An Adaptive Modelling Infrastructure for Context-Aware Mobile Computing

by

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DECLARATION

This thesis presents the work carried out by myself and does not incorporate without acknowledgement any material previously submitted by another person except where due reference is made in the text; and all substantive contributions by others to the work presented, including jointly authored publications, are clearly acknowledged.

.... 15th Nov, 2011

(Signature) (Date)

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation and gratitude to my supervisor and members of the dissertation committee for their support and guidance in the completion of this work. This dissertation would not have been possible without their assistance. Special thanks to my supervisor Prof. Hassan Kazemian for his guidance and invaluable advice throughout the study. I would like to thank my family members for their support and patience during the long journey in developing a profile of refereed academic publications for this study. Without their faith and support, completion never would have been possible. This dissertation is dedicated to them.

OUTCOMES/PUBLICATIONS

Excerpts from theoretical and practical contributions of this thesis have been published (or accepted for publication) in 24 peer-reviewed publications (five journal papers, five book chapters, nine refereed conference papers and five edited books), and another journal submission is currently under review for publication. All the publications are listed in the reference section of this thesis. The 25 refereed publications are research outputs that are generated from this research. They provide contributions to the modelling and development of infrastructures and applications for context-aware computing. This thesis provides a summary of the contributions of these publications, and explicit reference to the prior publications has been made to highlight the original significant contribution to knowledge.

An Adaptive Modelling Infrastructure

for Context-Aware Mobile Computing

ABSTRACT

Context provides information about the present status of people, places, things, network and devices in the environment. Context-awareness refers to the use of context information for an application to adapt its functionality to the current context of use. Development of context-aware applications is inherently complex. Previous researches on mobile computing emphasize on programmable interfaces for development of context-aware systems. There are limited researches that emphasize on the modelling aspects of adaptive applications. This research aims at developing a complete infrastructure for development of context-aware applications. The infrastructure consists of a middleware for context-aware application development that is supported by a set of context information modelling and reasoning facilities. It aims at extending the capabilities of context-aware middleware infrastructures by incorporating novel approaches to model context and situations under uncertainty.

This thesis addresses the key challenges in context-aware computing by a complete infrastructure that aims at achieving the following: (1) support for fuzzy composition of high level context abstraction from low level detector context, and fuzzy-based inference mechanisms, (2) support for mobile services that can be dynamically composed and migrated with reference to adaptation requirements for different context situations, (3) support for modelling of adaptation components and entities.

There are several contributions that can be summarized for the research. The first contribution is the development of a complete middleware infrastructure. The second contribution is the development of facilities for dynamic service composition and re-configuration. The third contribution is the introduction of the Fuzzy-based Service Adaptation model (FSAM) to improve the effectiveness of service adaptation. The fourth contribution is the development of Model Reference Adaptive Control (MRAC) mechanisms to fine tune the adaptation decisions. Finally, a number of adaptive mobile applications are developed by using the adaptive modelling and development infrastructure.

Glossary

HTTP	Hypertext Transfer Protocol is a standard which defines the way information is transmitted across the Internet between Web browsers and Web servers.
GPRS	GPRS is the short form for General Packet Radio Service. It is a radio technology for GSM networks that adds packet-switching protocols and shorter set-up time for ISP connections; it offers the possibility to charge by the amount of data sent rather than the connection time.
3G	Third-generation mobile telephone protocols that support higher data rates, for non-voice communications such as multimedia and Internet access.
TCP/IP	The Transmission Control Protocol is a transport-layer protocol that moves data between applications. The Internet Protocol is a network-layer protocol that moves packets across networks.
XML	XML is the short form for eXtensible Markup Language. It is a standard for transferring structured data.
Middleware	Software that augments operating systems and network infrastructure to make the creation of distributed applications in a heterogeneous environment easier.
WAP	The Wireless Application Protocol connects cellular networks to the Internet. It also alleviates the low bandwidth and protocol inefficiency problems inherent in cellular networks. Currently, all WAP clients interpret only the simplified Wireless Markup Language (WML) and WML script that form the baseline formatting language for presenting Web content over cellular networks.
WBI	Web Intermediaries is a programmable HTTP proxy designed to support development and deployment of intermediary Web applications, which can be located anywhere along a data stream to process or enhance the data as it passes through. WBI supports flexible composition of services via MEGelements - monitors, editors, and generators. These elements support HTTP request processing, HTTP response generating and processing, and monitoring of both requests and responses.

i-mode It is the first always-connected mobile service serving atop a packet-switching cellular network. The i-mode service enables its handset users to connect to any Web site via compact HTML, which defines a subset of HTML for small information appliances such as smart phones without using dial-up access. The i-mode service also supports i-appli, which is a customized, downloadable version of Java 2 Micro Edition that runs on i-mode phones.

WebPADS WebPADS is the short form for Web Proxy for Actively Deployable Services. The WebPADS proxy client and server coordinate to act as a Web proxy system to the Web application on mobile devices, which intercepts and optimizes all HTTP traffic for transport over the wireless network.

