPAN, and HA1 is Node1's HA.

Case D: UMNP and DID maintenance when the MR changes

Description: After the UMNP and the DID are held by the Local DME (i.e. after Case A), another personal device in this WPAN begins to work as the MR. This WPAN's UMNP needs to be kept unchanged.

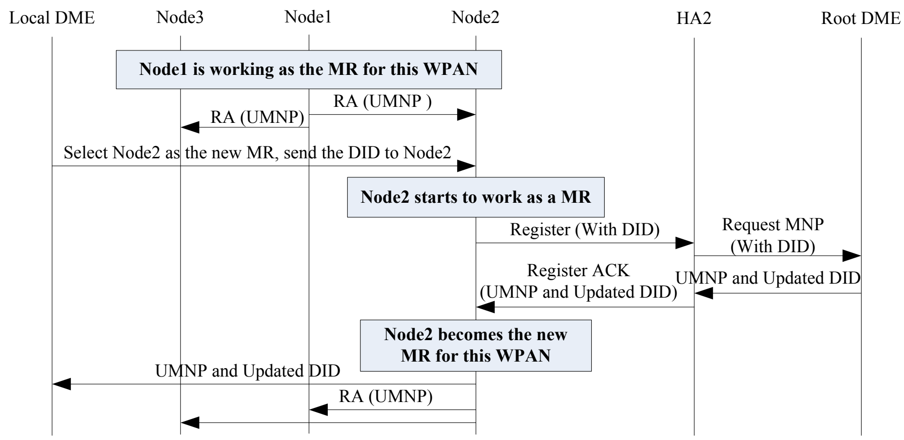


Figure 5.4: *Case D: UMNP and DID maintenance when the MR changes*

A MR change may often happen in a WPAN due to its heterogeneous and dynamic environment. When the Local DME/PCM of a WPAN selects another personal device to register to its HA for becoming a new MR, the Local DME firstly sends the DID to this personal device which then includes the DID in register messages sent to its HA. Its HA requests a MNP from the Root DME using this DID. If the DID can pass the security check, the Root DME checks its mapping table and replies with the corresponding UMNP to the HA. Also, this DID's security part is updated (i.e. an "Updated DID") by the Root DME and sent to the HA as well. The HA replies with a register acknowledgement (ACK) to this personal device including this UMNP and its updated DID. After receiving this register ACK, the personal device becomes the MR and starts to advertise the UMNP to other nodes in this WPAN. The updated DID is also stored by the Local DME. The procedure is shown in Fig. 5.4 where at the beginning, Node1 is working as the MR for this WPAN, and HA2 is Node2's HA.

With the proposed scheme, the different HAs of different MRs can get the same UMNP from the Root DME when they use the same DID which can show that these MRs are in the same WPAN. Any change or failure of MRs and HAs will not influence the UMNP since it is only decided by the Root DME. Any MR's HA needn't be aware of other MRs' HAs, and it only needs to know the address of the Root DME.

Case E: UMNP and DID maintenance when the MR changes and the WPAN re-connects to access networks

Description: After the UMNP and the DID are held by the Local DME (i.e. after Case A), this WPAN disconnects from access networks but re-connects after a while using another personal device as the MR. This WPAN's UMNP needs to be kept unchanged.

Case E is a combination of Case C and D. Its UMNP acquisition and DID refresh is as same as those in Case D. The only difference is that in Case E, the MNP request message from the HA of the new MR to the Root DME is also a DID refresh message that can set the corresponding UMNP-DID-mapping in the Root DME from inactive to active.

5.3.3 Summary

Based on these five cases, signalling messages with different formats of the UMNP and the DID are used in different cases. The Root DME and the HA perform different interactions according to these different signalling messages as shown in Fig. 5.5.

The proposed addressing scheme can provide security support. Although the UMNP is advertised in a WPAN, its DID is held only by the Local DME of this WPAN. The Local DME only gives the DID to the personal device selected to be the new MR. In addition, the DID's security part is updated periodically and changed when the MR changes. Therefore, if a personal device that previously worked as the MR leaves this WPAN, the DID that it holds will expire, and thus it can not apply for using the UMNP of this WPAN.

Some characteristics of the proposed addressing scheme are summarized as follows.

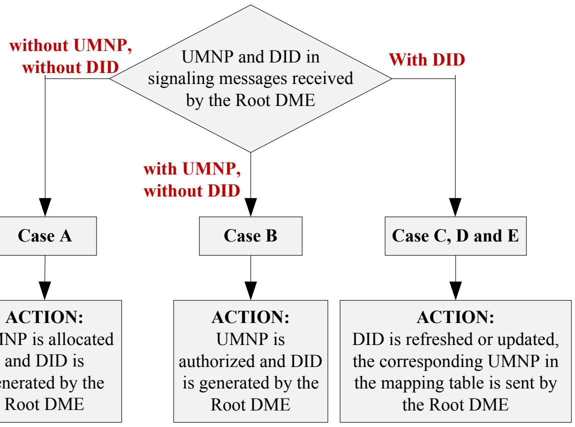


Figure 5.5: *Different interactions of the Root DME and the HA of the MR*

- The UMNP is owned by the Local DME, but is advertised in the WPAN, so every personal device in this WPAN can get the UMNP to generate their addresses.
- Registration, acquisition and maintaining of the UMNP is controlled by the Local DME using the DID, so the Local DME's ownership of the UMNP is embodied by the use of the DID.
- The proposed addressing scheme has advantages compared to related research. Firstly, it can directly support multiple MRs and HAs and each MR can have its own separate HA. In addition, HAs of different MRs do not need cooperation and thus no specific action or mechanism is needed among these HAs. Only communication between the Root DME and the HA is needed, which is easier to implement. Finally, each MR need not register to any other MR's HA. Each MR only works with its own HA, which makes processes of communications and signalling simple and compact.

5.4 MR Role Management

"Dynamically changing MRs" is one of the most important characteristics for WPANs as distinct from WVNs. This section concentrates on the research issue: *In a WPAN, how can a personal device dynamically change its role between a MR and a MNN?* A mechanism is proposed in this section to manage the role change of MR-capable personal devices in a WPAN. This issue is discussed in an IETF document [45] as one of the research scenarios for WPANs but few studies have been done on this and no solution has been proposed.

5.4.1 State and Binding of MRs

It is proposed that every MR-capable personal device in a WPAN has three states: MNN state, MR state and Mobile Host (MH) state.

MNN state: The personal device only works as a MNN - it only uses its short-range interface (e.g. Bluetooth) to communicate with the MR in the WPAN.

MR state: The personal device works as a MR in the WPAN - it uses its ingress (e.g. Bluetooth) and egress (e.g. UMTS) interfaces according to the NEMO protocol [2].

MH state: The personal device is an independent mobile node that does not belong to or has moved out of a WPAN.

The NEMO protocol [2] only defines a change from the MH state to the MR state. This is because it only considers fixed MRs that are pre-configured and pre-allocated for moving networks, and does not consider any role change from a MR to a MNN. Therefore, the BU is only designed for changes from the MH state to the MR state.

The three device states have different BCEs maintained in the HA, shown in Table 5.1. CoA(MH) denotes the personal device address obtained from its infrastructure-based interface (e.g. WiFi) when it is in the MH state. CoA(MNN) denotes its address generated from the MNP in a WPAN with its short-range interface (e.g. Bluetooth) when it is inside this WPAN. CoA(MR) denotes the address obtained from routers in its access network with its egress interface (e.g. WiFi or UMTS) when it is working as a MR.

State	Binding
MH	HoA : CoA(MH)
MNN	HoA : CoA(MNN)
MR	HoA : MNP : CoA(MR)

Table 5.1: *Bindings of different states*

5.4.2 State Change

The NEMO protocol [2] defines that changing the binding from the MH or the MNN to the MR state sets Flag (R) in the BU. However, changing the binding from the MR to the MH or the MNN state can use the traditional BU without Flag (R) according to the MIP protocol [1].

The detailed operations of state changes are proposed as follows, which is based on the MIP protocol [1] and the NEMO protocol [2].

Actions of a personal device for the change from the MNN to the MR state include: ***(1.1)*** the egress interface is set to active from standby state; ***(1.2)*** register to its HA as a MR using the egress interface (send a BU including the DID, the HoA, CoA(MR) and Flag (R) with "Implicit Mode" defined by the NEMO protocol); ***(1.3)*** get the register ACK, the UMNP and the updated DID from its HA and the Root DME; ***(1.4)*** the bi-directional tunnel is established; ***(1.5)*** send the RA to advertise the UMNP in the WPAN using the ingress interface; ***(1.6)*** the ingress and the egress interfaces begin to work according to the NEMO protocol.

Actions of a personal device for the change from the MR to the MNN state include: ***(2.1)*** stop sending the RA in the WPAN; ***(2.2)*** send a BU to its HA with the HoA and CoA(MNN) but without Flag (R); ***(2.3)*** get the BU ACK from its HA; ***(2.4)*** the bi-directional tunnel is removed; ***(2.5)*** the egress interface is set to standby from active state, and the ingress interface begins to communicate with another personal device that is working as the MR.

Actions of a personal device for the exchange between the MNN and the MH state include: ***(3.1)*** clear the DID (if the personal device has it) and the UMNP when the RA is not received or the lifetime expires for the change from the MNN to the MH state, or obtain the UMNP when the RA of a WPAN is received for the change from the MH to the MNN state; ***(3.2)*** send a BU to its HA with the HoA and CoA(MH) (or CoA(MNN)); ***(3.3)*** get the BU ACK from its HA.

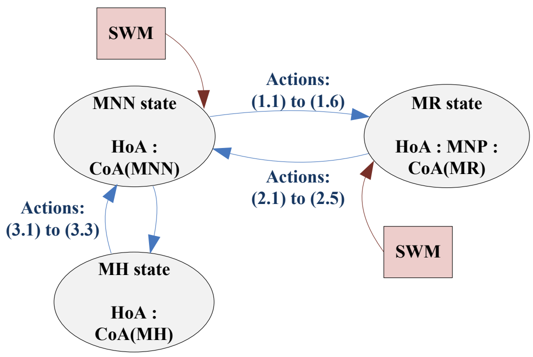


Figure 5.6: *Changes of the states*

Fig. 5.6 shows these changes of states. The exchange between the MNN and the MR state is triggered by a proposed State Switch Message (SWM) sent from the Local DME/PCM. The Local DME/PCM makes a decision on MR selection and sends the SWM to the personal device currently working as the MR and the one that will work as the new MR. On receiving the SWM, the personal devices switch their current state to the desired state. Therefore, it is proposed that the MR change in a WPAN is controlled by the Local DME/PCM by using this SWM.

It is also proposed that a personal device which moves out of a WPAN can only switch from the MNN to the MH state. If this personal device is currently in the MR state, the Local DME will first change it to the MNN state and select another personal device as the new MR. This may be because during movement, its ingress interface's wireless signal becomes weak, so the MR for this WPAN should be changed. Then, if it continues moving until the wireless signal of this WPAN can not be received, this personal device changes to the MH state.

5.5 A PDE-based Scheme for Multiple Dynamically Changing MRs

Based on the mechanisms proposed in Sections 5.3 and 5.4, a PDE-based scheme for multiple dynamically changing MRs is now proposed.

5.5.1 Scenario Description

Two scenarios are researched in this thesis: "The MR Changes in a WPAN" and "a WPAN and a WVN merge".

- **Scenario 1: The MR Changes in a WPAN**

  When device and network conditions vary or application and user requirements alter, the MR of a WPAN may be changed from the personal device currently working as the MR to another MR-capable device, according to decisions and commands from the Local DME/PCM. Every MR-capable personal device can dynamically change its role between a MR and a MNN in this WPAN. During and after these changes, ongoing communications need to be kept continuous. This is shown in Fig. 5.7.

- **Scenario 2: A WPAN and a WVN merge**

  An individual user may take a WPAN into a car that already has a WVN. This WPAN and the WVN can merge to form a new WPAN (or a new WVN from another point of view). During and after the merging, ongoing communications need to be kept continuous. This is shown in Fig. 5.8.

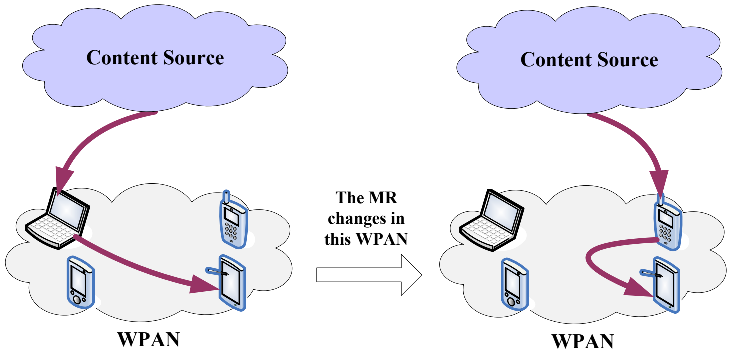


Figure 5.7: *Scenario 1: The MR Changes in a WPAN*

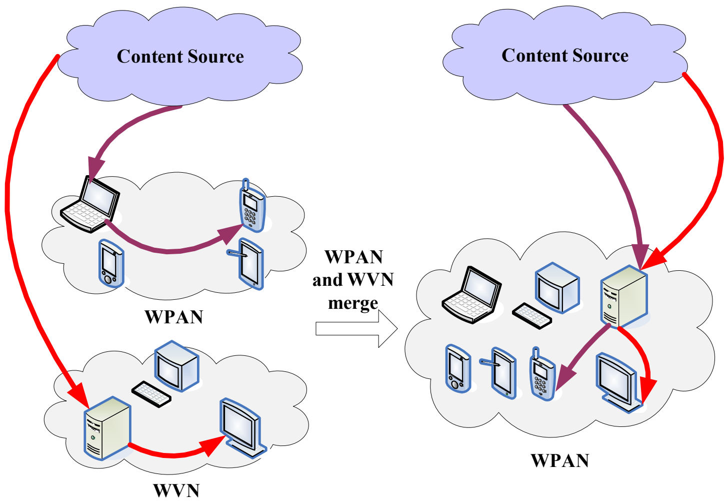
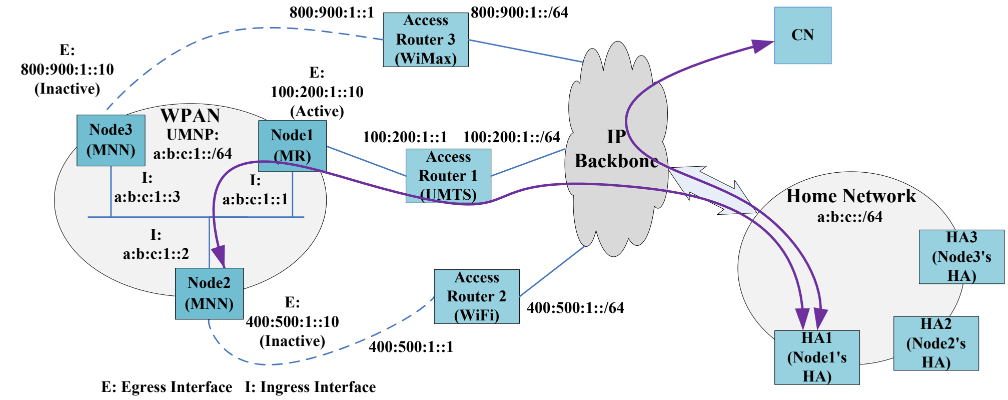


Figure 5.8: *Scenario 2: A WPAN and a WVN merge*

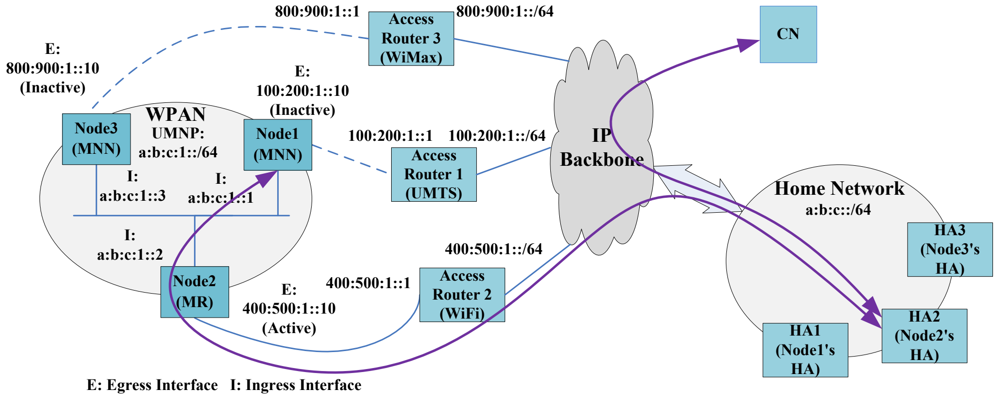
5.5.2 Scenario 1

An example is used to propose the detailed process, shown in Fig. 5.9. Three personal devices are included in a WPAN, and the MR is changed from Node1 to Node2. The example addresses shown in this figure are addresses that could be allocated in a real scenario and are intended to help clarify the descriptions. Node1, Node2 and Node3 respectively have a UMTS, a WiFi and a WiMax interface as their egress interfaces when working as the MR. Inside this WPAN, all three personal devices use short-range wireless interfaces (e.g. Bluetooth) as the ingress interface.

In this example, all three personal devices can obtain addresses via their egress interface from access routers, but only the personal device that is working as the MR sets its egress interface active for this WPAN's out/ingoing communications, shown by solid lines in Fig. 5.9. Dotted



(a) Node1 is working as the MR, others are working as MNNs



(b) Node2 is working as the MR, others are working as MNNs

Figure 5.9: *An example for the MR change in a WPAN*

lines in Fig. 5.9 represent communication paths that are inactive. In Fig. 5.9(a), Node1 is working as the MR, so its egress interface (100:200:1::10) is active for this WPAN. Node2 is working as a MNN, and it receives content from the CN via HA1 (Node1's HA) and Node1. In Fig. 5.9(b), Node2 is changed to become the new MR and Node1 is changed to be a MNN, so Node2's egress interface (400:500:1::10) is active for this WPAN and Node1's egress interface is set inactive (e.g. standby). Communications from the CN to Node1 go though HA2 (Node2's HA) and Node2. Due to the UMNP (a:b:c:1::/64), ingress interface addresses of the three personal devices are kept unchanged regardless of which one works as the MR.

Fig. 5.10 shows the detailed operation of the proposed PDE-based scheme which manages the dynamic change of personal devices in a WPAN between a MR and a MNN and how the UMNP is kept in the WPAN. According to the MR role management proposed in Section 5.4, every MR-capable personal device has two states while in the WPAN (MR state and MNN state). When such devices receive the SWM from the Local DME/PCM, they change their state using different BUs sent to their HAs. The DID is included with the SWM sent to the personal device which will become the new MR. According to the addressing mechanisms proposed in Section 5.3, the new MR can get the UMNP from the Root DME by using this DID. With this PDE-based scheme, ongoing communications between a WPAN and CNs can be kept continuous during and after the change of the MR because the change is transparent to MNNs inside this WPAN and their CNs. Another advantage is that MNNs do not need to send any BU to their HAs and CNs because the WPAN-CoA (i.e. the short-range interface address inside this WPAN) of every personal device is kept unchanged.