FSAM FSAM is the short form Fuzzy-based Service Adaptation Model. FSAM is developed for context modeling and context reasoning in a mobile environment. It employs a formal approach to service adaptation by using fuzzy linguistic variables and rules for implementing service adaptation.

1. Introduction

1.1. Motivation

In a mobile environment where mobile applications suffer from the limitation and variation of system resource availability, it is desirable for the applications to adapt to the changing context situations. Context provides information about the present status of people, places, things, network and devices in the environment [39, 45]. Context-awareness refers to the use of context information for an application to adapt its functionality to the current context of use [32]. Previous researchers have successfully used middleware technologies as intermediaries for providing transparent network services and environments for network applications [26, 30, 31, 37, 38]. However, completely hiding implementation details from applications in a mobile environment provides limited capabilities because mobile application designers need to model context situations, mobile services and adaptive components to develop systems that adapt to changes quickly. Application designers thus need a new form of awareness, not just transparency to let them inspect the application's context and adapt the middleware's behaviour accordingly. In this research, an adaptive infrastructure is developed to facilitate modelling and design of context-aware mobile applications.

1.2. Research Objectives and Significance of the Research

When we shift the underlying adaptation operations from mobile applications to a mobile computing infrastructure, several issues arise. The first issue is that a mobile application needs information on the current context (either primitive detector based or high level abstracted) for internal logic adaptation. It is desirable for the computing infrastructure to expose a set of generic interfaces for context subscription and query.

The second issue is that the mobile application needs to specify the requirements for service adaptations at a high level of abstraction. The third issue is that mobile application development requires facilities to model adaptation behaviours with reference to the requirements relating to system performance and quality of service levels. To address these issues, this research aims at developing an adaptive modelling and application development infrastructure for context-aware mobile computing that addresses the following requirements:

- Supporting the collection of contextual information from various detectors
- Support for fuzzy composition of high level context abstraction from low level detector context, and fuzzy-based inference mechanisms
- Support for mobile services that can be dynamically composed and migrated with reference to adaptation requirements for different context situations and different network domains
- Support for automated reasoning and adaptation to changing context, which controls the middleware services to optimize the available information and resources in the mobile environment.
- Support for modelling of adaptation components and entities
- Support for an application independent middleware infrastructure

This research aims at providing a modelling and application development infrastructure that allows generic mobile applications to exercise context awareness. The significance of the project is the integration of all the features, and the synergy provided by a well-established, unified baseline architecture that promotes the modelling and development of context-aware systems. Previous researches on mobile computing focus on the programmable interface of the middleware for development of context-aware systems [56, 57]. There are limited researches that emphasize on the modelling aspects of adaptive applications. This research extends the capabilities of context-aware mobile computing middleware infrastructures by facilitating the modelling of adaptive components, so that adaptive systems can be modeled at a high level of abstraction.

1.3. Structure of the Thesis

This thesis is comprised of five sections. Section one describes the motivations for the research, highlighting the objectives and significance of the research. Section two describes the contribution of knowledge to the mobile computing area by highlighting the citations in the related publications in this research. Section three discusses the details of a modelling and application development infrastructure for context-aware mobile computing. Section four provides a description of a modelling approach to context-aware application development. Finally, section five provides the evaluations, conclusion and future directions of research for this study.

2. Contribution to Knowledge

This thesis includes six journal papers, five book chapters, nine refereed conference papers and five edited books that are generated from this research in the area of context-aware computing and applications. The research publications focus on modelling and application development infrastructures for mobile applications and services. These publications provide significant contributions to the advancement of knowledge in the area and have resulted in a large number of citations from Google Scholar (as shown in Table 1):

My selected publications with citations – refer to reference list for details of submitted publications	**Number of Citations in Google Scholar (Nov 2011)**
[17]- Dynamic Service Reconfiguration for Wireless Web Access, *Proceedings of the 12th International World Wide Web Conference*, ACM Press, pp. 58-67, 2003	19
[16]- An Adaptive Middleware Infrastructure for Mobile Computing, *Proceedings of the 14th International World Wide Web Conference*, Chiba, Japan, ACM Press, pp. 996-997, 2005	13
[15]- An Adaptive Middleware Infrastructure Incorporating Fuzzy Logic for Mobile Computing, *Proceedings of the International Conference on Next Generation Web Services Practices*, Korea, IEEE Publication, pp. 449-451, 2005	10
[14]- A Fuzzy-based Service Adaptation Middleware for Context-aware Computing, *Lecture Notes in Computer Science*, vol. 4096, Springer, pp. 580-590, Aug, 2006 (best paper award)	4
[3]- Actively Deployable Mobile Services for Adaptive Web Access, *IEEE Internet Computing*, pp. 26-33, March/Apr 2004	16
[2]- A Fuzzy Service Adaptation Engine for Context-Aware Mobile Computing Middleware, *International Journal of Pervasive Computing and Communications*, pp. 147-165, 2008	4

Table 1. The Number of Citations for the Selected Publications in Google Scholar

As shown in the publications listed in Table 1, the significant contributions to knowledge include:

- A dynamic service reconfiguration model for adaptive Web Access, providing active deployment of new mobile services and dynamic reconfiguration of service migration for different mobile environments (paper 17 and paper 3).
- A comprehensive adaptive middleware infrastructure that facilitates the modelling of adaptive components (paper 15 and paper 16).
- A formal approach to context modelling and reasoning using fuzzy linguistic variables for service adaptation and context reasoning (paper 2 and paper 14).

3. An Adaptive Modelling Infrastructure and an Application Development Middleware for Mobile Computing

3.1. Adaptive Web Access

The convergence of wireless communication and portable devices has driven rapid advances in mobile computing. Combining with the rich accessibility and services of the World Wide Web, technologies related to mobile Web access have gained phenomenal growth in recent years. Technologies such as WAP, GPRS, and 3G are good examples that provide wireless access in a mobile environment by employing existing cellular technologies that bridge to the Internet. While significant advances have been achieved to improve on the wireless accessibility and development of smaller but more powerful devices, the underlying technologies driving the World Wide Web are largely based on the assumption of wired communication. As such, the assumptions about network characteristics such as large bandwidth availability, low error rates and always-on connectivity are invalidated in a wireless environment [28, 48, 51].

Previous researches have demonstrated promising results for overcoming these obstacles [33, 35]. However, they lack flexibility in the aspects that are important for supporting a robust Web service architecture in a wireless environment. First, new services should be deployable to the operating environment actively during runtime, without interrupting the execution of existing applications. Second, the Web architecture must be able to adapt to environmental changes dynamically so that services can reconfigure themselves to optimize the mobile device's operations.

Finally, the architecture must support service migration to maintain service provision as the mobile node moves across different networks and may require services that span across different network domains.

3.2. The WebPADS Platform

In order to exploit the desirable features for Web access in mobile environments, the *Web Proxy for Actively Deployable Services* (WebPADS) infrastructure was developed. The details of the WebPADS platform are described in paper [17]:

> S. Chuang, A. Chan, J. Cao, R. Cheung. Dynamic Service Reconfiguration for Wireless Web Access, *Proceedings of the 12th International World Wide Web Conference*, Budapest, Hungary, ACM Press, pp. 58-67, May 2003

The WebPADS architecture exploits the idea of injecting active services into an agent-proxy model that allows service deployment, reconfiguration and migration. The service architecture of WebPADS is derived from an agent-proxy model, which also is used in existing systems such as Mowgli [45] and WebExpress [43]. The idea is to place an agent in the mobile node and another agent in the fixed network, where all HTTP requests/responses are intercepted, transformed and optimized for transformation over a wireless network. Furthermore, the effects of varying characteristics in a wireless environment require the dynamic counteraction of an agent-proxy. As such, it is important that the agent-proxy can dynamically reconfigure the services that best match the wireless operating environment.

Based on the need for dynamic service updating, an active service model was introduced. It extends the agent proxy model to support dynamic service reconfiguration. In this active service model, the proxy is composed of a chain of service objects called mobilets. This model offers flexibility because the chain of mobilets can be dynamically reconfigured to adapt to the vigorous changes in the characteristics of a wireless environment, without interrupting the service provision for other mobile nodes. Furthermore, mobilets can migrate to a new proxy server when the mobile node moves to a different network domain.

A mobilet is a service entity that can be downloaded, pushed or migrated to a WebPADS platform for execution within an environment. The name, mobilet, bears a strong resemblance to applet. Applets are active codes executed within Web browsers, while mobilets are active mobile codes that run within the agent-proxy WebPADS environment. The mobilets are chained together on the client in a specified order, and the corresponding peer mobilets are chained together in a nested order on the server-side. The service chaining model of mobilet supports a general service composition paradigm that enables utmost flexibility in deploying service aggregation, while providing ease of re-configuration in response to the varying characteristics of a wireless environment.

Details of the dynamic reconfiguration process and evaluations of WebPADS are described in [17]. The experimental results show that the WebPADS platform out-performs other mobile middleware in terms of performance, flexibility and functionality [3] at the network and application levels.

3.3. Seeds of Internet Growth

With the advance of wireless technology, many mobile devices now feature dual wireless network interfaces, such as Bluetooth, GPRS, 3G and WiFi. As it would not be uncommon to have more than one network interface to access the Internet, a mobile device has to be able to choose which interface to use for Web access based on the cost, power consumption and performance of those interfaces. To address the impact of varying contextual characteristics of these mobile devices, the WebPADS platform has enhanced the Web architecture to address the issues of adaptive Web access in a mobile environment. As a featured article in IEEE Internet Computing, the paper "Actively Deployable Mobile Services for Adaptive Web Access" [3] is considered to be one of the publications classified in the "Seeds of Internet Growth" category. In publication [3], details of active deployment, dynamic service reconfiguration and migration are discussed.

Active Deployment

A static client–proxy architecture that offers fixed functionality cannot cope with the increasing demand for innovative wireless services. Moreover, mobile nodes and all fixed-network agents must be dynamically updatable to ensure compatible, consistent operation. To tackle the varying characteristics of a wireless environment, the WebPADS framework supports deploying new mobilets actively from a WebPADS client to a WebPADS server. The node carries relevant mobilets with it as it travels across foreign domains, and as the need arises, the client sends mobilets to a WebPADS proxy server, which configures them to operate in a coordinated manner.