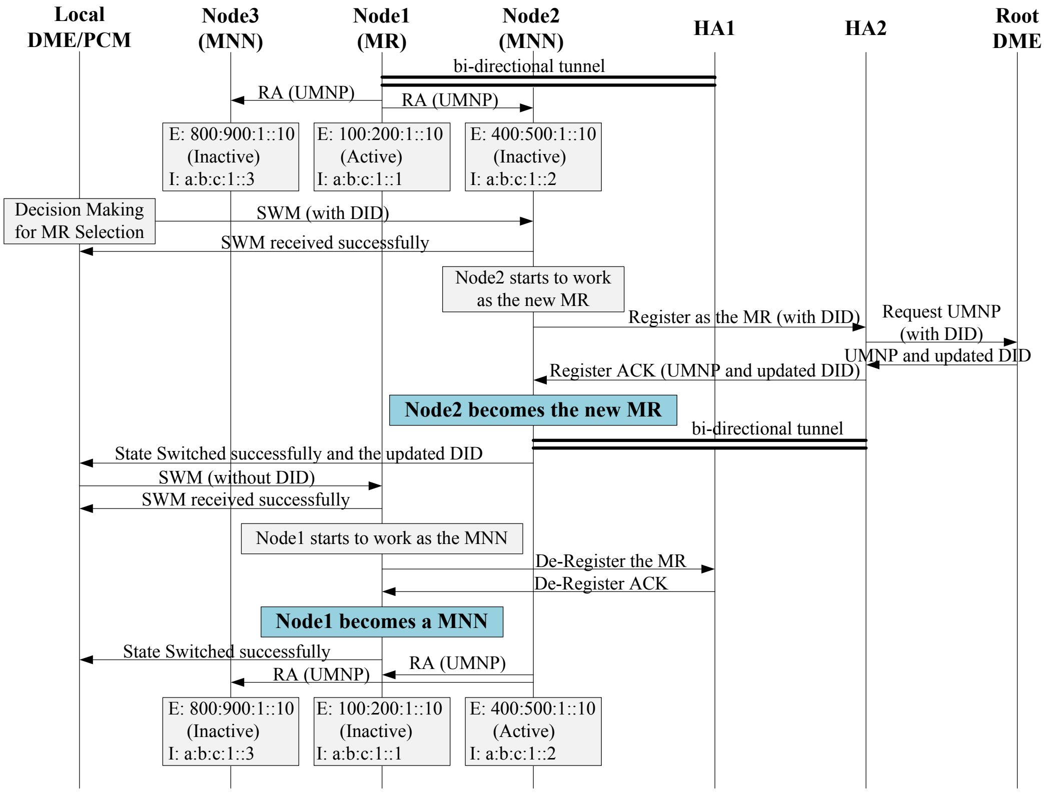


Figure 5.10: *The PDE-based scheme for Scenario 1*

5.5.3 Scenario 2

Since the fixed MR in a WVN is likely to be more powerful than a MR in the WPAN, an individual user is likely to prefer to use the fixed MR in this WVN after the WPAN enters the car. Therefore, this section mainly considers how MNNs in the WPAN can change to use the

MR of the WVN after they merge while keeping ongoing communications continuous.

Scenario 2 is also used in an IETF document [45] as one of the proposed research scenarios for WPANs but few studies have been done on this issue. This document [45] suggests two possible solutions. The first one is straightforward - directly use the MIP protocol [1]. When a WPAN and a WVN merge, a MNN can get the RA from the MR of this WVN. Thus this MNN can change to use a new CoA generated from the MNP of the WVN in order to use the MR of this WVN. However, this MNN must now perform a BU with its HA and CNs. Also, if this MNN wishes to change back to use the WPAN's MR, it has to change its CoA and perform a BU again. As discussed in Section 5.1 and 5.2, this will greatly increase delay and cost. The second suggested solution uses Nested NEMO. The MR of the WPAN connects to the MR of the WVN and becomes a subordinate MR, so forming a Nested NEMO network. MNNs in the WPAN can keep their addresses unchanged but incoming communications must go through the two MRs and their HAs. As discussed in Section 5.2, the multiple encapsulated tunnels used by this solution has a higher cost in overhead and delay.

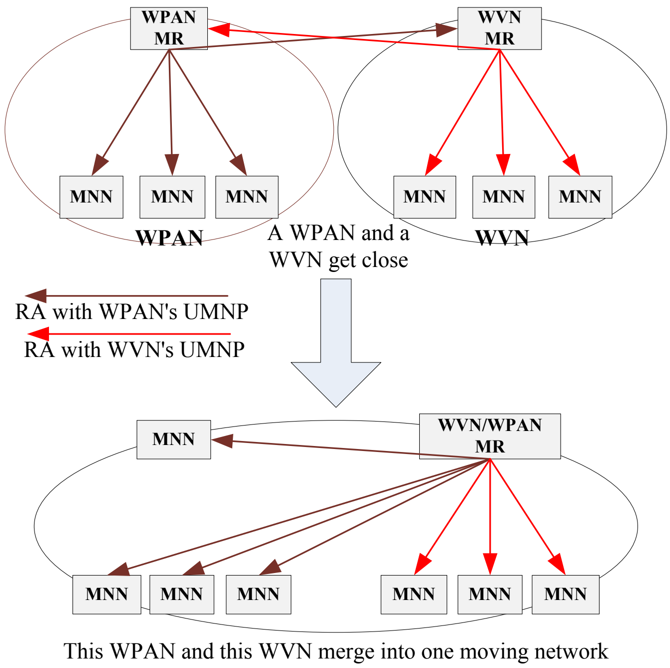


Figure 5.11: *A WPAN and a WVN merge*

The proposed PDE-based scheme assumes that MRs are multihoming [33], i.e. each of them can support multiple MNPs. Thus the MR of the WVN can be responsible for other MNPs besides the MNP of this WVN. Therefore, after the WPAN and WVN merge, the MR of the

WVN can also work as the MR of the WPAN and advertise the WPAN's UMNP to the MNNs that are using this UMNP, shown in Fig. 5.11. This MR therefore advertises two MNPs in the merged moving network. Since the same UMNP is still maintained in the merged network, although advertised by another MR, the MNNs previously belonging to the WPAN can keep their addresses unchanged and the WVN's MR becomes the MR for these MNNs. Therefore, the network merging and the MR changing are transparent to the MNNs previously belonging to the WPAN, and ongoing communications between these MNNs and their CNs can be kept continuous. Notice that since the WVN's MR is used, the personal device previously working as the MR for the WPAN can change its state to a MNN in this merged moving network.

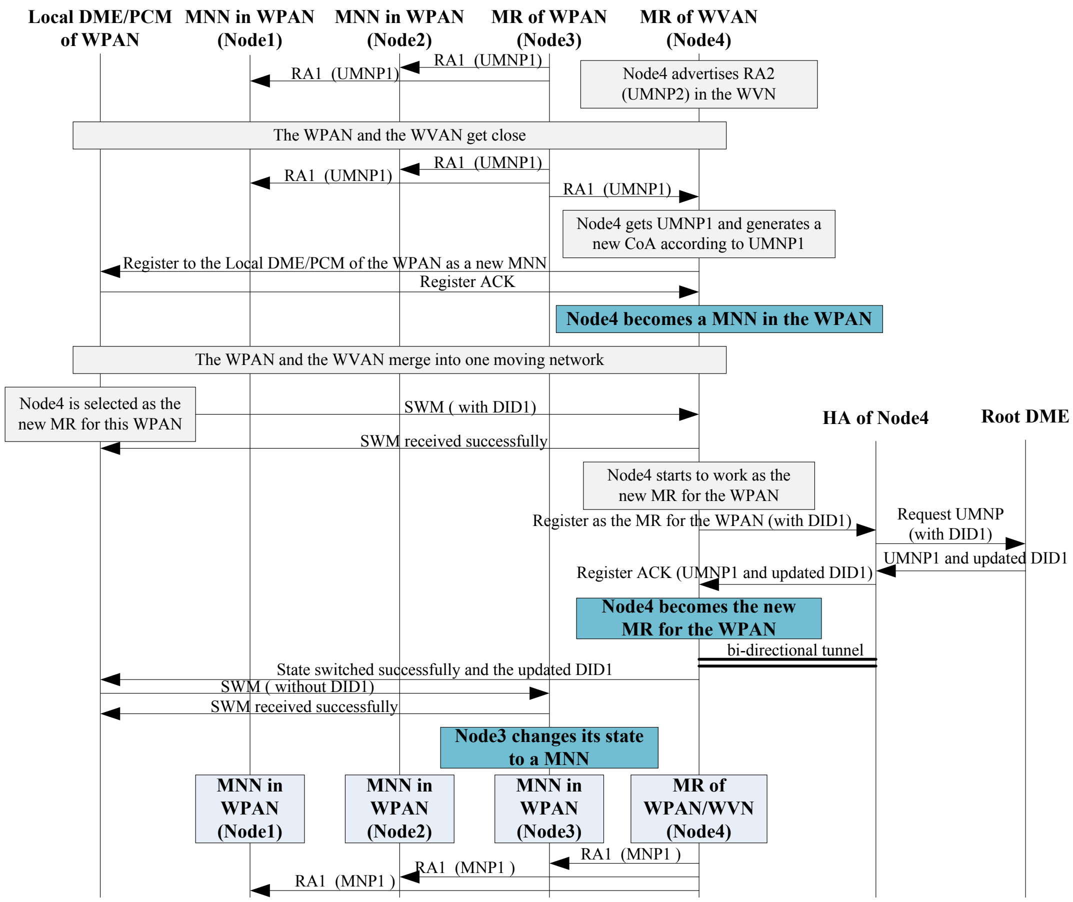


Figure 5.12: *The PDE-based scheme for Scenario 2*

Fig. 5.12 shows the operation of the proposed PDE-based scheme for Scenario 2. When the WPAN and the WVN get close, Node4 (the MR of the WVN) receives the RA1 from Node3 (the MR of the WPAN) obtaining UMNP1 (i.e. the UMNP of the WPAN), which is used by Node4 to generate its CoA in the WPAN. In this way, Node4 becomes a MNN in the WPAN, and at the same time still works as the MR for the WVN. Because Node4 is a multihoming MR, currently it has two states at the same time: it is in the MR state from the point of view of this WVN, but it is in the MNN state from the point of view of this WPAN. If Node4 is selected by the Local PCM of the WPAN to be the new MR for this WPAN, with the PDE-based scheme proposed for Scenario 1 in Section 5.5.2, Node4 changes its state in this WPAN from the MNN to the MR and gets UMNP1 from the Root DME by using DID1 (i.e. the DID of the WPAN) given by the Local DME of the WPAN. In this way, Node4 becomes the MR for the WPAN and advertises UMNP1 to the MNNs belonging to this WPAN. These MNNs' addresses are kept unchanged, so they are unaware of the network merging and the MR changing, and ongoing communications between these MNNs and their CNs are kept continuous.

5.6 Performance Evaluation

In this section, the performance of the proposed PDE-based scheme is evaluated for Scenario 1 and 2 and compared with MIP and Nested NEMO. The delay, the overhead cost, the packet loss and the throughput are analyzed.

5.6.1 Performance Evaluation for Scenario 1

5.6.1.1 Performance Analysis Model for Scenario 1

For Scenario 1, three personal devices are used in a WPAN: Node1, Node2 and Node3. Node1 is working as the MR for this WPAN, and Node2 is also MR-capable. A CN outside this WPAN is transferring content to Node3. Then, the MR is changed from Node1 to Node2. The signalling processes of the three schemes when they are used in Scenario 1 are shown as follows. Notice that the data packet shown in these models includes the MIP header and the IPv6 header.

The signalling processes for the PDE-based scheme, proposed in Section 5.5, are shown in Fig. 5.13. The PDE concept proposes that the Local DME/PCM is a logical entity that may change its location within the WPAN dynamically [70]. Here, it is assumed that the Local DME/PCM is located in the personal device currently working as the MR. Other MR-capable personal devices are assumed also to possess Local DME/PCM functionality (e.g. pre-installed software) which is currently inactive. When Node2 is selected as the new MR, the Local

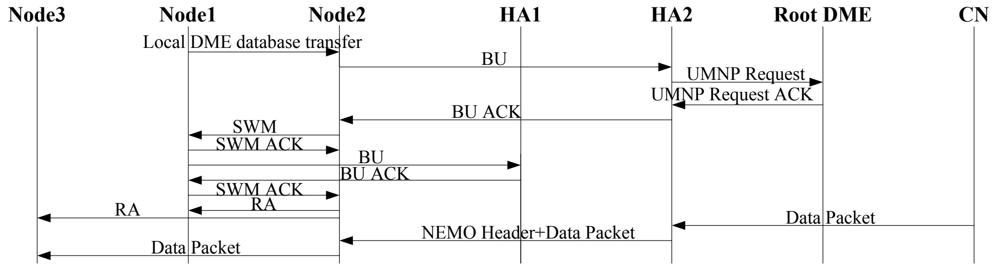


Figure 5.13: *Signalling processes of the PDE-based scheme for Scenario 1*

DME database, which includes necessary information such as current device condition and user requirements, is transferred from Node1 to Node2. On receiving this database, the Local DME/PCM function in Node2 is triggered. In this way, the Local DME/PCM is changed to be in Node2. The periodically updating signalling of the PDE environment is assumed to be included in the periodic MIP BU that is also used by MIP and Nested NEMO. Therefore, in this analysis of the three schemes, the periodic BU is not considered.

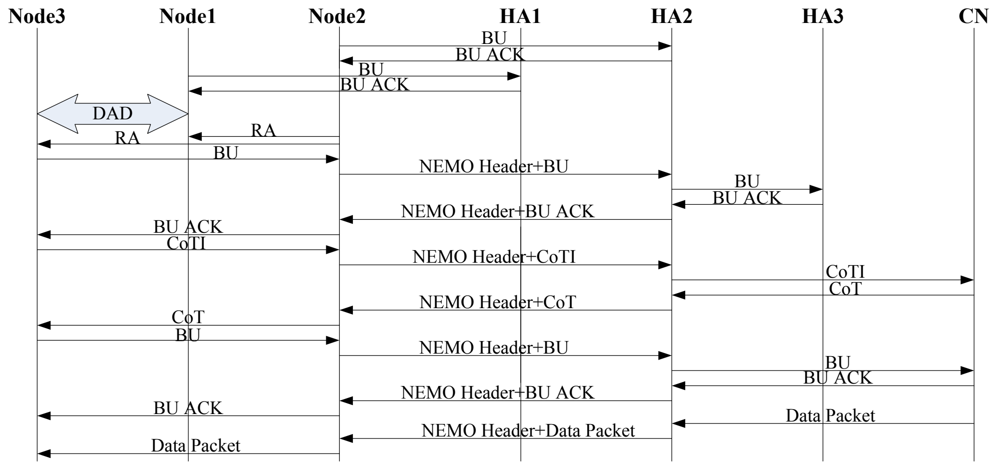


Figure 5.14: *Signalling processes of MIP for Scenario 1*

The signalling processes for the MIP scheme are shown in Fig. 5.14. When MIP is used, because the new MR (i.e. Node2) advertises a new MNP in this WPAN, MNNs (i.e. Node1 and Node3) must obtain new CoAs by using DAD (Duplicate Address Detection). The MIP protocol [1] defines that a MN must process a BU with both its HA and CN after it gets a new CoA. Furthermore, CoTI (CoA Test Initi) and CoT (CoA Test) must be performed before the BU processing between this MN and its CN.

The signalling processes for Nested NEMO are shown in Fig. 5.15. When Node2 becomes the new MR, it advertises a new MNP. The original MR (i.e. Node1) connects to Node2 and

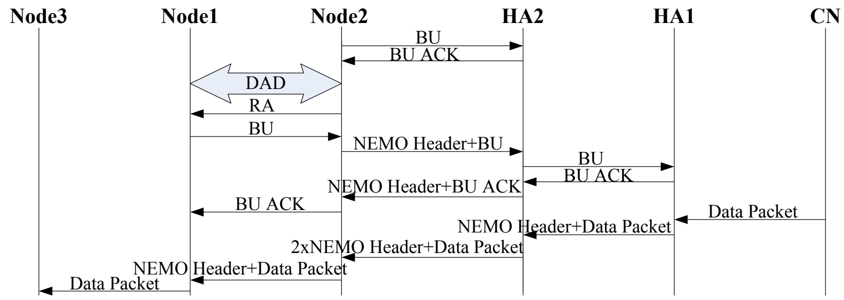


Figure 5.15: *Signalling processes of Nested NEMO for Scenario 1*

generates a new CoA according to this new MNP by using DAD. Node3 still connects to Node1 so its address is unchanged. Because this is a two-level Nested NEMO network, data packcts from the CN to Node3 must respectively go through HA1 (i.e. Node1's HA) and HA2 (i.e. Node2's HA). Furthermore, a two-level encapsulated tunnel must be used between Node2 and HA2, so two-level NEMO headers are added in data packets.

(A) Delay of MR Change

The delay of the MR change (D) denotes the delay produced by the one-time MR change that interrupts current content transfer from the CN to Node3, which is calculated by:

$$D = \sum_{s} \left(\left(\frac{PS_s + H_s}{b_s} + l_s \right) \cdot h_s \right) + l_{RA} + l_{DAD} \tag{5.1}$$

where

$$H_s = H_{IPv6} + H_{MIP} + n_{H(s)} \cdot H_{NEMO}, \qquad n_{H(s)} = 0, 1, 2 \tag{5.2}$$

PS_s, H_s, b_s, l_s and h_s respectively denote the signalling packet size, the packet header size, the network bandwidth, the network latency and the number of communication hops in the s-th step of the MR change process. l_{RA} and l_{DAD} respectively denote the latency cost by RA and DAD, which are added to D if a scheme includes these processes. The PDE-based scheme only has a RA process, but MIP and Nested NEMO both have RA and DAD processes. A packet header (H) includes three parts: a header of IPv6 (H_{IPv6}), a header of MIP (H_{MIP}) and a header of NEMO (H_{NEMO}) (if packets are transferred between the MR and its HA). For signalling packets defined by MIP/NEMO, PS already includes H_{IPv6} and H_{MIP}, and no PS in these schemes is tunneled by the MN's HA (otherwise an extra H_{MIP} is added), so only H_{NEMO} should be considered. However, in a Nested NEMO network, multiple NEMO headers are used by multiple-level encapsulated tunnels, and thus $n_{H(s)}$ is used in equation 5.2

to denote the number of NEMO headers used in the s-th step. In Scenario 1, two MRs form a two-level Nested NEMO network, so $n_{H(s)}$ is up to 2. Notice that if more new MRs are used in this Nested NEMO network that will establish more levels of encapsulated tunnels, $n_{H(s)}$ will increase due to more NEMO headers added in data packets.

(B) Overhead Cost of MR Change

The overhead of a scheme for MR change includes two parts: all signalling packets used by this scheme and headers added in data packets. Two kinds of overheard cost are analyzed by this model: the signalling overhead cost of the MR change (C_{signal}) and the total overhead cost (C_{total}).

(B.1) Signalling Overhead Cost of MR Change (C_{signal})

C_{signal} is the cost produced by all signalling packets that are used for the one-time MR change, which is calculated as follows:

$$C_{signal} = \sum_{s} ((PS_s + H_s) \cdot h_s) \tag{5.3}$$

where H_s uses equation 5.2. PS_s, H_s and h_s respectively denote the signalling packet size, the packet header size and the number of communication hops in the s-th step of the MR change process where signalling packets are used.

(B.2) Total Overhead Cost of MR Change (C_{total})

Besides C_{signal}, the overhead cost is also produced by headers of every data packet (C_{data}) transferred from the CN to Node3. C_{total} is the sum of C_{signal} and C_{data}, but these two overhead costs can not be added directly because C_{signal} considers the one-time MR change and C_{data} considers a data packet. C_{total} is normalized in one session to be compared, which is shown as follows:

$$C_{total} = C_{signal} \cdot M + C_{data} \cdot E \tag{5.4}$$

where M and E respectively denote the average ratio of the MR change frequency to one session and the average number of data packets in one session. The larger M is, the more frequently the MR changes in one session. M, E and C_{data} are calculated as:

$$M = \frac{t_{session}}{t_{MRChange}} \tag{5.5}$$

$$E = \frac{R}{PD} \cdot t_{session} \tag{5.6}$$

$$C_{data} = \sum_{s} (H_s \cdot h_s) \tag{5.7}$$

$t_{session}$ and $t_{MRChange}$ in equation 5.5 respectively denote the average session connection time and the average MR change time that means how long a MR is connected and then is changed to another. R and PD in equation 5.6 respectively denote the data rate of content transferred between the CN and Node3 and the original size of data packets sent by the CN that only includes H_{IPv6}. H_s and h_s in equation 5.7 respectively denote the packet header size and the number of communication hops in the s-th step of transferring a data packet from the CN to Node3. H_s is calculated by equation 5.2. A NEMO header is added to data packets when they are transferred between the MR and its HA with the PDE-scheme and MIP. However, in a Nested NEMO network, multiple NEMO Headers are added to data packets due to multiple-encapsulated tunnels. Therefore, C_{total} is calculated as:

$$\begin{aligned} C_{total} &= \sum_{s(signal)} \big((PS_{s(signal)} + H_{s(signal)}) \cdot h_{s(signal)} \big) \cdot \frac{t_{session}}{t_{MRChange}} \\ &\quad + \sum_{s(data)} \big(H_{s(data)} \cdot h_{s(data)} \big) \cdot \frac{R \cdot t_{session}}{PD} \end{aligned} \tag{5.8}$$

(C) Packet Loss of MR change

(C.1) Packet Loss of MR change (Pl)

The packet loss (Pl) is the number of data packets lost during the one-time MR change, which is shown as follows. Notice that only the steps using signalling packets are calculated in this equation.

$$\begin{aligned} Pl &= D \cdot \frac{R}{PD} \\ &= \left(\sum_{s} \left(\left(\frac{PS_s + H_s}{b_s} + l_s \right) \cdot h_s \right) + l_{RA} + l_{DAD} \right) \cdot \frac{R}{PD} \end{aligned} \tag{5.9}$$

(C.2) Packet Loss Ratio of MR change (r_{Pl})

The packet loss ratio (r_{Pl}) is the average ratio of the number of data packets lost due to the MR change to the total number of data packets. r_{Pl} is normalized in one session to be compared. It is calculated as follows, where only the steps using signalling packets are calculated.

$$\begin{aligned} r_{Pl} &= \frac{Pl \cdot M}{E} \\ &= \frac{\sum_{s} \left(\left(\frac{PS_s + H_s}{b_s} + l_s \right) \cdot h_s \right) + l_{RA} + l_{DAD}}{t_{MRChange}} \end{aligned} \tag{5.10}$$

***(D) Throughput** (Th)*

The throughput (Th) denotes the average content transfer throughput in Scenario 1 where the MR may be changed. Th is normalized in one session to be compared, which is calculated as follows, where $D_{session}$ denotes the time that one session takes to be transferred.

$$Th = \frac{E \cdot PD}{D_{session} + D \cdot M} \tag{5.11}$$

According to queuing theory, $D_{session}$ is calculated as follows, where $D_{datapkt}$ and σ respectively denote the end to end delay of a data packet and the average sending interval of data packets in one session.

$$D_{session} = D_{datapkt} + (E - 1) \cdot \sigma \tag{5.12}$$

$D_{datapkt}$ and σ are calculated as follows, where only the steps that transfer data packets from the CN to Node3 are calculated in this equation. PD already includes H_{IPv6}, so only H_{MIP} and H_{NEMO} should be calculated in H_s that uses equation 5.2.

$$D_{datapkt} = \sum_{s} \left(\left(\frac{PD + H_s}{b_s} + l_s \right) \cdot h_s \right) \tag{5.13}$$

$$\sigma = \frac{t_{session}}{E} \tag{5.14}$$

Therefore, Th is calculated as follows, where D is obtained by using equation 5.1.

$$\begin{aligned} Th &= \frac{E \cdot PD}{\sum_{s} \left(\left(\frac{PD + H_s}{b_s} + l_s \right) \cdot h_s \right) + \frac{(E-1) \cdot t_{session}}{E} + D \cdot M} \\ &= \frac{R \cdot t_{session}}{\sum_{s(data)} \left(\left(\frac{PD + H_{s(data)}}{b_{s(data)}} + l_{s(data)} \right) \cdot h_{s(data)} \right) + \frac{(R \cdot t_{session} - PD)}{R} + \frac{D \cdot t_{session}}{t_{MRChange}}} \end{aligned} \tag{5.15}$$

5.6.1.2 Numerical Simulation Results for Scenario 1

(A) Parameter Settings

The common parameters used in this performance evaluation are listed in Table 5.2. IPv6 defines a random delay before sending the RA message, which is between 0-500ms, so the average delay for receiving a RA message is taken as 250ms. IPv6 also defines a random delay for the DAD procedure that is 0-1s, so the average delay for DAD is set to 500ms. This analysis considers communications that have already been established between a MNN and its CN, so the routing optimization (RO) is established. The MIP protocol [1] defines that the MIP header with RO is 24 Bytes. The NEMO protocol [2] defines that the NEMO header is same as the IPv6 header, which is 40 Bytes. PS is different in different steps of communications according to the definition of the MIP protocol [1] and the NEMO protocol [2]. The size of different signalling messages are listed in Table 5.3.

Parameter	Value	Parameter	Value
PD	1000 Bytes	H_{MIP}	24 Bytes [1]
b (MR egress interfaces)	3 Mbps	H_{NEMO}	40 Bytes [2]
b (MR ingress interfaces)	50 Mbps	$t_{session}$	60 s
b (IP backbone)	100 Mbps	R	200 Kbps
l (wireless link)	2 ms	h (between MR and MNN)	1
l (wired link)	0.5 ms	h (between HA and CN)	10
l_{RA}	250 ms	h (between HAs)	1
l_{DAD}	500 ms	h (between MNNs)	1
Database of Local DME	2000 Bytes	h (between MR and MR's HA)	10
H_{IPv6}	40 Bytes [1]		

Table 5.2: *Common Parameter Settings*

Signalling Message	Size	Signalling Message	Size
BU (MNN to HA)	80 Bytes	BU (MNN to CN)	96 Bytes
BU ACK (HA to MNN)	80 Bytes	BU (CN to MNN)	96 Bytes
BU (MR to HA)	80 Bytes	CoTI	56 Bytes
BU ACK (HA to MR)	80 Bytes	CoT	64 Bytes

Table 5.3: *Signalling messages defined by MIP and NEMO [1, 2]*

(B) Result Discussion

The performance analysis model is calculated for the PDE-based scheme, MIP and Nested NEMO according to their signalling processes proposed by Fig. 5.13, Fig. 5.14 and Fig. 5.15 in Section 5.6.1.1.

The delay of the MR Change (D) is shown in Fig. 5.16. The hops between the MR and the HA

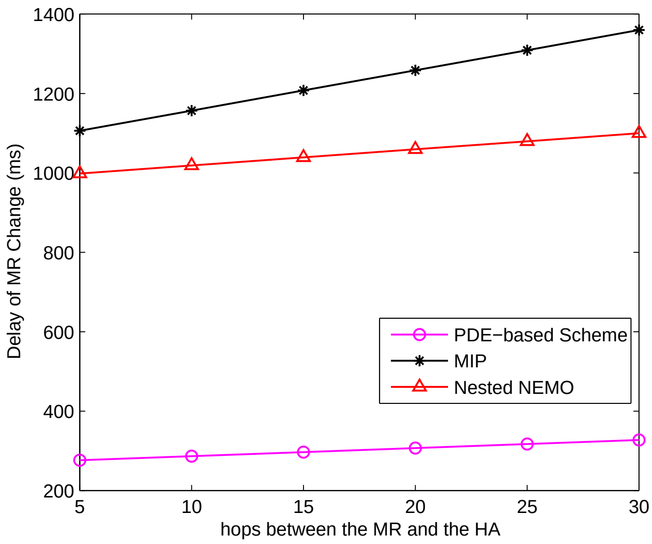


Figure 5.16: *The Delay of the MR Change for Scenario 1*

is changed from 5 to 30, which can represent the WPAN located from close to the HA to far away from the HA. The delay D of the three schemes increases with the increase in the number of hops between the MR and the HA. This means that the further the MR is away from the HA, the larger D becomes. The PDE-based scheme's D is the lowest, about 23% to 30% of that of MIP and Nested NEMO. MIP has the largest D, because its signalling processes are more time consuming than the other schemes.

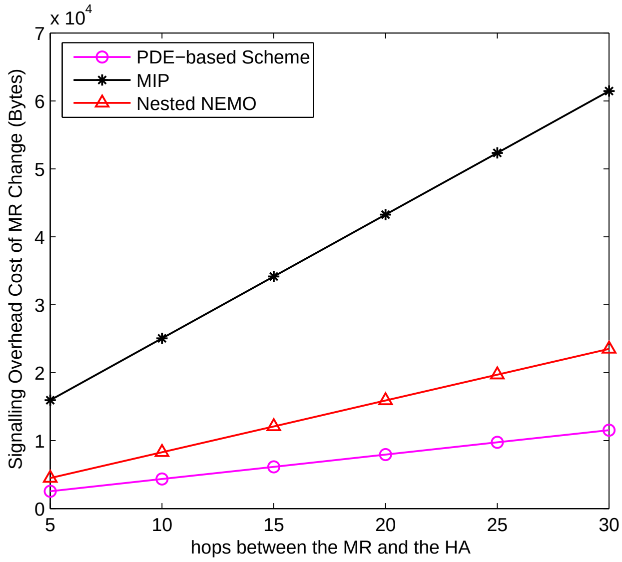


Figure 5.17: *The Signalling Overhead Cost of the MR Change for Scenario 1*

The signalling overhead cost of the MR Change (C_{signal}) is shown in Fig. 5.17. The number of hops between the MR and the HA is again changed from 5 to 30. Again the signal overhead cost C_{signal} of the schemes all increase with increasing number of hops. Again the C_{signal} for MIP is much higher than the other schemes, because in MIP, MNNs must generate new CoAs and use the BU procedure, which requires more signalling. The C_{signal} of Nested NEMO is similar to that of the PDE-based scheme when the number of hops is small (e.g. hops=5), but is much higher when the number of hops becomes large (e.g. hops=30). This is because the Nested NEMO and PDE-based schemes have similar signalling processes, but Nested NEMO must use extra NEMO headers and signalling processes due to its multiple-level configuration. Therefore, for few hops, the overhead cost of the extra NEMO headers is small and not significant. However, for many hops, the overhead cost is large and its effect on C_{signal} is obvious.

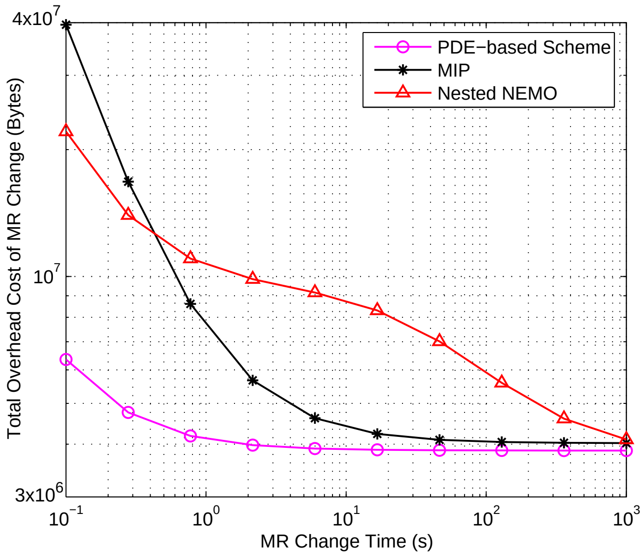


Figure 5.18: *The Total Overhead Cost of MR Change for Scenario 1*

The total overhead cost of the MR Change (C_{total}) is shown in Fig. 5.18. The MR change time ($t_{MRChange}$) ranges from 0.1s to 1000s, which can represent situations where the MR in the WPAN is changed very frequently (every 0.1s) to situations where the MR is seldom changed (1000s). The C_{total} for the three schemes decreases when $t_{MRChange}$ increases. This is because when the $t_{MRChange}$ is small, the MR is changing very frequently and thus C_{signal} plays an important role in C_{total}, but when $t_{MRChange}$ becomes large, the MR seldom changes and thus the overhead cost produced by the headers in data packets (C_{data}) plays a more important role in C_{total}. Also, C_{signal} is relatively large compared to C_{data}. Therefore, when C_{signal} matters, C_{total} is large, but when C_{data} matters, C_{total} becomes small. On the other hand, when $t_{MRChange}$ is small, MIP has the largest C_{total}, but when $t_{MRChange}$ increases, Nested NEMO has the largest C_{total}. This is because MIP has the largest C_{signal} among these three schemes, and Nested NEMO has the largest C_{data} due to the extra NEMO headers. Therefore, when C_{data} becomes more important in C_{total}, C_{total} of Nested NEMO becomes the largest. Compared to Fig. 5.17, it can be seen that although MIP is the worst for a one-time MR change due to its high C_{signal}, when the MR changes less frequently, Nested NEMO may become the worst due to its high C_{data}. From Fig. 5.18, it can also be seen that the PDE-based scheme has the least C_{total} no matter how $t_{MRChange}$ changes. However, when $t_{MRChange}$ is very high in terms of $t_{session}$ (e.g. $t_{MRChange} = 1000s$), the PDE-based scheme has a similar C_{total} to other schemes. This is because when $t_{MRChange}$ is very high, it means that the MR only changes after a very long time or almost never changes in one session. Therefore, C_{data} matters most in C_{total}. Also, if the MR isn't changed, because these three schemes all use the typical MIP and NEMO protocols for the data packet transfer, their C_{data} are the same and thus C_{total} are similar. Therefore, this situation can also be considered as the one before the MR is changed.

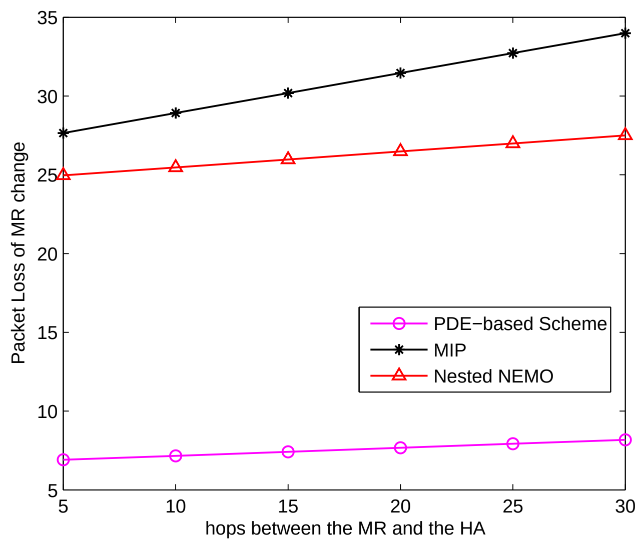


Figure 5.19: *The Packet Loss of the MR Change for Scenario 1*

The packet loss of the MR change (Pl) is shown in Fig. 5.19. Again the hops between the MR and the HA are changed from 5 to 30. Pl of these three schemes all increase with the increase in hops. This means that the further the MR is away from the HA, the more data packets are lost. The PDE-based scheme has the lowest Pl, about 20% to 27% of MIP and Netsted NEMO, because the PDE-based scheme has the smallest D.

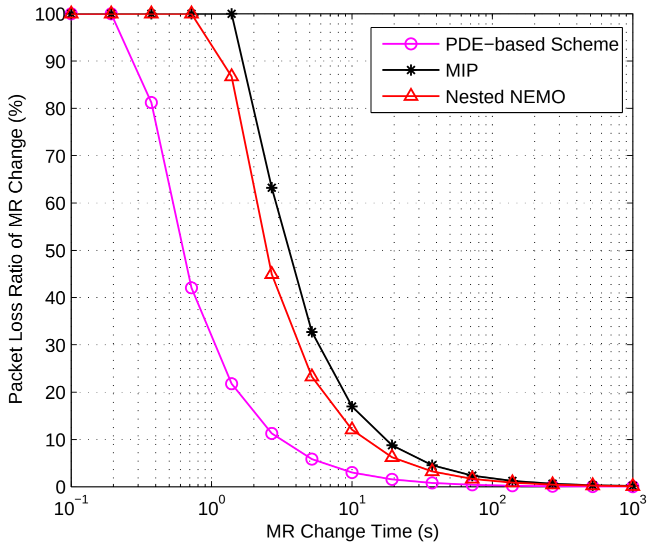


Figure 5.20: *The Packet Loss Ratio of the MR Change for Scenario 1*

The packet loss ratio of the MR change (r_{Pl}) is shown in Fig. 5.20. Again, $t_{MRChange}$ is changed from 0.1s to 1000s. When $t_{MRChange}$ is smaller than 10s, r_{Pl} of MIP and Nested NEMO are both high, but the PDE-based scheme has a much smaller r_{Pl}. When $t_{MRChange}$ is smaller than 1s, r_{Pl} of MIP and Nested NEMO are both about 100%, but the PDE-based scheme can have a r_{Pl} of 30%. When $t_{MRChange}$ is large (e.g. larger than 100s), r_{Pl} of these three schemes are all similar and very small because the MR seldom changes.