Dynamic Service Reconfiguration

To adjust services provided by the WebPADS system, the WebPADS proxy client coordinates the dynamic service reconfiguration process to best adapt to the current context. On initialization of a reconfiguration process, based on descriptions of an XML configuration file, the WebPADS client forwards the concerned event and the associated new service chain map to the WebPADS server. When specific contextual changes trigger a dynamic service reconfiguration, the mobilets specified in the new service chain map first go through source-code-loading procedures to locate all the new mobilet classes' sources (this same process occurs simultaneously at both the WebPADS client and server). When all the new mobilet classes are ready, the current service composition undergoes a service deletion–addition process, during which the WebPADS proxy client and server reconfigure the existing service composition to match the new service-chain map's description. Once the current service composition is updated, the mobilets' execution threads resume, and service execution recommences.

Service Migration

Although dynamic reconfiguration aims to configure mobilet services actively on the basis of the localized operating environment, it does not address the issue of adaptability as the mobile unit moves across network domains. The WebPADS server and client operate in a geographically co-located domain to minimize transit latency. As shown in Fig. 1, a mobilet unit may initially be set up to operate within domain A, for example, with a WebPADS server in domain A serving as the peer proxy. The client then moves to domain B, which is geographically distant from domain A. It is clear that information flow via the previous WebPADS server has now become sub-optimal, possibly incurring unnecessary latency. In this case, the WebPADS system discovers that the client has been relocated to domain B and initiates a transfer of the WebPADS server service chain from domain A to domain B, in order for the WebPADS client-server pair to maintain a close proximity to one another. The technical details of a two-phase migration process to avoid service interruption are described in [3].

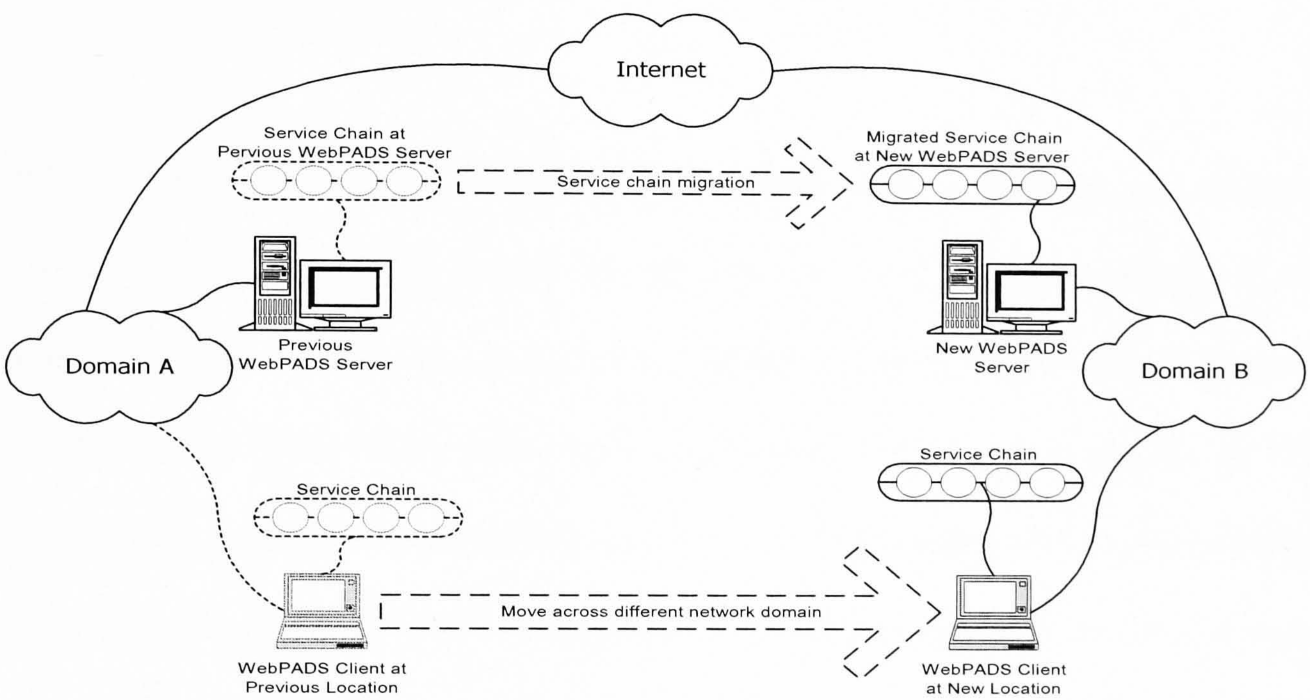

Fig. 1. Mobility of the WebPADS client leads to service migration

3.4. Adaptive Applications

Besides providing a proxy model for enhancing mobile services, the WebPADS platform also facilitates the development of mobile applications. A number of context-aware systems are implemented using the WebPADS platform. Details of the applications and enhancement of the WebPADS platform are described in the following publications:

[1] R. Cheung. An Adaptation Control Model to Support Mobile Web Access, *International Journal of Control and Automation*, 1*(1)*, pp. 9-16, 2008

[7] R. Cheung. A Context-Aware Adaptation Model for Efficient Web Browsing on Mobile Devices, in *Advances in Communication and Networking, Communications in Computer and Information Science*, vol. 27, Springer, pp. 41-54, 2009

[12] R. Cheung, H. B. Kazemian. Adaptive Service Composition for Meta-Searching in a Mobile Environment, *Proceedings of the Workshop on the Applications of Soft Computing to Telecommunications in the 12th EANN / 7th AIAI Joint Conferences*, Greece, pp. 412-421, Sept, 2011

In [7], an adaptation model is developed for mobile users to visualize and navigate through a Web structure in related document clusters without downloading all the related links in a Web site. A document cluster graph represents the high level structure of the related Web documents for providing the navigation models. In [1], the navigation model is enhanced by providing a three-dimensional implementation for viewing the document clusters. Based on the access requirements, current activities and contextual information, the users can specify the adaptation model in an XML configuration file. The adaptation control model is implemented using the WebPADS framework. Depending on the detailed requirements, the adaptation mechanisms for mobile access are configured according to the contextual information of the mobile station, including battery level, display resolution, storage information, processor utilization and network bandwidth information.

To address the impact of contextual characteristics on mobile access, the deployment of mobile services and service composition in a dynamic environment becomes a new challenge. Service composition refers to the integration of a set of services based on the requirements of the mobile environment. The intersection of service-oriented computing and autonomic computing [40] presents a rich source of problems [36]. In [12], a rule-based approach is described in detail for the adaptive service composition process. The major contribution of the paper is the abstraction of the dynamic service composition process using the WebPADS architecture. The dynamic service composition process is illustrated using a meta-search engine application as an example. The self-organizing approach allows a user to specify the desired adaptation and quality of service (QoS) requirements through adaptation rules. These QoS characteristics are broken down into requirements for individual services in the rule base using a novel approach for active service composition.