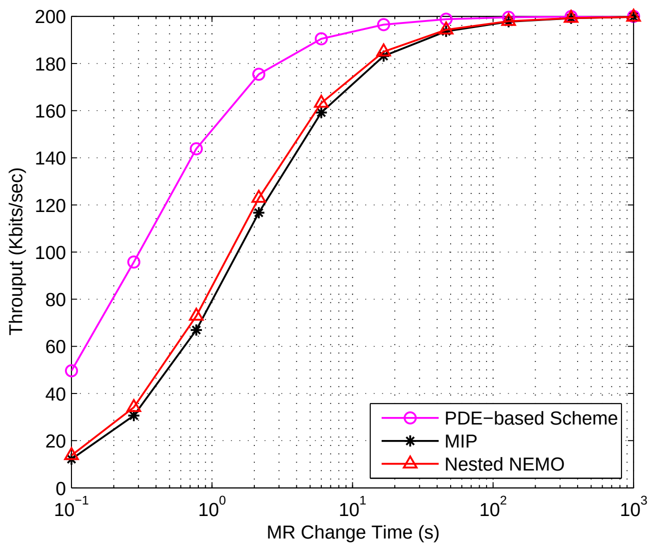


Figure 5.21: *The Throughput of the MR Change for Scenario 1*

The throughput of the content transfer (Th) is shown in Fig. 5.21. $t_{MRChange}$ is also changed from 0.1s to 1000s. The PDE-based scheme always has the highest Th among these three schemes no matter how $t_{MRChange}$ changes because the PDE-based scheme has the least D. When $t_{MRChange}$ increases, Th of these schemes all increase because the MR changes less frequently. When $t_{MRChange}$ is large (e.g. larger than 100s), Th of these three schemes are all similar and very high because the MR seldom changes.

5.6.2 Performance Evaluation for Scenario 2

5.6.2.1 Performance Analysis Model for Scenario 2

For Scenario 2, two personal devices are used in a WPAN: Node1 and Node3. Node1 is working as the MR for this WPAN. A CN outside this WPAN is transferring content to Node3. Node2 is the MR for a WVN, and Node2 is also a multihoming MR. This WPAN and the WVN merge, Node2 gets a CoA from the WPAN (i.e. from Node1). Then, the MR of the WPAN is changed from Node1 to Node2. The signalling processes of these three schemes when they are used in Scenario 2 are as follows.

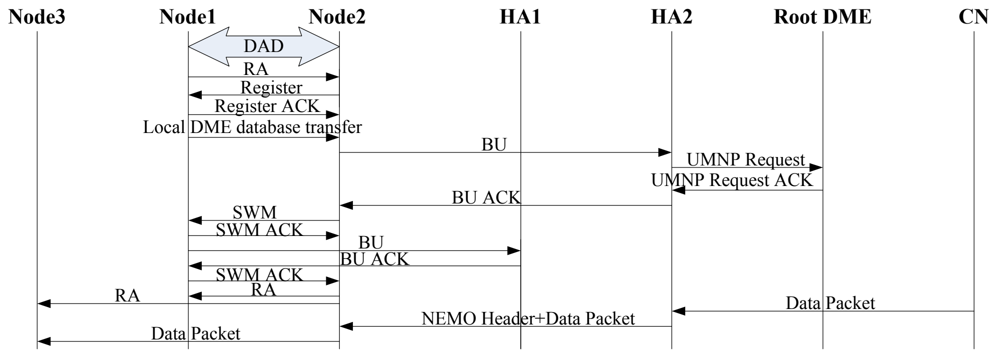


Figure 5.22: *Signalling processes of the PDE-based scheme for Scenario 2*

The signalling processes for the PDE-based scheme, proposed in Section 5.5, are shown in Fig. 5.22. This is similar to the signalling processes for scenario 1 (Fig. 5.13). However, Node2 needs to have a RA and a DAD procedure to obtain a new CoA from the WPAN. Also, according to the definition of the PDE environment, Node2 needs to register to the Local DME of the WPAN. It is proposed that the PDE register and ACK messages use the BU and BU ACK signalling messages of MIP.

The signalling processes for MIP are shown in Fig. 5.23. This is similar to signalling processes

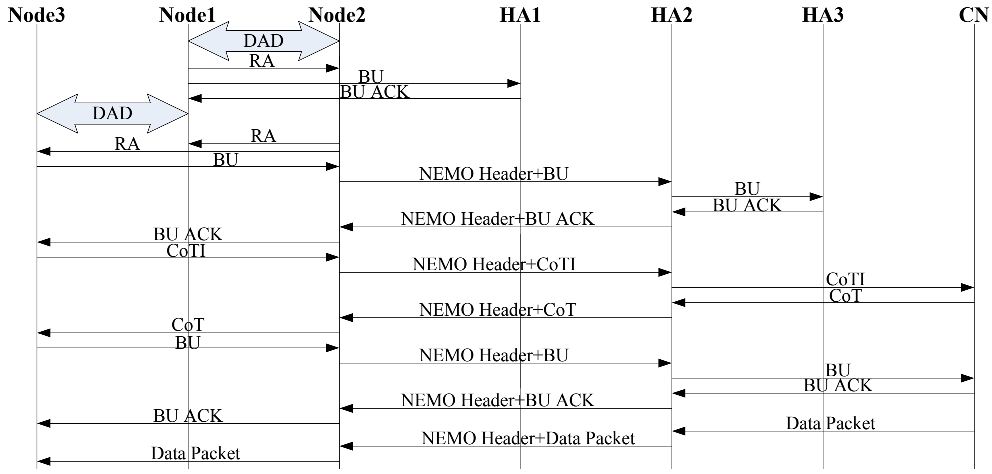


Figure 5.23: *Signalling processes of MIP for Scenario 2*

for scenario 1 (Fig. 5.14). However, Node2 needs to have a RA and a DAD procedure to obtain a new CoA from the WPAN because it is multihoming. Also, Node2 does not need to request a MNP from its HA because it is already a MR advertising the MNP of the WVN. After Node1 finds Node2, it is decided that the MR of the WPAN is changed to Node2. Then, Node1 un-registers its MR function with its HA, and Node3 obtains a new CoA from Node2.

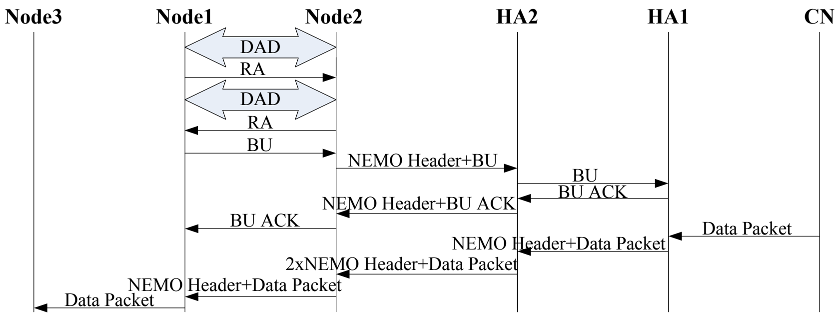


Figure 5.24: *Signalling processes of Nested NEMO for Scenario 2*

The signalling processes for Nested NEMO are shown in Fig. 5.24. This is also similar to signalling processes for scenario 1 (Fig. 5.15), but also has some differences, which are the same as discussed for MIP.

Because the three schemes all add the same RA and DAD procedure in Scenario 2, these procedures are not considered in the performance analysis models. The performance evaluation focuses on the differences between these schemes. On the other hand, the merge of a WPAN and a WVN (Scenario 2) is likely to happen much less frequently than the MR change in Scenario 1. Therefore, the performance evaluation is focused on the one-time MR change when networks merge. Mathematical performance analysis models are as same as those proposed in Scenario 1.

5.6.2.2 Numerical Simulation Results for Scenario 2

The parameter settings used in Scenario 2 are as same as those in Scenario 1, shown in Table 5.2 and 5.3. D, C_{signal} and Pl are respectively shown in Fig. 5.25, 5.26 and 5.27. They are similar to the results in Scenario 1. The PDE-based scheme has a a better performance than other schemes no matter how the number of hops changes. However, C_{signal} of MIP and Nested NEMO are smaller than those in Scenario 1 because less signalling processes are needed in Scenario 2 with these two schemes. C_{signal} of the PDE-based scheme is slightly larger than that in Scenario 1 because it needs more signalling processes in Scenario 2.

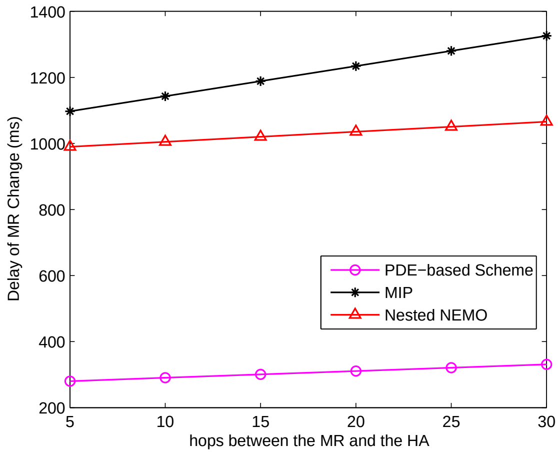


Figure 5.25: *The Delay of the MR Change for Scenario 2*

5.7 Conclusion

Existing research on “Multiple MR” is mainly from the point of view of a WVN where fixed MRs are pre-allocated. Therefore, solutions proposed by current research are not suitable for a WPAN in a heterogeneous environment, where multiple personal devices may dynamically change their roles between a MR and a MNN, leave this WPAN and easily lose wireless signal. A PDE-based scheme has been proposed to manage the operation of these dynamically changing MR-capable personal devices. A novel point of view, that a UMNP is owned by a particular

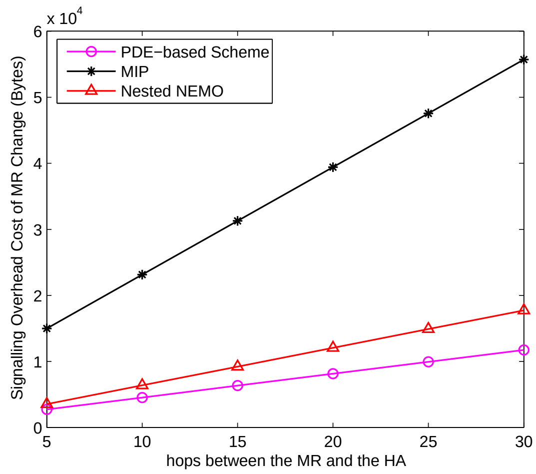


Figure 5.26: *The Signalling Overhead Cost of the MR Change for Scenario 2*

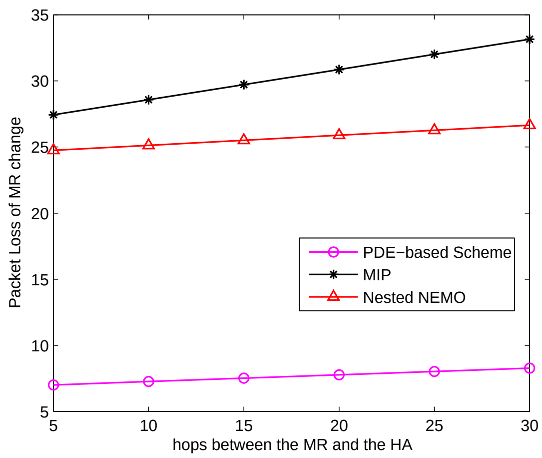


Figure 5.27: *The Packet Loss of the MR Change for Scenario 2*

WPAN but not by any personal device or its HA has also been proposed.

In the PDE-based scheme, two mechanisms are provided - an "Addressing Mechanism" solving addressing problems for acquisition of the UMNP and "MR Role Management" controlling dynamic role changes of personal devices. Two scenarios were considered for this PDE-based scheme: the MR changes in a WPAN, and a WPAN merges with a WVN. Its performance was also evaluated in these two scenarios and compared to two typical solutions - MIP and Nested NEMO.

The PDE-based scheme has benefits, which can simplify the design of communication procedures and thus achieve compact protocols and efficient communications:

(1) Directly support separate HAs: Every personal device can have its own separate HA and need not register to other devices' HAs (only needs to communicate with its own HA).

(2) The synchronization and cooperation of HAs of different devices is not needed, and every HA only needs to know the address of the Root DME.

Chapter 6
Decision Making Mechanism of Dynamically Changing MR Selection Adapted to User Needs

The work in Chapter 5 proposes a scheme that controls dynamically changing MRs in a NEMO-based WPAN. However, a critical problem arises: which MR-capable device should be selected by the Local PCM/DME to work as the new MR in the WPAN. In this chapter, a novel mechanism for decision making is proposed for selecting the most appropriate dynamically changing MR in the NEMO-based WPAN.

6.1 Introduction

The user's WPAN comprises many personal devices, some of which are MR-capable, with dynamically changing device conditions (such as battery power) and their role between MR and MNN, e.g. a mobile phone, a PDA and a laptop. In addition, these personal devices differ from each other in the diverse wireless access technologies they are equipped with, e.g. the mobile phone uses UMTS and the laptop has WiFi. When the user is mobile with their WPAN, these access technologies can provide different network speeds and cost due to changes of the wireless network coverage. On the other hand, the user may have differing requirements for the usage of the WPAN, e.g. the user may require the WPAN to prolong battery lifetime or to speed up downloading. Therefore, in such a heterogenous and dynamically changing environment, designing a mechanism to select the MR according to the user's needs is a challenge.

The MR selection in this work involves not only choosing a suitable personal device to work as the new MR, but also deciding an appropriate content transfer route for the WPAN according to the user's application and requirements. This work's aim is to design a decision making mechanism to select the "best" MR from all the MR-capable devices in the NEMO-based WPAN, i.e. select the most suitable content transfer mode for the WPAN, in order to fulfill the user's requirements or optimize the user's experience when using the WPAN. In the PDE environment, the core of this mechanism will be logically located in and used by the PCM.

The rest of this chapter is structured as follows. Section 6.2 analyzes related research and discusses relevant issues. In Section 6.3, the decision making mechanisms are proposed. In Section 6.4, numerical simulations are performed and the results are analyzed.

6.2 Related Work and Research Issues

6.2.1 Analysis of Related Research

There are two main areas of research related to MR selection in a NEMO network: "Multiple MRs" and "Network Selection".

"Multiple MRs" has been discussed in Chapter 5. It is mainly about the management and cooperation of multiple MRs in a NEMO network, which is closely related to our work in Chapter 5. It also includes MR selection as one of NEMO networks' requirements [33], but until now most of the research in "Multiple MRs" does not consider MR selection. Only a few papers mention MR selection, but simplify the problem with straightforward policies. [94] chooses the MR according to its handover state. [95] selects the MR with the strongest signal strength based on its location. These papers only consider fixed MRs with the same wireless access technology or with uniform device conditions (e.g. all MRs are the same type), so the simplified policy can work. However, when considering a heterogenous environment, dynamically changing MRs and users' needs, a simplified policy is inadequate and a well-designed mechanism for MR selection is needed.

Basic methods of "Network Selection" has been summarized in Chapter 2. However, the research reported there is not directly applicable for MR selection in a NEMO network. "Network Selection" [59] mainly considers a single terminal (from the terminal aspect) or the access network and service provider (from the access network aspect), but it does not consider a moving network. A WPAN, which is considered in this thesis, can be a moving network of multiple personal devices. Furthermore, it may be a dynamic NEMO-based network that is composed of personal devices which may change their roles and conditions dynamically and flexibly, which leads to higher complexity. On the other hand, the cost of MR change is considered in this thesis in the MR selection mechanism. The research on "Network Selection" typically considers a single terminal, and thus a handover is only processed by one device (even by the same wireless interface in this device) [3, 60–64]. Therefore, from the terminal aspect, the cost of a network handover is tiny compared to other factors such as bandwidth or power, and thus can be ignored. However, when MR selection is considered, the cost of enacting a MR change can not be ignored. This is because several personal devices are involved in the handover, and the total cost of the cooperation of these devices is much higher than the cost of network handover for a single terminal, and thus may become comparable with other factors.

6.2.2 Research Issues Discussion

Three kinds of methods for approaching a solution to MR selection are summarized in Chapter 2. A utility function [66, 67] can be used to allocate the best bandwidth and other QoS parameters among users in an access network, resource sharing in a multiclass IP network or autonomic system self-optimization capability. Therefore, this is appropriate for QoS-related and access network-based decision making. Compared to the weighted cost function [3, 60, 61], MADM-based approaches [65] are effective and sensitive, but complicated and hard to implement. They are mainly used in mathematical optimization problems. In this thesis, mathematical optimization is not included, but will be proposed for use as a "toolbox" to optimize the selection results for future work. When user-centric or terminal-based selection is the focus, most researchers [62, 96, 97] adopt a weighted cost function. This can incorporate various parameters derived from different aspects, like power and money usage, to dynamically represent the user's needs. Therefore, this method of a weighted cost function is adopted in this thesis.

Power consumption is a critical problem for mobile devices, especially for personal devices, because they are powered by a battery that has a capacity limited by overall dimensions as well as battery technology. Therefore, power consumption is one of the most important factors in the selection strategy. Three methods used by related work to research power consumption are discussed below:

Interface Power Consumption: Most research uses general values of the power consumed by different types of wireless interfaces directly as the power parameters for comparison [60, 62]. This is a straightforward method but has many limitations. Firstly, it does not consider the battery capacity and the power consumed by the device, and thus it can only be used in network selection for a single terminal or in the scenario that all terminals are identical. Therefore, it is not suitable for a WPAN composed of dynamically changing devices. In addition, it only considers interface power and does not consider different types of user application and the power consumed by handovers. For example, the power consumed by non-real-time and real-time applications may be different because they have different usage modes. Also, a MR change in a WPAN involves the cooperation of multiple devices. This method does not allow power used by a MR change to be considered.

Interface Lifetime: This method is derived from "Interface Power Consumption". By using the battery capacity and the general value of the interface power consumption, the lifetime when using an interface is obtained and compared [61, 98]. However, it is only the lifetime of the interface, and still does not consider the type of user application and the power consumed by the devices and the handover.

Power Consumption Model: some power models have been proposed for theoretical analysis. These models are based on the number of network hops and the communication distance, and are proposed for ad hoc networks and wireless sensor networks [99, 100]. They compute the overall power consumption of the whole network, and thus are not suitable for the present scenario. In addition, they do not consider the power consumed by devices and handovers because sensors consume very little power that can be ignored. In [64, 101, 102], a model based on the interface speed and the transmission time is proposed that computes the total power consumed by the interface for a certain type of communication. It can be used for different applications but does not consider the battery capacity and the power consumed by the devices.

Due to their limitations, none of the three methods is suitable for MR selection in a WPAN. In this thesis, a mechanism combining the lifetime and power consumption models is proposed, which can take the different types of applications and the power used by devices and handovers into consideration in the design.

6.3 Proposed Mechanism

In this section, a decision making mechanism for dynamically changing MR selection in a NEMO-based WPAN is proposed. This mechanism takes the cost of the MR change as one of the metrics in the decision making. It is composed of two parts for non-real-time and real-time applications in order to represent the user's requirements for different applications.

6.3.1 Scenario Description

An individual user has a WPAN that is composed of multiple personal devices, e.g. a mobile phone, a laptop, a PDA and a video player, as shown in in Fig. 6.1. One device is working as the MR for the WPAN, named CMR (Current MR). Some other devices are MR-capable but have not begun to work as the MR (they may be working as MNNs), and are named as the Potential MR (PMR). A certain content (non-real-time or real-time) is required by the user to be transferred from the content source outside the WPAN to a device in the WPAN. In this thesis, it is assumed that only one transfer exists at any time for a WPAN. Two cases are selected according to the user's needs.

Case 1: The CMR continues to be selected, and no any action is needed.

Case 2: One of the PMRs is selected, e.g. PMR1 in Fig 6.1, and a MR change is needed.

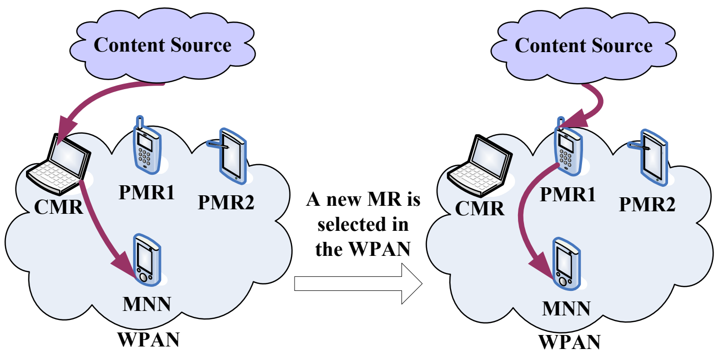


Figure 6.1: *Scenario of the dynamically changing MR selection in the WPAN*

6.3.2 Cost Function Proposal

The basic cost function is given in Equation 6.1. Three factors are considered: money, network speed and power consumption, denoted as C_m, C_s and C_p respectively, in the total cost (C), to reflect the user's concerns in real life. W_m, W_s and W_p denote the weights of money, network speed and power consumption respectively, used in the decision making process. Adjusting these weights can represent the user's different needs. The larger C is, the worse the performance is for this usage.

$$C = W_m \cdot C_m + W_s \cdot C_s + W_p \cdot C_p \tag{6.1}$$

This thesis proposes that two kinds of cost are considered in the design of the decision making mechanism: the cost of the content transfer (C_T) and the cost of the MR change (C_H), which are both represented in Equation 6.1 as follows.

$$\begin{cases} C_T = W_m \cdot C_{Tm} + W_s \cdot C_{Ts} + W_p \cdot C_{Tp} \\ C_H = W_m \cdot C_{Hm} + W_s \cdot C_{Hs} + W_p \cdot C_{Hp} \end{cases} \tag{6.2}$$

For keeping the CMR (**Case 1**), no action is needed, and thus its cost (C_{CMR}) is only C_T, shown as follows:

$$\begin{aligned} C_{CMR} &= W_m \cdot C_{m(CMR)} + W_s \cdot C_{s(CMR)} + W_p \cdot C_{p(CMR)} \\ &= W_m \cdot C_{Tm(CMR)} + W_s \cdot C_{Ts(CMR)} + W_p \cdot C_{Tp(CMR)} \end{aligned} \tag{6.3}$$

For considering changing to a PMR (**Case 2**), a MR change is needed, and thus its cost (C_{PMR}) is composed of C_T and C_H, shown as follows. If there are *n* PMRs, their costs are denoted by $C_{PMR1}, C_{PMR2}, \ldots, C_{PMRn}$.

$$\begin{aligned} C_{PMR} &= W_m \cdot C_{m(PMR)} + W_s \cdot C_{s(PMR)} + W_p \cdot C_{p(PMR)} \\ &= W_m \cdot (C_{Tm(PMR)} + C_{Hm(PMR)}) + W_s \cdot (C_{Ts(PMR)} + C_{Hs(PMR)}) \\ &\quad + W_p \cdot (C_{Tp(PMR)} + C_{Hp(PMR)}) \end{aligned} \tag{6.4}$$

Each parameter is calculated by algorithms proposed in Sections 6.3.3 and 6.3.4 according to the type of application. Based on these cost functions' results, potential procedures for MR selection are also proposed in Sections 6.3.3 and 6.3.4.

6.3.3 Mechanism Proposed for Non-Real-Time Applications

In this section, the mechanism details for non-real-time applications are proposed. In this thesis, data file transfer is considered as a non-real-time application. Its data could be very small (e.g.

an email) or very large (e.g. a high definition movie).

6.3.3.1 The Money Cost

C_m is represented by the price (m) of the access network used. Because the MR change is inside the WPAN, which is assumed to use a zero money cost network, and only local signalling messages are used, for PMR, there is no C_{Hm}. C_m of the CMR and all PMRs are normalized and calculated using Equation 6.5, where i denotes CMR, PMR1, PMR2, ... , PMRn. The higher m is, the larger C_m is, which means that a higher-price MR has a worse performance (i.e. a higher cost) for the user.

$$C_{m(i)} = \frac{m_i}{\max(m_{CMR}, m_{PMR1}, m_{PMR2}, ..., m_{PMRn})} \tag{6.5}$$

6.3.3.2 The Network Speed Cost

C_{Ts} is computed by the content transfer time (t). Different wireless interfaces result in a different t when considering the same file size (f). On the other hand, C_{Hs} is computed by the MR change delay (d). b denotes the data rate of the wireless interface.

When keeping the same CMR (**Case 1**), only C_{Ts} is considered, and thus t_{CMR} is calculated as: $t_{CMR} = \frac{f}{b_{CMR}}$

When considering changing to a PMR (**Case 2**), C_{Ts} and C_{Hs} are both considered, therefore the sum of t_{PMR} and d_{PMR} is used to represent the total time that the PMR needs to finish the MR change and the content transfer, which is denoted by t'_{PMR}. d_{PMR} is obtained by the algorithm in Chapter 5. t'_{PMR} is calculated as follows.

$$t'_{PMR} = t_{PMR} + d_{PMR} = \frac{f}{b_{PMR}} + d_{PMR} \tag{6.6}$$

Therefore, C_s of the CMR and all PMRs are normalized and calculated as Equation 6.7, where i denotes CMR, PMR1, PMR2, ... , PMRn. The higher t or t' is, the higher C_s is, which means that the longer-transfer-time MR has a worse performance for the user.

$$C_{s(i)} = \frac{t_i}{\max(t_{CMR}, t'_{PMR1}, \ldots, t'_{PMRn})} \qquad t_i = t_{CMR}, t'_{PMR1}, \ldots, t'_{PMRn} \tag{6.7}$$

6.3.3.3 The Power Consumption Cost

C_p is represented by the MR's remaining working lifetime (L). L denotes that after finishing the current required whole file transfer, how long the MR can continue to work for a WPAN's average data rate content transfer which represents the average data rate of an individual user's normal network usage for receiving content with this WPAN in real life, i.e. the time of how long the MR can continue to operate in the WPAN. The longer L is, the longer the lifetime of the WPAN is and the better the power performance of the WPAN is for the user. This mechanism proposes L because this thesis considers a WPAN, in which multiple devices have various wireless interfaces and diverse batteries, and thus only comparing the power consumption of wireless interfaces, which is common among other researchers, is not enough for decision making. On the other hand, the influence of the MR change also needs to be considered in the power calculation.

The power consumption model for the interface power (P, unit: watt) in this thesis is from [101] shown as Equation 6.8. PB, PT and PR (watt/kbps) respectively denote the power consumption of background, transmissions and receptions in the wireless interface. b_t and b_r (kbps) respectively denote the data rate of transmissions and receptions.

$$P = PB + PT \cdot b_t + PR \cdot b_r \tag{6.8}$$

The System Standby Power (SP, unit: watt) is used to represent the standby power consumed by the device's hardware and software when working as the MR, excluding the power used by wireless interfaces. According to different types and designs, some devices may shut down all other parts only using the MR module, but some must keep the main parts running. Therefore, the calculation of L is divided into two situations: without considering SP and with considering SP.

- **L without considering SP**

b_a denotes the average data rate of an individual user's normal network usage for content transfer with this WPAN. This is an average value that is estimated by counting common users' communications in real life for a long time. Some prediction methods can be designed, but in this thesis, an estimation model from [83] is directly used (prediction methods can be further researched in future work). b_a is shown in Equation 6.9, where the session interarrival time follows an exponential distribution with rate λ_S, the average session length in packets is E(S) and PS is the average packet size.

$$b_a = \lambda_S \cdot \mathrm{E}(S) \cdot PS \tag{6.9}$$

P_a (unit: watt) denotes the average power consumption of wireless interfaces for b_a of content transfer. The MR uses the egress interface (e.g. UMTS) for receiving the file from the content source outwith the WPAN, and uses the ingress interface (e.g. Bluetooth) for transmitting the file to a MNN inside the WPAN. This thesis uses superscripts - (i) and (e) respectively denoting ingress and egress interfaces, and subscripts - at and ar respectively denoting the average data rate of transmissions and receptions. By using Equation 6.8, P_a of ingress and egress interfaces are obtained as follows.

$$\begin{cases} P_a = {P_a}^{(i)} + {P_a}^{(e)} \\ {P_a}^{(i)} = {P_{at}}^{(i)} = PB^{(i)} + PT^{(i)} \cdot b_{at} = PB^{(i)} + PT^{(i)} \cdot (\lambda_S \cdot \mathrm{E}(S) \cdot PS) \\ {P_a}^{(e)} = {P_{ar}}^{(e)} = PB^{(e)} + PR^{(e)} \cdot b_{ar} = PB^{(e)} + PR^{(e)} \cdot (\lambda_S \cdot \mathrm{E}(S) \cdot PS) \end{cases} \tag{6.10}$$

$$P_a = PB^{(i)} + PB^{(e)} + \left(PT^{(i)} + PR^{(e)}\right) \cdot (\lambda_S \cdot \mathrm{E}(S) \cdot PS) \tag{6.11}$$

RB (unit: watt-hour) denotes an estimated prospective remaining capacity of the battery that will be after the current required whole file transfer is finished. Therefore, L is calculated as Equation 6.12:

$$L = \frac{RB}{P_a} \tag{6.12}$$

When keeping the CMR unchanged (**Case 1**), only C_{Tp} is considered, and thus the power is only used by the file transfer. RB is calculated as Equation 6.13. CB (watt-hour) denotes the current remaining capacity of the battery that is measured at the start of a whole file transfer or measured during this transfer. If CB is measured at the start of this transfer, f is the whole file size. If CB is measured during this transfer, f is the size of this file's remaining segment at the moment when CB is measured (In other words, CB is measured at the start of transferring a certain remaining segment of this file). B_T (watt-hour) denotes an estimated prospective capacity of the battery that will be used by the whole file transfer or by the transfer of this file's remaining segment. P_T (watt) denotes the power consumed by the wireless interfaces for this transfer. t is obtained from the calculation of C_{Ts} in Section 6.3.3.2 using f. The MR is to relay the file, and thus $b_t = b_r = b$. Therefore:

$$\begin{cases} RB_{CMR} = CB - B_T = CB - P_T \cdot t \\ P_T = P^{(i)} + P^{(e)} = PB^{(i)} + PT^{(i)} \cdot b + PB^{(e)} + PR^{(e)} \cdot b \end{cases} \tag{6.13}$$

$$RB_{CMR} = CB - (PB^{(i)} + PT^{(i)} \cdot b + PB^{(e)} + PR^{(e)} \cdot b) \cdot t \tag{6.14}$$

By using Equations 6.12, 6.11 and 6.14, L_{CMR} is calculated as follows.

$$L_{CMR} = \frac{CB - (PB^{(i)} + PT^{(i)} \cdot b + PB^{(e)} + PR^{(e)} \cdot b) \cdot t}{PB^{(i)} + PB^{(e)} + \left(PT^{(i)} + PR^{(e)}\right) \cdot (\lambda_S \cdot E\left(S\right) \cdot PS)} \tag{6.15}$$

When considering switching to a PMR (**Case 2**), C_{Tp} and C_{Hp} are both considered, so the capacity of the battery consumed by the MR change (B_H, unit: watt-hour) is also involved. The PMR's RB is calculated as follows. B_H is calculated according to the scheme in Chapter 5. P_{Hk} (watt) and t_k respectively denote the power consumed by the wireless interface and the data transfer time in the k-th step of the signalling procedure. P_{Hk} and t_k are calculated according to the parameters of the particular wireless interface and the signalling messages used in the k-th step.

$$\begin{cases} RB_{PMR} = CB - B_T - B_H \\ B_T = P_T \cdot t = (PB^{(i)} + PT^{(i)} \cdot b + PB^{(e)} + PR^{(e)} \cdot b) \cdot t \\ B_H = \sum\limits_k P_{Hk} \cdot t_k = \sum\limits_k (PB_k + PT_k \cdot b_{tk} + PR_k \cdot b_{rk}) \cdot t_k \end{cases} \tag{6.16}$$

$$RB_{PMR} = CB - (PB^{(i)} + PT^{(i)} \cdot b + PB^{(e)} + PR^{(e)} \cdot b) \cdot t - \sum_k P_{Hk} \cdot t_k \tag{6.17}$$

By using Equations 6.12, 6.11 and 6.17, L_{PMR} is calculated as follows.

$$L_{PMR} = \frac{CB - (PB^{(i)} + PT^{(i)} \cdot b + PB^{(e)} + PR^{(e)} \cdot b) \cdot t - \sum\limits_k P_{Hk} \cdot t_k}{PB^{(i)} + PB^{(e)} + \left(PT^{(i)} + PR^{(e)}\right) \cdot (\lambda_S \cdot E\left(S\right) \cdot PS)} \tag{6.18}$$

- L **when considering** SP

Some personal devices consume SP to maintain operations of the hardware and basic software, e.g. a laptop needs to keep the CPU and memory powered on. Most research on power-saving mechanisms for terminals is for wireless sensor networks. They ignore SP because the sensor's

SP is tiny. However, in some personal devices, like a laptop, SP can not be ignored.

For the CMR, SP is included in the calculation as follows. When the CMR's RB is calculated, because CB is measured at the start of a whole file transfer or during this transfer, the influence of power, which is consumed by previous file transfer and SP, to the remaining transfer is avoided. SP is consumed in both processes of the current required content transfer and the average data rate content transfer afterwards, and thus is included in both of the two parts of Equation 6.19.

$$\begin{cases} RB_{CMR} = CB - B_T = CB - (P_T + SP) \cdot t \\ L_{CMR} = \frac{RB_{CMR}}{P_a + SP} \end{cases} \tag{6.19}$$

$$L_{CMR} = \frac{CB - (PB^{(i)} + PT^{(i)} \cdot b + PB^{(e)} + PR^{(e)} \cdot b + SP) \cdot t}{PB^{(i)} + PB^{(e)} + \left(PT^{(i)} + PR^{(e)}\right) \cdot (\lambda_S \cdot E\left(S\right) \cdot PS) + SP} \tag{6.20}$$

For a PMR, SP is included in the calculation as follows. Notice that SP is also considered in the MR change.

$$\begin{cases} RB_{PMR} = CB - B_T - B_H = CB - (P_T + SP) \cdot t - B_H \\ L_{PMR} = \frac{RB_{PMR}}{P_a + SP} \end{cases} \tag{6.21}$$

$$L_{PMR} = \frac{CB - (PB^{(i)} + PT^{(i)} \cdot b + PB^{(e)} + PR^{(e)} \cdot b + SP) \cdot t - \sum_k (P_{Hk} + SP) \cdot t_k}{PB^{(i)} + PB^{(e)} + \left(PT^{(i)} + PR^{(e)}\right) \cdot (\lambda_S \cdot E\left(S\right) \cdot PS) + SP} \tag{6.22}$$

- **C_p calculation**

C_p of the CMR and all PMRs are normalized calculated as Equation 6.23, where i denotes CMR, PMR1, PMR2, ... , PMRn. The longer L is, the smaller C_p is, which means that the longer-lifetime MR has a better performance for the user.

$$C_{p(i)} = \frac{{}^{1}/_{L_i}}{\max({}^{1}/_{L_{CMR}}, {}^{1}/_{L_{PMR1}}, \ldots, {}^{1}/_{L_{PMRn}})} \quad L_i = L_{CMR}, L_{PMR1}, \ldots, L_{PMRn} \tag{6.23}$$

6.3.3.4 The Total Cost and the Decision Making

C is calculated by Equation 6.1 using C_m, C_s and C_p obtained by Equations 6.5, 6.7 and 6.23. In order to compare the cost of the CMR and the PMRj (j=1, 2, ..., n), the ratio of the cost of CMR and the PMRj (D_j) is defined as follows.

$$D_j = \frac{C_{PMRj}}{C_{CMR}} \tag{6.24}$$

When $D_j < 1$, C_{PMRj} is less than C_{CMR}, and thus PMRj can be considered to work as the new MR. In order to avoid oscillation and hysteresis in decision making, a threshold ($\triangle$) is set. Only when $D_j < \triangle < 1$, is MR change triggered : the PMR with the smallest D ($D < \triangle$) is selected as the new MR, i.e. the new MR satisfies the condition:

$$D(newMR) = \min_{\forall D_j < \Delta} D_j \tag{6.25}$$

The flowchart of the proposed mechanism is shown in Fig. 6.2.

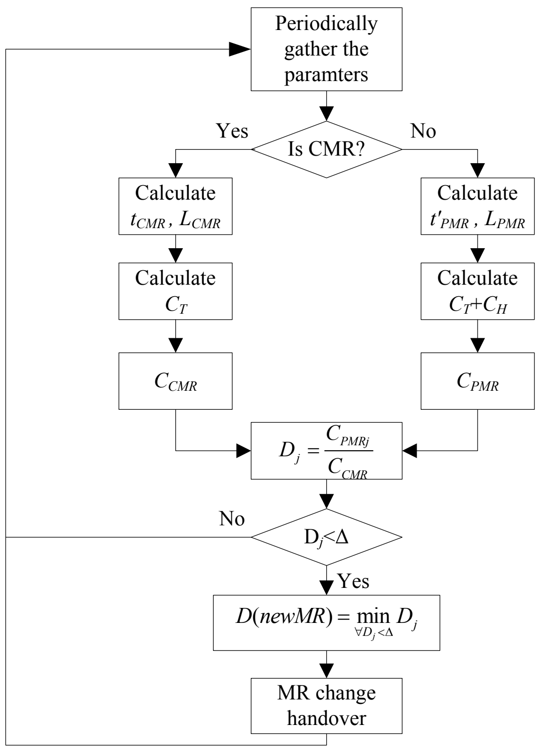


Figure 6.2: *The flowchart of the proposed mechanism*

6.3.4 Mechanism Proposed for Real-Time Applications

In this section, the mechanism details for real-time applications are proposed. Two kinds of real-time applications are considered in this thesis: Voice-over-IP (VoIP) and online video. The mechanism is generally similar to that for non-real-time applications in Section 6.3.3, but also has some differences.

The calculation of C_m is the same as Equation 6.5 in Section 6.3.3.1. This section focuses on the calculation of C_s and C_p.

6.3.4.1 The Network Speed Cost

C_{Ts} is computed by the packet end-to-end delay (t_d). C_{Hs} is computed by the MR change delay (d).