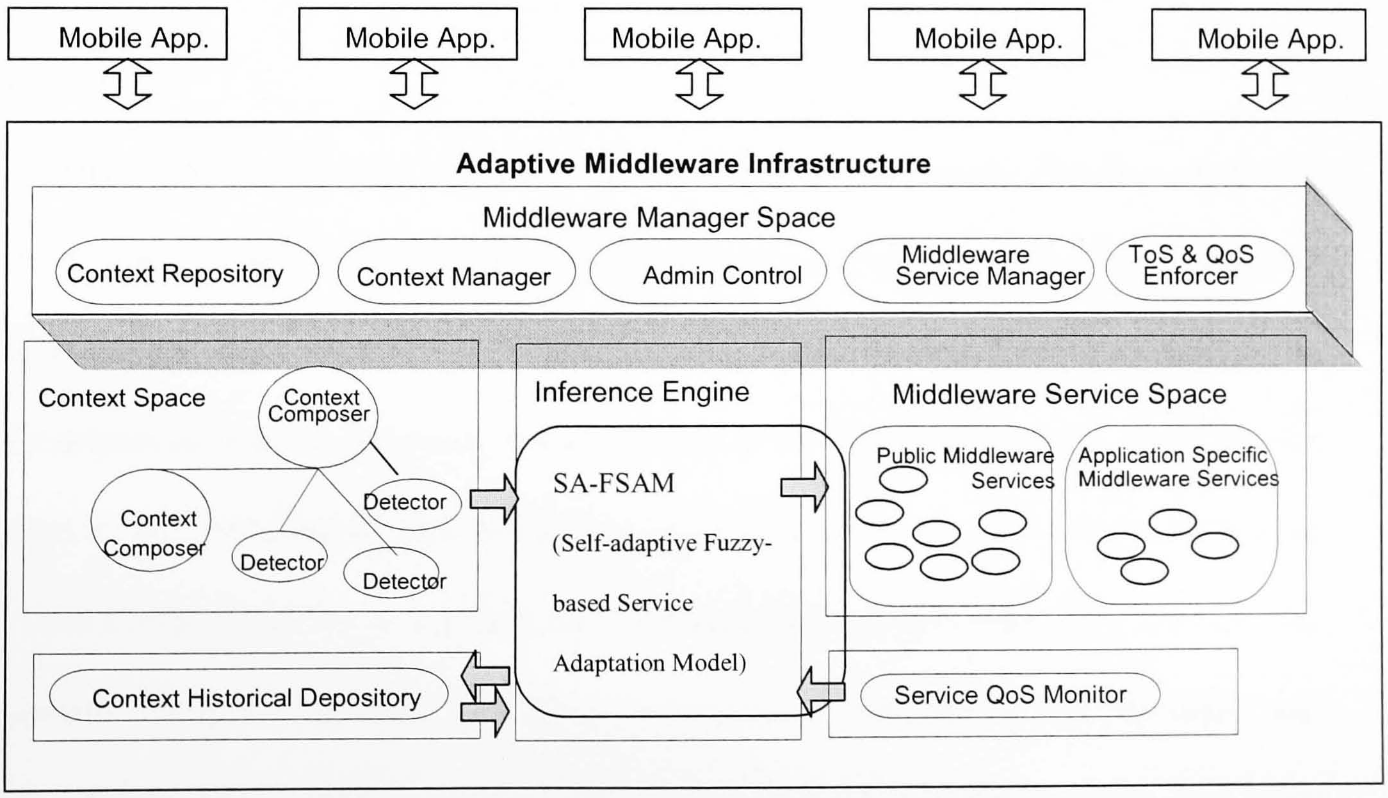

Fig. 2. The Adaptive Middleware Infrastructure

3.5. Middleware Approach

Previous researchers have successfully used middleware technologies as intermediaries for providing transparent network services and environments for network applications [56, 57]. However, completely hiding implementation details from applications makes little sense in a mobile environment because mobile applications need to adapt to changes in the current context quickly. Application designers thus need a new form of awareness, not just transparency to let them inspect the application's context and adapt the middleware's behaviour accordingly [13]. An adaptive middleware infrastructure is described in [16]. The middleware platform also incorporates fuzzy logic for context composition and reasoning in the service adaptation engine [15]. It provides a platform for application designers to model and develop context-aware applications that provide service adaptations in real-time [20].

As shown in Fig. 2, there are four major modules in the system. The first module is the Context Space, which contains Context Detector objects and Context Composers that reason and compose low level contexts into higher level representations. Examples of context detectors include wrappers for OS events, which could also be directly communicating with the device drivers. At a higher level, context detectors could also be detecting an application's communication and computation activity. The context composer gathers low level information, marshalling the dynamic and uncertainty of the mobile environment, and describe the current context in a more generic and coarse form. For example, a context composer could be monitoring all the network related detectors, and determine the quality of network connectivity – good, average, poor and no connectivity. High level contextual information is also useful for adaptation with mobile applications.

The second module is the Middleware Service Space. This is the execution environment for both Public Middleware Services (one set of services that are shared among all mobile application) and Application Specific Middleware Services (each mobile application has its own set of services). These adaptive middleware services are categorized by their service nature into either public or application specific. For example, a Web caching and prefetching middleware service is categorized as public service, and a media transcoding service is categorized as application specific.

The third module is the Adaptation Engine, which adjusts the middleware services according to the current context and the requirement of mobile application specific type of services (ToS) and quality of service (QoS). In order to control the middleware services, the adaptation engine is aware of the programmable properties of the middleware service. To adjust quantitative controllable parameters for the middleware services, the adaptation engine calls the corresponding adjustment functions. The middleware services are responsible for exporting the required interface for adaptation control, and to adjust the internal logics to follow the adjustments specified by the adaptation engine.

The fourth module is the Middleware Manager Space. The middleware manager space coordinates all operations within the mobile middleware. It contains five system components: The Administration Control component manages the admission of mobile applications that subscribe the services of the middleware. The Context Manager controls the runtime environment for the context objects, including the low level context detectors and high level context composers. The Context Repository stores the records on all contextual information, such that queries on context history are possible. Moreover, the past records can be used for predicting the future trend of the contexts. The Middleware Service Manager coordinates with admission control. It also allocates and controls the resources for newly subscribed services. The ToS and QoS Enforcer are used for monitoring the ToS and QoS levels for each connected mobile application.

3.6. Fuzzy-based Context-Aware Mobile Computing Middleware

The middleware infrastructure facilitates the development of environmental context reasoning and presentation entities, adaptive system services and context-aware mobile applications. There are two central issues in the development of adaptive context-aware applications. First, access to an abstract-generalized description of context is required for implementing mobile applications. It would be redundant and inefficient for individual applications to maintain the required context independently and it would not be feasible for developers to check the statuses and to provide description of every possible context. The extra layer of contextual description can be implemented by a middleware approach. Second, applications cannot fully utilize the underlying system services to adapt to the current context since it is challenging for application developers to enable each application to implement their own adaptation down to the system level. Again a mobile middleware environment provides the generic system services, which are programmable for adapting to the current context.

One requirement of an adaptive infrastructure is to develop the layers that implement the abstracted contextual description of contextual information and adaptation mechanisms. The middleware sits between the applications and the operating system, and the fairness in maintaining services among the applications and low level operating system features are taking into account. In order to handle the vast amount of contextual information and numerous combinations of adaptive system services, fuzzy logic is used to cope with the uncertainties in adaptation control. Fuzzy theory has been used solving problems in control system and decision making where uncertainty exists in the control states and the behaviours cannot be analyzed using conventional techniques [42, 53, 58]. The use of fuzzy logic is two-fold, besides using it for adaptation control, fuzzy logic is also applied to context reasoning and used to represent low level detector-based contexts and composite abstract contexts.