The packet end-to-end delay (t_d) is one of the most important QoS parameters for real-time communications. It is composed of the packet transmission delay, the path propagation delay and the queuing delay at the router of each hop. This work is not focused on the QoS adaptation, therefore, latency (l) is used to represent the path propagation delay and the queuing delay at each router. t_d is calculated as follows. b_h, l_h and H_h denote the bandwidth, latency and extra headers (e.g. Mobile IP and NEMO MR header) at the h-th hop for the packet size (PS).

$$t_d = \sum_h \left(\frac{PS + H_h}{b_h} + l_h \right) \tag{6.26}$$

For the CMR, only C_{Ts} is considered, and thus:

$$t_{d(CMR)} = \sum_h \left(\frac{PS + H_{h(CMR)}}{b_{h(CMR)}} + l_{h(CMR)} \right) \tag{6.27}$$

For a PMR, C_{Ts} and C_{Hs} are both considered, therefore the sum of $t_{d(PMR)}$ and d_{PMR} is used to represent the total delay for real-time applications considering the MR change, which is denoted by $t'_{d(PMR)}$. d_{PMR} is obtained by the algorithm in Chapter 5. $t'_{d(PMR)}$ is calculated as follows.

$$t'_{d(PMR)} = t_{d(PMR)} + w_d \cdot d_{PMR} = \sum_h \left(\frac{PS + H_{h(PMR)}}{b_{h(PMR)}} + l_{h(PMR)} \right) + w_d \cdot d_{PMR} \tag{6.28}$$

w_d is the weight for d_{PMR}. Its value is from 0 to 1. It is used to show how important the user considers d. For example:

If $w_d = 0$, it means that the user never considers the MR change handover delay. Although real-time applications may be interrupted due to delay and packet loss during the MR change, the user can accept it since it is a one-time MR change, after which the delay can be reduced to the value that the QoS requires.

If $w_d = 1$, it means that the user considers the MR change delay equally important as the packet end-to-end delay. In this case, the user may care about the real-time application so seriously that no interruption is acceptable. Therefore, the effects of d and t_d both matter in the decision making.

Therefore, C_s of the CMR and all PMRs are normalized and calculated using Equation 6.29, where i denotes CMR, PMR1, PMR2, ... , PMRn. The higher t_d or t'_d is, the higher C_s is, which means that the higher-delay MR has a worse performance for the user.

$$C_{s(i)} = \begin{cases} 1, t_i \geq t_{d(max)} \\ \frac{t_i}{t_{d(max)}}, t_i < t_{d(max)} \end{cases} \quad t_i = t_{CMR}, t'_{PMR1}, \ldots, t'_{PMRn} \tag{6.29}$$

In Equation 6.29, $t_{d(max)}$ denotes the maximum delay that the real-time application can accept. t_i is compared with $t_{d(max)}$ to get a ratio. When $t_i \geq t_{d(max)}$, the real-time application will be interrupted, and thus network speed cost is 1. When $t_i < t_{d(max)}$, the network speed cost is smaller than 1, and the smaller t_i is, the smaller the network speed cost is.

6.3.4.2 The Power Consumption Cost

C_p is computed by the MR's remaining working lifetime (L). The difference between real-time and non-real-time applications is that the duration of real-time applications is unknown. Therefore, L in real-time applications is defined as the time that the MR can sustain the real-time application for the WPAN.

P_{rt} (watt) denotes the power consumption of the wireless interface for the real-time application. B_{rt} denotes the required bandwidth of the real-time application, which is another important QoS parameter. By using Equation 6.8, P_{rt} is obtained as follows, where (i) and (e) respectively denotes ingress and egress interfaces.

$$P_{rt} = {P_{rt}}^{(i)} + {P_{rt}}^{(e)} = PB^{(i)} + PB^{(e)} + \left(PT^{(i)} + PR^{(e)}\right) \cdot B_{rt} \tag{6.30}$$

The calculation of L is also divided into two situations: without considering SP and with considering SP. Similarly to the algorithm in Section 6.3.3.3, L is obtained as follows by using Equation 6.30.

- L **without considering** SP

$$L_{CMR} = \frac{CB}{P_{rt}} = \frac{CB}{PB^{(i)} + PB^{(e)} + \left(PT^{(i)} + PR^{(e)}\right) \cdot B_{rt}} \tag{6.31}$$

$$L_{PMR} = \frac{CB - B_H}{P_{rt}} = \frac{CB - \sum_k P_{Hk} \cdot t_k}{PB^{(i)} + PB^{(e)} + \left(PT^{(i)} + PR^{(e)}\right) \cdot B_{rt}} \tag{6.32}$$

- L **when considering** SP

$$L_{CMR} = \frac{CB}{P_{rt} + SP} = \frac{CB}{PB^{(i)} + PB^{(e)} + \left(PT^{(i)} + PR^{(e)}\right) \cdot B_{rt} + SP} \tag{6.33}$$

$$L_{PMR} = \frac{CB - B_H}{P_{rt} + SP} = \frac{CB - \sum_k (P_{Hk} + SP) \cdot t_k}{PB^{(i)} + PB^{(e)} + \left(PT^{(i)} + PR^{(e)}\right) \cdot B_{rt} + SP} \tag{6.34}$$

The calculation of C_p is the same as Equation 6.23.

6.3.4.3 The Total Cost and the Decision Making

C is calculated by Equation 6.1 using C_m, C_s and C_p obtained by Equation 6.5, 6.29 and 6.23. In order to compare the cost of the CMR and the PMRj (j=1, 2, ..., n), D_j is still used. However, the procedure of decision making in real-time applications is different from that in non-real-time applications.

Step 1: Compare the bandwidth of the wireless interface of the PMR (b_{PMR}) with the QoS required bandwidth (B_{rt}). If $b_{PMR} < B_{rt}$, this PMR can not be selected as the new MR.

If $b_{PMR} \geq B_{rt}$, this PMR can be taken into the second step. It is assumed that the CMR fulfills B_{rt}.

Step 2: Calculate the corresponding C_m, C_s and C_p of the CMR and any PMR that fulfils the requirements in step 1. Calculate D_j by

$$D_j = \frac{C_{PMRj}}{C_{CMR}} \tag{6.35}$$

If $D_j < \triangle < 1$, select the PMR that satisfies the following condition as the new MR.

$$D(newMR) = \min_{\forall D_j < \Delta} D_j \tag{6.36}$$

6.4 Numerical Simulation

To present the behavior of these decision making mechanisms, numerical simulation results are undertaken for different types of applications and diverse users' needs. The results are divided into two parts: non-real-time applications (various-size file transfers) and real-time-applications (VoIP and online videos).

6.4.1 Parameter Setting

6.4.1.1 Scenario Setting

The overall scenario is shown in Fig. 6.1. Four devices are included in a WPAN. Three of them are MR-capable: the laptop, the mobile phone and the PDA; one can only be a MNN: the video player. The Laptop is the CMR, and the mobile phone and the PDA are the PMRs.

6.4.1.2 Device and Interface Parameter Setting

The devices' parameters are shown in Table 6.1. Wireless interface parameters are shown in Table 6.2, where the power parameters are derived from published research [64, 101, 102].

Device	Mobile Phone	Laptop	PDA	Video Player
MR-Capability	Yes	Yes	Yes	No
MNN-Capability	Yes	Yes	Yes	Yes
Egress Interface	UMTS	WiFi	WiFi	Not Available
Ingress Interface	Bluetooth	Bluetooth	Bluetooth	Bluetooth
SP (watt)	0.02	2	0.02	0.02
Max Battery Capacity (watt-hour)	4	80	6	6

Table 6.1: *Device Parameter Setting*

Interfaces	UMTS	Wifi	Bluetooth
Speed	384 Kbps	4.3 Mbps	1.6 Mbps
PB (μwatt)	107.20	262.74	118.5
PT (μwatt/kbps)	8.28	1.22	8.56
PR (μwatt/kbps)	4.92	1.22	4.35
Usage Price	0.01 pounds/KByte	free of charge	free of charge

Table 6.2: *Wireless Interface Parameter Setting*

6.4.1.3 Application Parameter Setting

For the file transfer, the file size changes from 1 KBytes to 1 GBytes, which can represents situations from a tiny file (such as an email) to a very large file (such as a high definition movie).

For the online video, H.264 [103] is used, which is the most popular codec for online video. “Youtube” is used as the example. “Youtube” uses H.264 with a resolution of 320x240, which requires a bandwidth of 384 kbps and maximum delay of 400 ms. The packet size in H.264 is changeable. Some papers propose a mechanism of how to choose the packet size in video streaming. An average packet size of 700Bytes (not including the IP header) is used here.

For VoIP, G.711 [104] is used, which is the most popular codec for the VoIP. It requires a bandwidth of 64 kbps, a packet size of 180 Bytes (not including the IP header) and a maximum delay of 150 ms.

6.4.1.4 Mechanism Parameter Settings

Other parameters used in the mechanism are set as follows: $\lambda_S = 1$, $E(S) = 10$, $PS = 1000Bytes$.

The threshold of D is set as $\Delta = 0.8$. The weight of d_{PMR} is set as: $w_d = 0.5$, which means the user cares about the MR change delay in real-time applications but can accept some interruption caused by the delay.

Different weights are set as follows to represent the diverse requirements of users. Three of them concentrate on the power because it is the most critical problem for mobile users, and thus in this thesis, the results related to power are the main focus.

Requirement 1: $W_m = 0.05$ $W_s = 0.05$ $Wp = 0.9$: the user only cares about power consumption.

Requirement 2: $W_m = 0.05$ $W_s = 0.35$ $Wp = 0.6$: the user cares mostly about the power consumption with a secondary consideration of speed, but does not care about the money.

Requirement 3: $W_m = 0.05$ $W_s = 0.475$ $Wp = 0.475$: the user cares about the power consumption and speed equally but does not care about the money.

Requirement 4: $W_m = 0.4$ $Ws = 0.4$ $Wp = 0.2$: the user cares about the money and speed equally, but cares less about the power.

6.4.2 Numerical Simulation Results

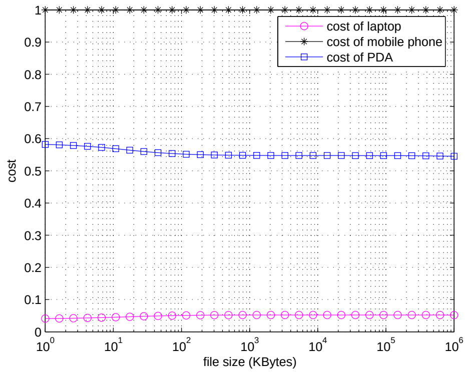
The numerical simulation is performed for non-real-time and real-time applications when the device condition, the application and the user's requirements change, in order to present the results of the decision making mechanism in the dynamic environment.

6.4.2.1 Numerical Simulation Results for Non-Real-Time Applications

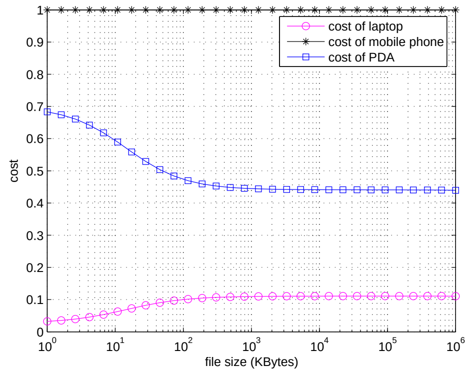
Simulations not considering SP and considering SP are performed, in order to show the effect of SP in the decision making.

- **Simulations not considering SP**

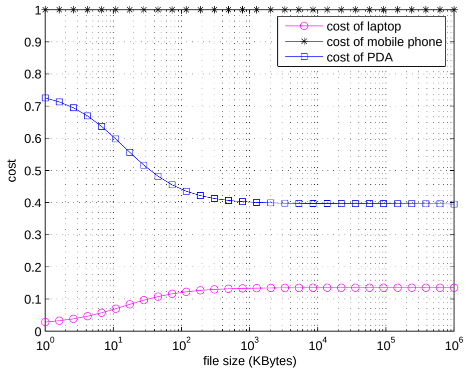
Fig. 6.3 shows the cost of the three devices for four requirements when the file size changes from 1 KBytes to 1 GBytes. The batteries of the three devices are all start at a charge of 100%. The laptop always has a smaller cost than the mobile phone and the PDA, and thus the MR will not be changed. This is because the laptop has a much higher battery capacity than the



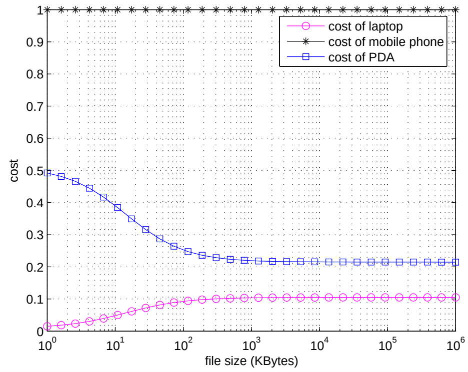
(a) Requirement 1



(b) Requirement 2



(c) Requirement 3

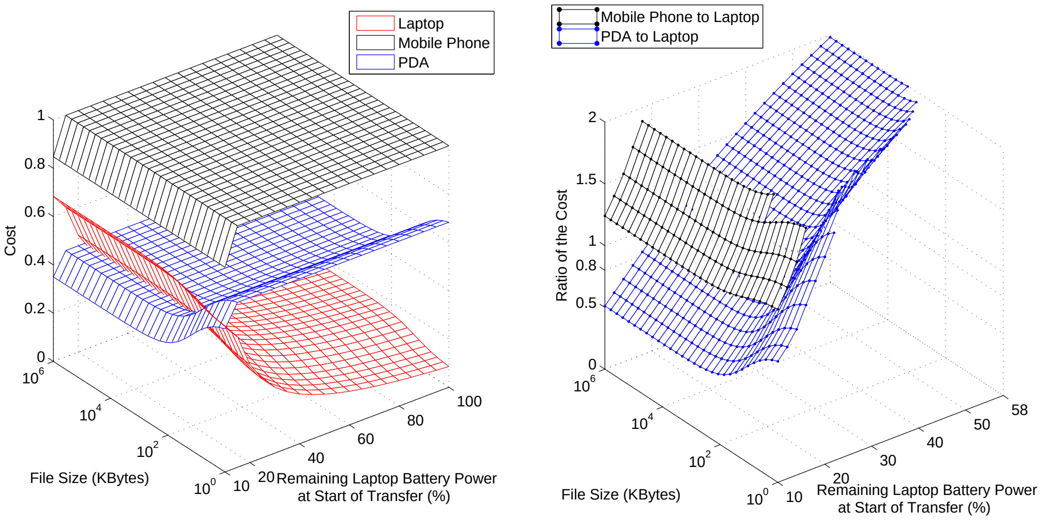


(d) Requirement 4

Figure 6.3: *The cost when the file size changes*

two other devices, which makes its remaining working life time (L) the longest, and its WiFi interface has a faster speed than the UMTS interface of the mobile phone. The cost of mobile phone is always the highest. This is because its price and the content transfer time is the highest and it always has the shortest L. Therefore, based on Equation 6.1, the mobile phone's C_m, C_s and C_p are all 1, and thus its total cost is 1. From Fig. 6.3(a) to 6.3(d), the cost of the PDA reduces. This is because the weighting of the power factor in the decision making becomes smaller, and thus the PDA cost reduces if the user cares less about the power factor.

In order to investigate the effect of the concurrent change of file size and power on the decision making, the laptop's remaining battery charge is changed from 100% to 10% at the start of file transfer, and the file size is also changed. The batteries of the mobile phone and the PDA are both kept at an initial charge of 100%. This can simulate the situation where the laptop becomes short of power. **Requirement 2** is used here. Fig. 6.4 shows the simulation results, where Fig. 6.4(a) shows the cost of the three devices and Fig. 6.4(b) shows the ratio of the

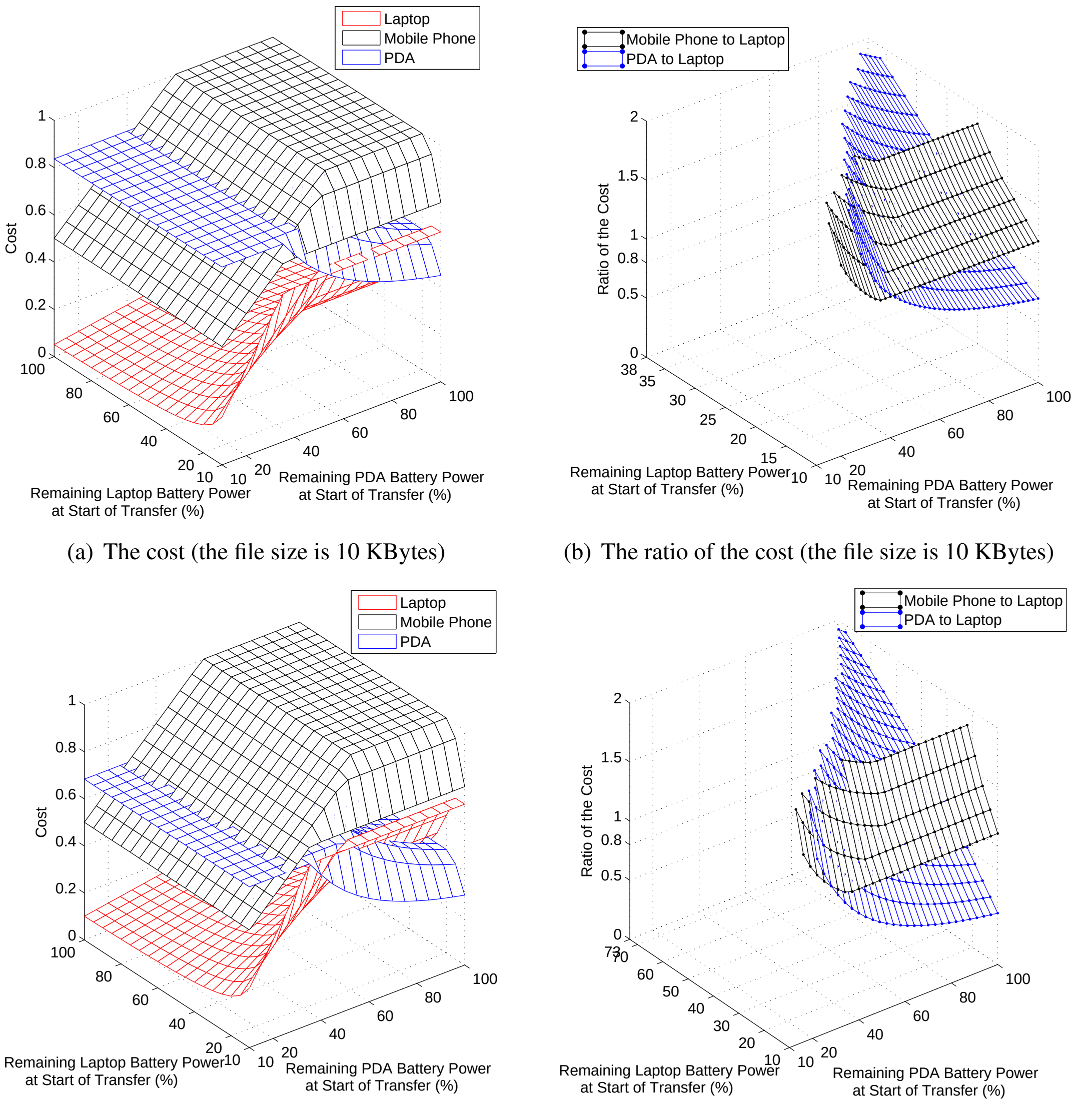


(a) The cost (b) The ratio of the cost

Figure 6.4: *The cost and the ratio of the cost when the file size and the remaining battery capacity of the laptop both change*

cost (D) for the PMRs (i.e. the mobile phone and the PDA). D is truncated to [0,2] in these figures, since only values smaller than 0.8 matter in the decision making as $\Delta = 0.8$. When the remaining battery capacity of the laptop is less than 23% and the file size is larger than 8 KBytes, the PDA's cost is smaller than that of the laptop (Fig. 6.4(a)), and its D is the minimum and smaller than Δ (Fig. 6.4(b)), therefore, the MR will change to the PDA. The small remaining battery capacity of the laptop leads to a small L and large C_p for the laptop. When the file size becomes large, the MR change delay becomes less important compared to the file transfer time, which leads to a small C_t for the PDA. Therefore, the less the remaining battery capacity of the laptop is and the larger the file size is, the lower the PDA's cost is and the more likely that the PDA will be selected as the new MR. The mobile phone's cost is always the highest among the three devices, and thus is never selected.

In order to investigate the effect of the simultaneous change of two devices' power on the decision making, the remaining charge of the batteries of the laptop and the PDA are both set from 100% to 10% of capacity at the start of file transfer. The charge of the battery of the mobile phone is set to 100%. Two file transfers are considered: 10 KBytes and 100 MBytes. This can simulate the situation that the laptop and the PDA both become short of power. **Requirement 2** is used here. According to Fig. 6.5(a) and 6.5(b) (the file size is 10 KBytes), when the laptop's battery is smaller than 12% and the PDA's battery capacity is larger than 83%, the laptop's cost



(a) The cost (the file size is 10 KBytes)

(b) The ratio of the cost (the file size is 10 KBytes)

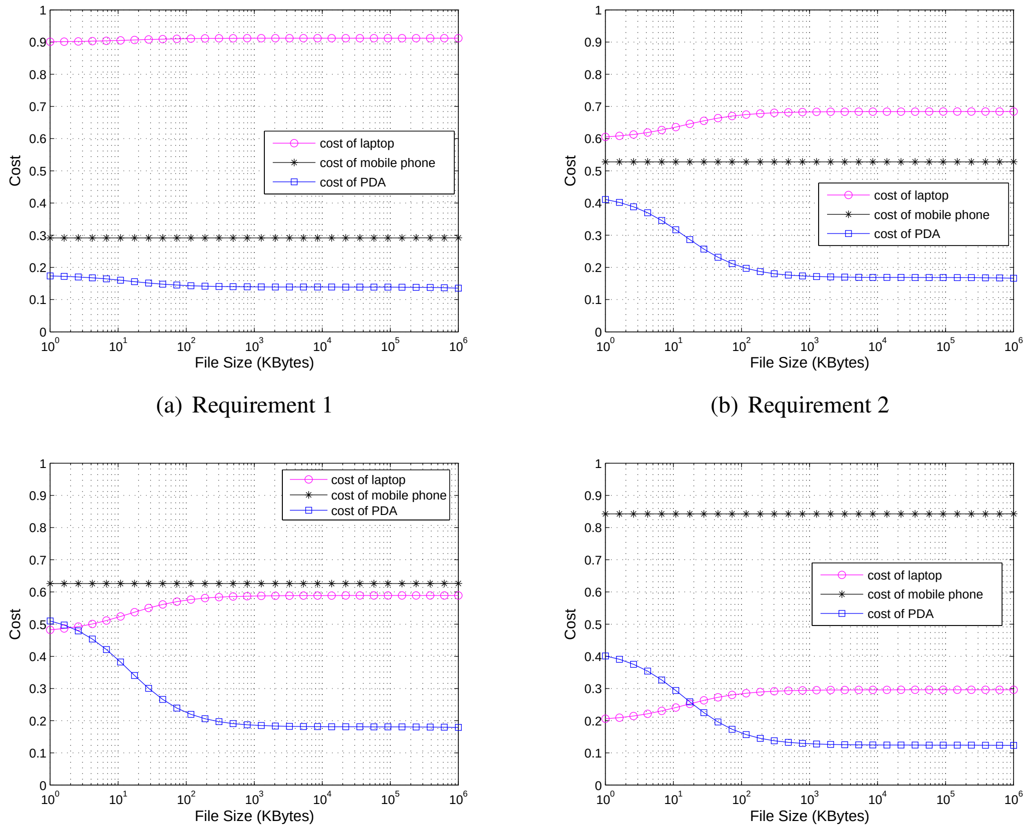
(c) The cost (the file size is 100 MBytes)

(d) The ratio of the cost (the file size is 100 MBytes)

Figure 6.5: *The cost and the ratio of the cost when the remaining battery capacities of the laptop and the PDA both change*

is larger than that of the PDA and $D_{PDA} < 0.8$, therefore, the MR will change to the PDA. Similarly, according to Fig. 6.5(c) and 6.5(d) (the file size is 100 MBytes), when the laptop's battery capacity is smaller than 20% and the PDA's battery capacity is larger than 71%, the MR will change to the PDA. Compared to Fig. 6.5(b), the MR more likely changes to the PDA in Fig. 6.5(d). This is because the larger the file size is, the lower the PDA's C_t becomes compared to the laptop, due to the reason discussed in Fig. 6.4.

- **Simulations incorporating consideration of SP**



(a) Requirement 1

(b) Requirement 2

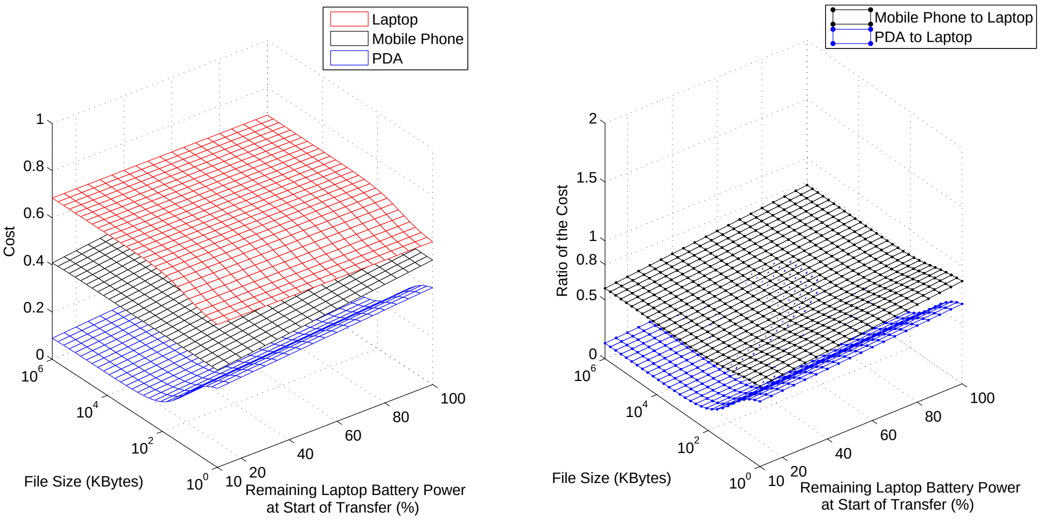
(c) Requirement 3

(d) Requirement 4

Figure 6.6: *The cost when the file size changes*

Fig. 6.6 shows the cost of the three devices for four requirements when the file size changes and SP is considered. The batteries of the three devices all start at a charge of 100%. From Fig. 6.6(a) to 6.6(c), the PDA always has the smallest cost, and thus the MR will change to the PDA. This is because the laptop has the highest SP which seriously shortens its L. When the user cares most about the power (i.e. **requirement 1**, **2** and **3**), the laptop is the worst device to select. In Fig. 6.6(d), when the file size is smaller than 10 KBytes, the laptop has the smallest cost, and thus the MR will not be changed. This is because the small file size leads to a small file transfer time, and thus MR change delay becomes more important in the cost calculation, which leads to a large C_t for the PDA. When the user cares about the time (i.e. **requirement 4**), the PDA is less likely to be selected since the device may take a much longer time for the MR change than to transfer the file.

In order to investigate the effect of the concurrent change of the file size and the power on the decision making, the laptop's remaining battery capacity is changed from 100% to 10% at the



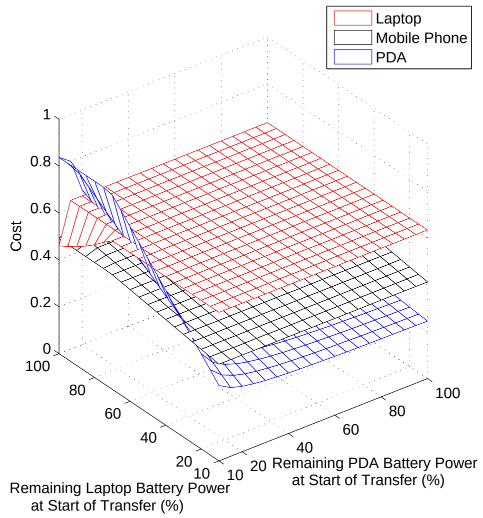
(a) The cost

(b) The ratio of the cost

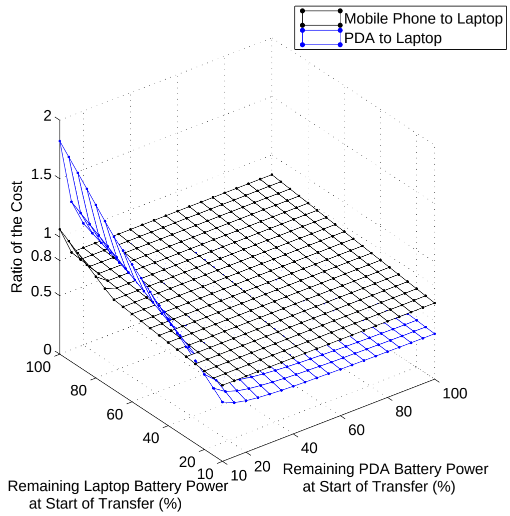
Figure 6.7: *The cost and the ratio of the cost when the file size and the remaining battery capacity of the laptop both change*

start of the file transfer, and the file size is also changed. The batteries of the mobile phone and the PDA are both kept at an initial charge of 100%. This can simulate the situation of the laptop becoming short of power. **Requirement 2** is used here. Fig. 6.7 shows that no matter how the file size and the laptop's remaining battery capacity change, the PDA always has the smallest cost and its $D < 0.8$, therefore, the MR always changes to the PDA. Compared to Fig. 6.4 which does not consider SP, the laptop changes from being the best device to the worst one for selection because its high SP leads to a very short L.

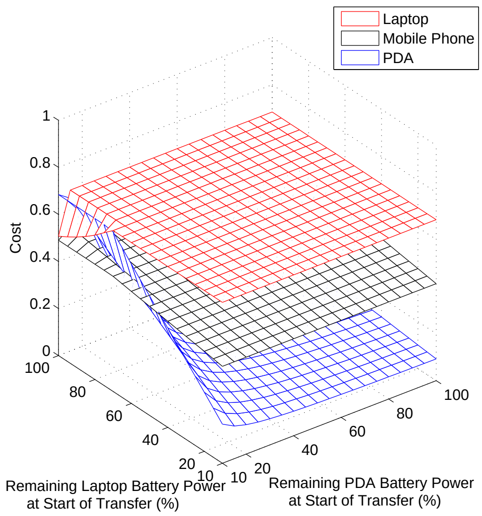
In order to investigate the effect of the concurrent change of two devices' power on the decision making, the remaining battery capacities of the laptop and the PDA are both changed from 100% to 10% at the start of the file transfer. The remaining battery capacity of the mobile phone is kept at 100%. Two file transfers are considered: 10 KBytes and 100 MBytes. This can simulate the situation that the laptop and the PDA both become short of power. **Requirement 2** is used here. According to Fig. 6.8(a) and 6.8(b) (the file size is 10 KBytes), in most situations, the PDA is selected as the new MR. However, when the laptop's remaining battery capacity is larger than 27% and the PDA's remaining battery capacity is smaller than 20%, the mobile phone is selected as the new MR because the PDA becomes short of power and is worse than the mobile phone for selection due to its high power consumption cost. When the laptop's remaining battery capacity is larger than 93% and the PDA's remaining battery capacity is



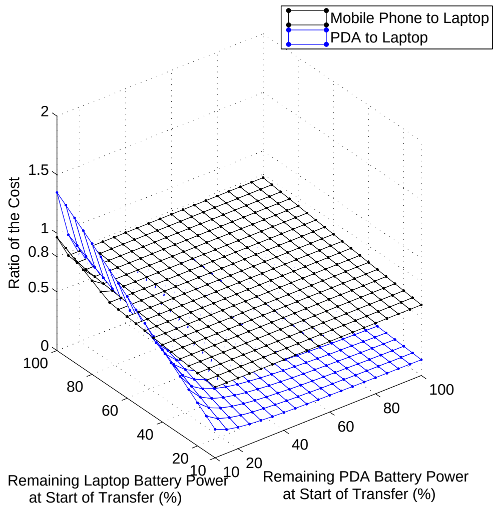
(a) The cost (the file size is 10 KBytes)



(b) The ratio of the cost (the file size is 10 KBytes)



(c) The cost (the file size is 100 MBytes)



(d) The ratio of the cost (the file size is 100 MBytes)

Figure 6.8: *The cost and the ratio of the cost when the remaining battery capacities of the laptop and the PDA both change*

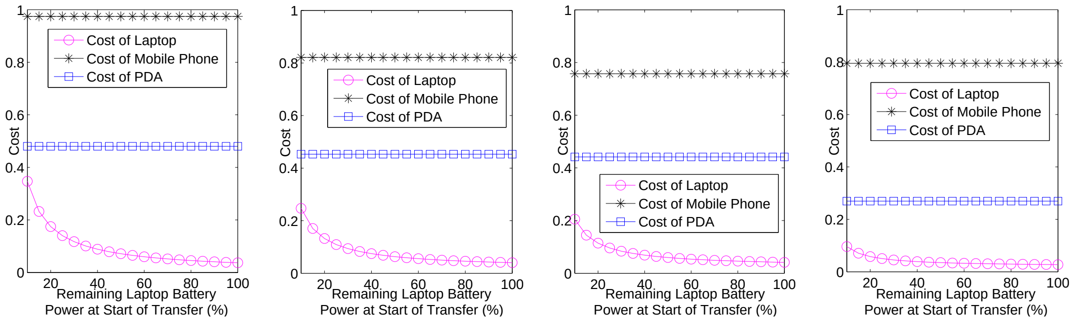
smaller than 12%, although the mobile phone may still have a smaller cost than the laptop, its $D \geq 0.8$, therefore, the MR will not be changed. This is because although the mobile phone is better than the laptop in terms of power consumption, it is worse in terms of price and network speed. In addition, the PDA's tiny battery power produces the shortest L that makes the laptop's C_p become relatively small, and thus the laptop's total cost becomes small. Similar results are also shown in Fig. 6.8(c) and 6.8(d) (the file size is 100 MBytes). Compared to Fig. 6.8(b), the MR more likely changes to the PDA or the mobile phone in Fig. 6.8(d). This is because the larger the file size is, the less the PMR's C_t becomes compared to the CMR, due to the reason in

Fig. 6.4. Therefore, different device conditions and applications will lead to different decision making depending on the user's requirements.

6.4.2.2 Numerical Simulation Results for Real-Time Applications

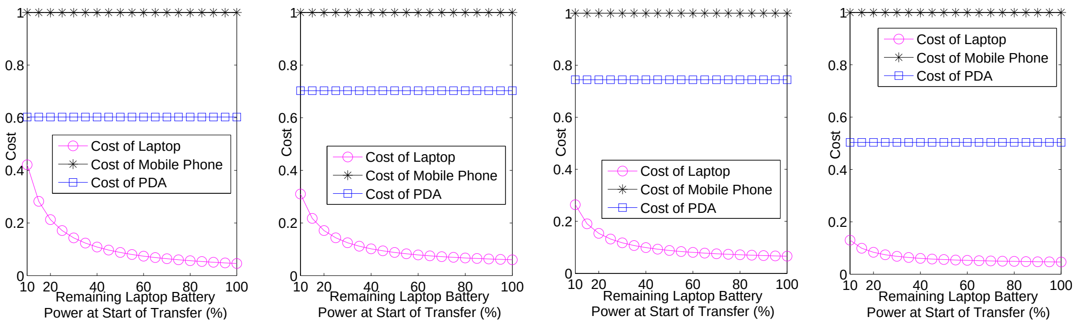
The simulations without considering SP and when considering SP are performed, in order to show the effect of SP in the decision making.

- **Simulations without considering SP**



(a) Requirement 1 (b) Requirement 2 (c) Requirement 3 (d) Requirement 4

Figure 6.9: *The cost when the laptop's remaining battery capacity changes (Online Video)*

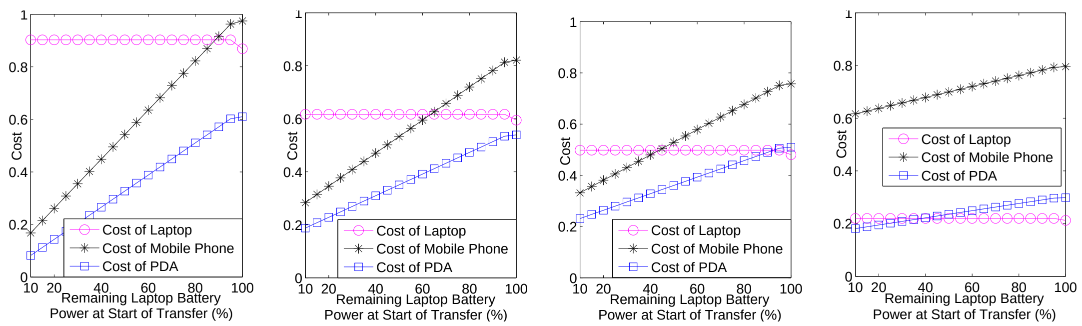


(a) Requirement 1 (b) Requirement 2 (c) Requirement 3 (d) Requirement 4

Figure 6.10: *The cost when the laptop's remaining battery capacity changes (VoIP)*

Fig. 6.9 and 6.10 show the cost of the three devices in the online video and VoIP respectively without considering the SP. The simulation is performed for four requirements when the laptop's remaining battery capacity changes from 10% to 100%. The batteries of the mobile phone and the PDA are both at 100% of available capacity. The laptop always has the smallest cost, and thus the MR will not be changed, due to its highest battery capacity, fastest interface and lowest price. The mobile phone's cost is 1 in Fig. 6.10, but smaller than 1 in Fig. 6.9, because the mobile phone can fulfill the Online Video's maximum delay requirement but can not fulfill the VoIP's. (The VoIP has a stricter limit on delay than the Online Video.) The MR will not change even when the laptop's battery is 10%, therefore, the change of the PMR's batteries does not need to be simulated since the decision making result will be the same.