As shown in fig. 2, the fuzzy-based inference engine is the key component of the middleware for service adaptation. The major contribution of this research is the development of the Fuzzy-based Service Adaptation Model (FSAM) for context modelling and context reasoning. The details of the FSAM platform are presented in the following paper [14]:

> R. Cheung, J. Cao, G. Yao, A. Chan. A Fuzzy-based Service Adaptation Middleware for Context-aware Computing, *Proceedings of the IFIP International Conference on Embedded and Ubiquitous Computing, Lecture Notes in Computer Science*, vol. 4096, Springer, Korea, pp. 580-590 (**Best Paper Award**), 2006

Most researches on context-aware computing are based on conventional linear adaptation algorithms, which are not sufficient to handle the ambiguity in contextual information. This research employs a formal approach to service adaptation by using fuzzy linguistic variables to define the context situations and the rules for implementing service adaptations. A campus mobile assistant application is implemented to evaluate the adaptive middleware. The evaluations show that the fuzzy-based solution performs better than the conventional threshold-based approach. The conference paper for FSAM was selected as the best paper award [14] in the *IFIP International Conference on Embedded and Ubiquitous Computing* out of more than 500 paper submissions.

To elaborate on the major contributions of the FSAM approach, an extended version of the paper was published in a journal in the theme of *recent advances in ubiquitous computing*:

> R. Cheung, G. Yao, J. Cao, A. Chan. A Fuzzy-based Service Adaptation Engine for Context-Aware Mobile Computing Middleware, *International Journal of Pervasive Computing and Communications*, 4(2), pp. 147-165, 2008

The quality of the paper [2] is also reflected by the highly selective nature of the paper review process – quoted from the editors of the special issue:

*"There were more than **500** paper submissions from all over the world. Each paper was reviewed by three members of the program committee. It is therefore extremely difficult to select the papers for this special issue because there were so*

many excellent and interesting submissions. Based on the refereed reports, a total of six extended papers from the proceedings of EUC were selected for inclusion in this special issue." – Xioabo Zhou, Bin Xiao and Edwin H.-M.

In the adaptive middleware platform, the fuzzy-based inference engine is the most important module to implement adaptation decisions. The details of the fuzzy-based service adaptation engine are described in paper [2]. In this journal paper, details of the definitions and formulas used for the fuzzy-based approach are discussed. The inference engine employs fuzzy-based reasoning by using linguistic variables to define context situations, services, adaptation policies, reference situations, fitness functions and mapping of context situations to suitable adaptation policies. The research is further extended and the detailed operations of service adaptation implementations are presented and published in a book chapter in [8].

3.7. Model Reference Adaptive Control (MRAC) in Mobile Computing Middleware

An increasingly mobile work force and the computerization of mobile activities are driving the need for powerful mobile applications integrated with an adaptive infrastructure. Mobile smart phones are widely available, and users are required to use email and Web services while traveling. In addition, new multimedia applications are emerging for Web-enabled telephones and mobile computers with integrated communications. However, portable computing devices introduce particular problems of highly variable communication quality, reliability and timeliness (including jitter), cost of data transmission, restrictions on battery and CPU processing power, which all impact on the ability to deliver the quality of service required in a mobile environment.

In addition, mobile computing devices also need to access different applications, such as electronic mail and related documents, text chats, voice chats and video applications. It is observed that although context-aware applications react to changes in the environment, it is not desirable to adapt too frequently to drastic changes in context situations. For example, for multimedia playback, being too sensitive to any change in contextual situations could deteriorate application performance. Rather than just maintaining on-going services, mobile applications are required to maintain stability in quality of service and minimized communication cost. In paper [5], an improved version of the FSAM infrastructure is described to improve the quality of services delivered to users and to maintain the stability of service adaptation:

> R. Cheung, H. B. Kazemian. Model Reference Adaptive Control in Fuzzy-based Context-Aware Middleware, *submitted to the International Journal of Computational Intelligence Systems* (under review)

In this paper, a fuzzy-based service adaptation approach is employed to deliver a stable quality of service by introducing elements of self-adaptation [50]. Self-adaptation refers to the ability of the system to adapt autonomously in response to contextual variations [54]. The major contribution of the research is the implementation of the Self-Adaptive Fuzzy-based Service Adaptation Model (SA-FSAM) in the inference process by taking historical adaptation information into account. A closed-loop control mechanism [44, 55] is also introduced to fine-tune adaptation decisions. The SA-FSAM middleware employs a novel approach by incorporating Model Reference Adaptive Control (MRAC) techniques in control engineering [27, 41]. Based on historical adaptation information, the system is able to adjust the adaptation function and fine-tune adaptation decisions based on a Model Reference Depository.