- **Simulations when considering SP**

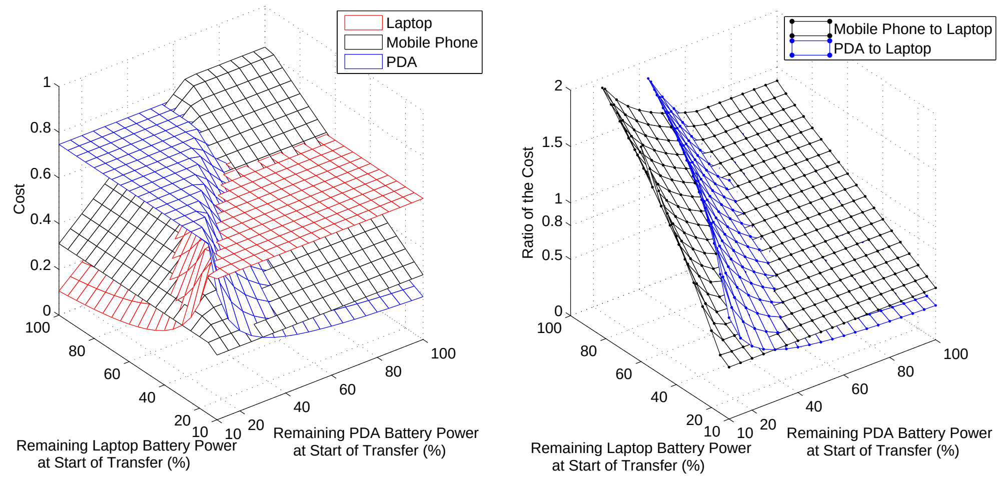


(a) Requirement 1 (b) Requirement 2 (c) Requirement 3 (d) Requirement 4

Figure 6.11: *The cost when the laptop's remaining battery capacity changes (Online Video)*

Fig. 6.11 shows the cost of the three devices in the online video scenario when considering SP. The simulation is performed for four requirements when the laptop's remaining battery capacity changes from 10% to 100%. The batteries of the mobile phone and the PDA are both at 100% of capacity. In **Requirement 1**, **Requirement 2** and most conditions in **Requirement 3**, the PDA is selected as the new MR. This is because when SP is considered, the laptop has a much shorter L than the mobile phone and the PDA. In **Requirement 4**, the MR will not change unless the laptop's remaining battery capacity is smaller than 25%, because the user cares less about the power in **Requirement 4**. Therefore, different requirements of the user affect the decision making results. Compared to Fig. 6.9, the laptop comes out much worse in the selection process due to SP being considered in this simulation.

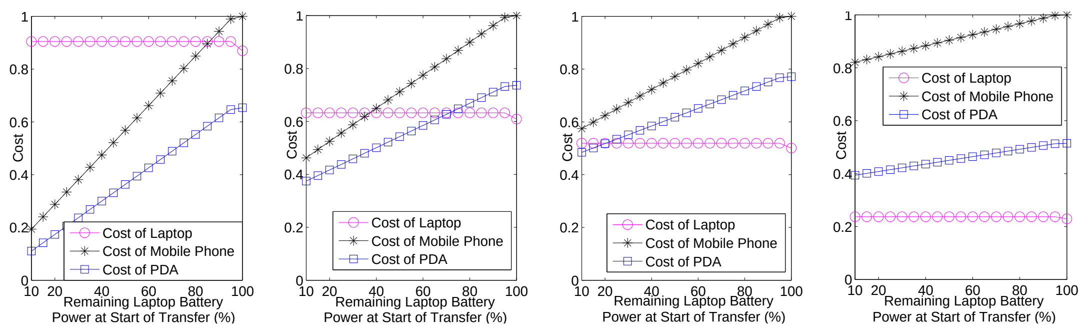
In order to investigate the effect of the concurrent change of two devices' power on the decision making, battery changes of the laptop and the PDA are shown in Fig. 6.12. **Requirement 2** is used here. In most conditions, the PDA is selected as the new MR, but the mobile phone is selected as the new MR when the PDA's remaining battery capacity is smaller than 33% and the laptop's remaining battery capacity is smaller than 30% because the PDA becomes short of power. When the PDA's remaining battery capacity is smaller than 33% and the laptop's remaining battery capacity is larger than 30%, the MR will not be changed because the laptop



(a) The cost (b) The ratio of the cost

Figure 6.12: *The cost and the ratio of the cost when the remaining battery capacities of the laptop and the PDA both change in Online Video (the mobile phone's remaining battery capacity is 100%))*

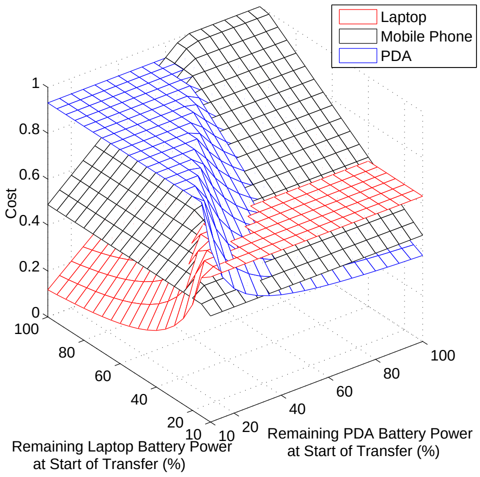
is better than the mobile phone in terms of price and network speed and also due to the same reason in Fig. 6.8(a).



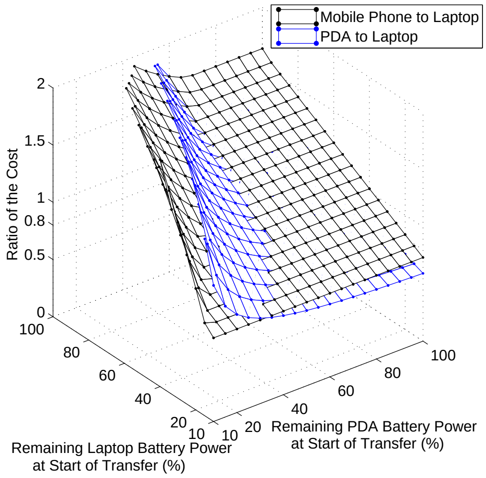
(a) Requirement 1 (b) Requirement 2 (c) Requirement 3 (d) Requirement 4

Figure 6.13: *The cost when the laptop's remaining battery capacity changes (VoIP)*

Fig. 6.13 shows the cost of the three devices for VoIP when considering SP. The simulation is performed for four requirements when the laptop's remaining battery capacity changes from 10% to 100%. The batteries of the mobile phone and the PDA are both at 100% available capacity. In **Requirement 1** and most conditions in **Requirement 2**, the PDA is selected as the new MR because the laptop has the shortest L due to its high SP. In **Requirement 3** and **Requirement 4**, the MR will not be changed because the user cares less about power than delay. The laptop is the best device in terms of delay due to its high-speed interface and also because it has no MR change delay. Compared to the online video in Fig. 6.11, the PDA is less likely to be selected as the new MR because the PDA has a MR change delay that can not fulfill the VoIP's delay requirement, which is stricter than that of the online video.



(a) The cost



(b) The ratio of the cost

Figure 6.14: *The cost and the ratio of the cost when the remaining battery capacities of the laptop and the PDA both change in VoIP (the mobile phone's remaining battery capacity is 100%))*

According to Fig. 6.13, the PDA or the laptop is selected when the laptop's battery changes when considering SP. In order to investigate the effect of the concurrent change of two devices' power on the decision making, the remaining battery capacity of the laptop and the PDA are changed, shown in Fig. 6.14. **Requirement 2** is used. Similar results to Fig. 6.12 can be observed. However, compared to the online video in Fig. 6.12, the PDA and the mobile phone are less likely to be selected as the new MR due to the MR change delay discussed in Fig. 6.13.

6.5 Conclusion

Selection of the MR in a NEMO-based network is a novel area, seldom addressed by researchers. Traditional research on "Network Selection" mainly focuses on a single terminal, rather than a dynamic WPAN. To solve these problems, a decision making mechanism for a dynamically changing MR selection has been proposed and its numerical simulation results have been demonstrated. This chapter focuses on the selection of a MR that is dynamically changing its roles and conditions in a heterogenous environment.

The proposed mechanism is user-centric and content-centric. It can adjust the selection according to the various requirements of users and the different types of applications. The mechanism is designed for non-real-time and real-time applications. In addition, the MR change is included in the decision making mechanism, which has mainly been ignored by traditional research. This can handle the effect that MR changes make on the decision making.

A mechanism of power consideration combining the lifetime and the power consumption model has also been proposed. It can include the different types of applications and the power used by the devices and the MR change into the decision making.

The future work in this topic could use mathematical optimization tools to process the decision making results.

Chapter 7
Conclusions

Chapter 7 draws conclusions from the results presented in previous chapters. The limitations of this work and future work are also discussed.

7.1 Summary and Achievements of the Work

The work presented in this thesis has addressed the technical barriers to implementing ubiquitous communications for individual users with their WPANs. An individual user should not be considered as a single terminal but as a WPAN that moves accompanying this user. The major challenges are from the heterogeneous environment composed of not only multiple wireless networks but also dynamic changes of the WPAN. Ubiquitous communications require that content should be efficiently and continuously transferred to individual users across various wireless networks outside WPANs and via different personal devices inside WPANs, wherever users move. These have been addressed by a framework proposed in this thesis, based on which two main issues were researched.

The first issue was how to implement content transfer in such environment allowing this transfer to be initiated no matter which wireless network is used and kept continuous when a user moves across various networks and their WPAN dynamically changes. MIP and NEMO can be used as basic protocols but they only support a few elementary mobile communication scenarios and cannot implement the ubiquitous communications required in this work. Another issue is how to implement this transfer in the most efficient way, i.e. select the most suitable transfer mode for a WPAN according to user and application requirements.

In this thesis, user-centric (personal-area-centric) and content-centric schemes have been proposed to solve these issues. The PDE concept was described as a logical user-based management entity with an extended architecture. Two mechanisms based on the PDE and a decision making algorithm were proposed to solve the technical problems arising in implementing the new functions for WPANs required by ubiquitous communications, which are seldom considered in current research.

The first problem, solved in Chapter 4, was how to implement ubiquitous communications in both infrastructure-less and infrastructure-based networks, arising from the first research issue discussed above. Local direct (infrastructure-less) and global mobile (infrastructure-based) communications are both often used by individual users in real life. Two practical scenarios were proposed to evaluate local direct communications - intra-WPAN and inter-WPANs, which concluded that existing approaches are only suitable for one of the two kinds of communication and can not implement ubiquitous communications across infrastructure-less and infrastructure-based networks. This chapter proposed a PDE-based scheme that can initiate content transfer immediately with local direct communications when this is preferred, or when users are currently in an infrastructure-less network environment, while keeping this transfer continuous when users move and gain access to other infrastructure-based networks. This scheme uses local management entities of the PDE to handle mobile communications in a local area without relying on infrastructure, making this a user-centric solution, while existing approaches must contact remote controlling entities through fixed access networks. Therefore, this scheme combines these two kinds of communication and gathers advantages from both of them. The performance analysis models proposed in this chapter, showed that the PDE-based scheme is able to provide much lower delay and cost for establishment of local direct communications with smaller overhead, compared to existing protocols. The experiments performed with real devices using this scheme also verified that it can support ubiquitous communications when WPANs' networking environment changes between infrastructure-less and infrastructure-based networks, where existing approaches can not work properly. The scheme proposed in this chapter is particularly suitable for individual users. In real life, they often move into places where no wireless signal from access networks can be received, or they often prefer to use short-range wireless technologies to directly transfer content from sources in close vicinity to them. Therefore, individual users may often need WPANs to work in such infrastructure-less networks, i.e. stand-alone WPANs, but mobility support is also required by them, which can all be implemented by this user-centric scheme.

After a WPAN's ubiquitous communications are established, the second problem, solved in Chapter 5, is how to keep them continuous in a WPAN that is composed of dynamically changing MRs. This type of WPAN is a special NEMO-based moving network, in which personal devices may dynamically change their roles between a MNN and a MR or leave this WPAN. This is different from WVNs that are considered by most of the current research on NEMO, in which fixed MRs are located. Therefore, existing approaches are not suitable for keeping ongoing communications continuous in a heterogeneous environment where a WPAN's MR dynamically changes among all MR-capable personal devices. The novel point of view for WPANs proposed in this chapter was that a Unique MNP is owned by a particular WPAN (i.e. personal-area-centric) rather than by any personal device or its HA (i.e. terminal-centric) as assumed in most current research. In this way, personal device addresses inside this WPAN can be kept unchanged regardless of dynamic changes of MRs which therefore become transparent to ongoing communications between this WPAN and content sources. This addressing mechanism was designed for address initiation, acquisition and maintenance in both infrastructure-less and infrastructure-based networks. Also, a MR role management was proposed to control dynamic role changes of personal devices in different states. These two mechanisms were integrated to give another PDE-based scheme that implements two practical scenarios: the MR dynamically changing in a WPAN, and a WPAN merging with a WVN, which have seldom been researched in other studies. Performance analysis models were also proposed to evaluate this scheme. It was shown that this scheme has better performance in terms of the delay, overhead cost, packet loss and throughput of mobile router changes in these two scenarios, compared to existing approaches. The proposed scheme has particular benefits in simplifying the design of communication procedures and achieving compact protocols and efficient communications. This is because the novel personal-area-centric view of WPANs, proposed in this chapter, does not need synchronization and cooperation of personal devices and their remote controlling entities (i.e. HAs) in fixed access networks, which are required by existing approaches and thus lead to the extra controlling protocols proposed in other research.

The third problem, solved in Chapter 6, is which MR-capable personal device should be selected as the MR in a WPAN, arising from the second research issue discussed at the beginning of this section. This selection is decided by the differing requirements of users and applications, and also by the heterogeneous environment where wireless access network speed and coverage and personal device conditions and roles are all dynamically changing. A user-centric (personal-area-centric) and content-centric decision making mechanism was proposed in Chapter 6 to select the most suitable dynamically changing MR adapted to user needs, i.e. the most appropriate content transfer mode for a WPAN to implement an individual user's ubiquitous communications in such a heterogeneous environment. Current research on NEMO and WPANs seldom addresses how a MR is selected, and existing approaches mainly focus on the network selection for a single terminal (i.e. terminal-centric). Therefore, the work presented in this chapter, as far as we are aware, may be the first systematic solution to decide MR selection from a WPAN aspect in a heterogeneous environment. This mechanism uses weighted cost functions to design a decision making algorithm, where weights can represent users' requirements and cost parameters can represent users' considerations from the aspects of money, network speed and power consumption. WPANs' power consumption is particularly researched because most personal devices can not be equipped with large-capacity batteries so often have a limited lifetime, for which novel power consumption models of WPANs were proposed in this Chapter included in the decision making algorithm. Furthermore, this algorithm is divided into two kinds to suit various types of applications - real-time and non-real-time. Also, the proposed mechanism has a benefit in that it includes the process of MR change in the decision making and thus can handle its effect on the selection, which is usually ignored by traditional research on network selection. A scenario was proposed to simulate lots of practical cases which change user requirements, applications and the WPAN's conditions. Simulation results showed that the MR with the lowest cost can be selected in different cases, and the proposed mechanism is verified to be able to adjust the selection according to various requirements of users and different types of applications. It was also demonstrated that the power condition has the most significant influence on decision making, and different selections can be made by the proposed mechanism according to the changes of the power.

7.2 Limitations and suggestions for Future Work

Throughout the research and its achievements presented in this thesis, there are also limitations that should be acknowledged. In view of these limitations, suggestions for future work are presented below.

This work only considers the NEMOBS protocol that does not support MRs' routing optimization (RO). The RO support of NEMO is still under development by the IETF working group. In Chapters 4 and 5, the proposed mechanisms based on NEMO could usefully be extended to support RO for MRs if an extended NEMO protocol is published by IETF.

This thesis proposes mechanisms to implement vertical handoff for WPANs aimed at keeping ongoing ubiquitous communications continuous in a heterogeneous environment, but does not focus on this handoff's duration time. This is because the major objective was to practically implement such ubiquitous communications, which are seldom considered in other research, so the handoff duration was simply determined by the MIP/NEMO basic support protocols used in the proposed mechanisms. Future work should include research aimed at reducing the handoff time to optimize the mechanisms proposed in Chapters 4 and 5.

The addressing mechanism proposed in Chapter 5 has included security information, but this thesis does not focus on security issues. Therefore, future work could include research aiming at providing further security support for WPANs.

More mathematical optimization could valuably be considered in future work to optimize the selection results obtained by the mechanisms proposed in Chapter 6. This work has concluded that the available power is the most significant parameter for WPANs, but it can only obtain a power-saving selection result by increasing the weight of the remaining power in the algorithm. Therefore, a particular power-saving method based on further mathematical optimization solutions should be considered in future work.

By including these research issues, future work will overcome the limitations of this work and provide further capabilities and functions of WPANs for ubiquitous communications in the heterogeneous environment.

Appendix A
Testbed Details for Experiments

Technical details of a testbed used for experiments in Chapter 4 are presented in this appendix.

A.1 Hardware

Dell Inspiron 1525 laptop computers were used to establish the testbed. This laptop has a CPU of Intel Core2 T7250 (2.0GHz), a memory of 2GBytes and a hard disk of 160GBytes. It also has three network interfaces: a 100Mbps Ethernet interface, a Bluetooth interface and a WiFi interface. The testbed is established as shown in Fig. A.1. The interface and network connections for experiments have been discussed in Chapter 4 shown in Fig. 4.19 and 4.20.

Figure A.1: *Hardware of the testbed (Project Demonstrator)*

A.2 Software

The operation system of these laptop computers was Ubuntu 7.10 Linux. Two software components are used to support MIP and NEMO. The first one is MIPL (Mobile IPv6 for Linux) [105] which was developed in cooperations between the Go-Core Project (Helsinki University of Technology) and the Nautilus6 project [106] from WIDE [57]. It implements MIP in Linux. Another is NEPL (NEMO Platform on Linux, version 2.4) [107] which is based on MIPL and developed by the Nautilus6 project [106]. NEPL consists of NEMO MR and HA prototypes. In the laptops working as VMNs, Linux shell scripts are programmed based on MIPL to implement the VMN functions. In the laptops working as MRs and HAs, different Linux shell scripts respectively based on NEPL MR and NEPL HA are programmed to implement the MR and HA functions. These scripts include the IPv6 routing information according to the experimental requirements. The DME functions are implemented based on binding functions of NEPL HA and also included in Linux shell scripts for the laptops where the DME is located. For the experiments in Chapter 4, the Iperf [108] utility was used to generate and measure TCP traffic. The default maximum window size for TCP in Linux - 16 KBytes was used for all measurements.

Appendix B
Publications

The author of this thesis has the following publications during the PhD study:

- Junkang Ma, John M Hannah and David I Laurenson, "Ubiquitous Personal Content Transfer in a Hybrid and Heterogeneous Wireless Network Environment", in *Proc. IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2008)*, Canners, France, Sept. 2008.
- Junkang Ma, John M Hannah and David I Laurenson, "A Personal Content Management Architecture for Ubiquitous Content Delivery in a Heterogeneous Network Environment", in *Proc. International Conference on the Latest Advances in Networks 2007 (ICLAN 2007)*, Paris, France, Dec. 2007.

The author of this thesis has the following patent during the PhD study:

- Junkang Ma and John M Hannah, "UMNP - Unique Mobile Network Prefix for a Dynamically Changing Personal Area Network based on a Personal Distributed Environment", UK Patent No. GB09 01082.8, 2009, UK.

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