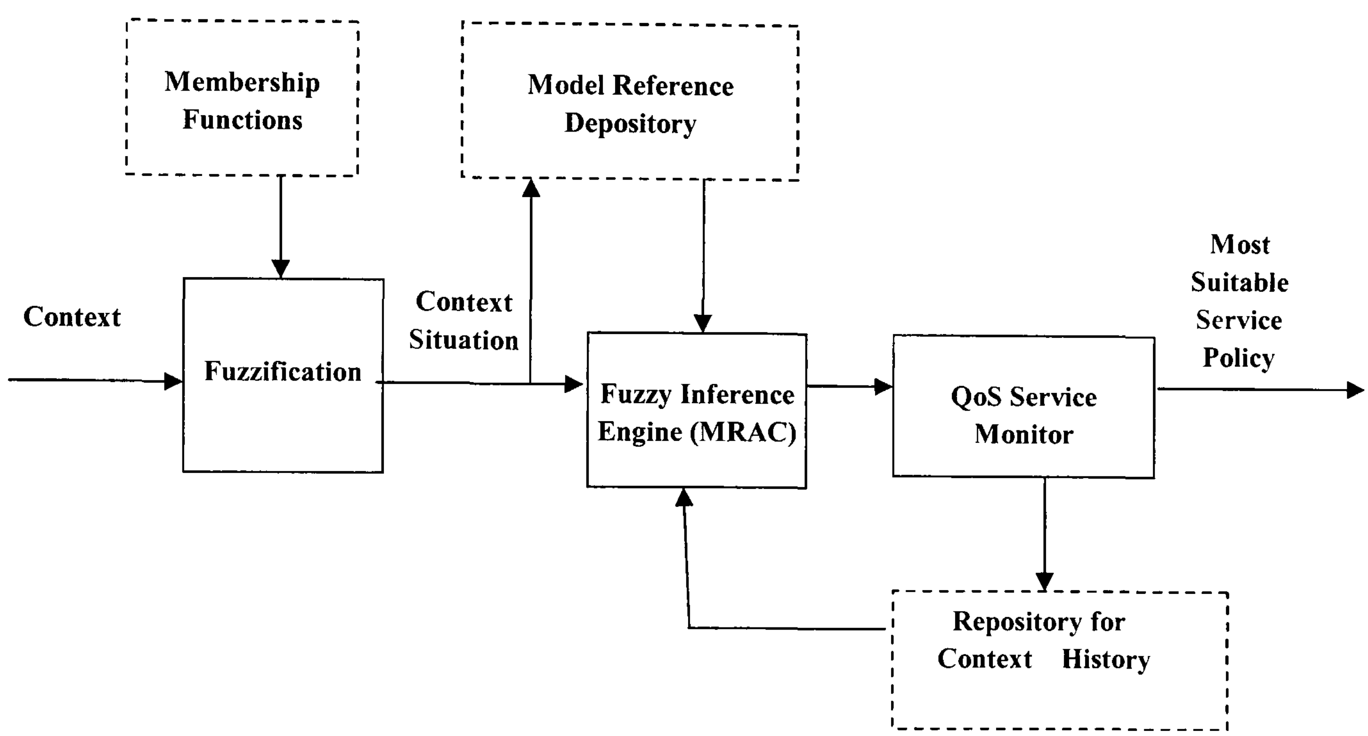

Fig. 3. The SA-FSAM Architecture

As shown in Fig. 3, when the output of the service adaptation engine meets certain conditions (e.g. number of service adaptations in a time period greater than a threshold value), the inference engine repeats the contextual reasoning by taking historical contextual information into account. The details of MRAC architecture are discussed in paper [5].

4. A Modelling Approach to Context-Aware Application Development

4.1. Modelling Adaptive Applications

Previous researches have demonstrated the advantages of a middleware infrastructure for context-aware mobile computing [26, 30, 31, 37, 38]. However, these researches focus on the programmable aspects of the middleware for developing context-aware mobile applications. There are some researches that emphasize on the software engineering and information hiding aspects, but little research has been done on a comprehensive infrastructure that facilitates the modelling of adaptive components [34]. This research provides a comprehensive infrastructure that integrates research areas in mobile computing middleware, fuzzy logic and control engineering for modelling and development of context-aware adaptive applications, based on different requirements:

- **Enhanced Effectiveness.** Based on the current context situation, the application provides appropriate contents and features at the right time to enhance the effectiveness. For example, when a user is accessing the Web pages and documents using a personal digital assistant and moving from a wireless network in an office environment to a neighboring shopping mall, the system displays a low resolution graphics image for the Web page when the bandwidth drops drastically.

- **Functional Needs**. Based on context data, applications need to adapt to changes and intrinsically adjust application features in a structural manner [49]. For example, in location-aware applications, maps and services are provided based on current locations, which represent mandatory functional requirements rather than improving performance.

- **Adaptive Personalization.** User profile attributes for personalization purposes may present different levels of variability in time, which may represent fast changing properties (e.g. number of pages that a user has accessed) as well as static ones (such as user preferences). Adaptive personalization mechanisms take into account of the user models for providing personalized features. For example, an adaptive personalized e-learning system may take into account the user model, the domain model, and the adaptation model for implementing personalized course contents. Such models facilitate the implementation of personalized content that adapts to students' preferences, progress and learning needs.

4.2. Modelling Adaptive Applications in WebPADS

The adaptive infrastructure developed in this research provides conceptual frameworks for modelling of adaptation components in context-aware applications. In this section, an example of a context-aware meta-search application is described [12]. To enhance user experience in a mobile environment, the system adapts to changes in network bandwidth by an adaptive service composition that is configured according to the adaptation model defined in a system configuration file (as shown in Fig. 4):

```
<RECONFIGURATION>

    <ENVIRONMENT config_option="COMPRESSION">
            <CONDITION_ATTRIBUTE value="CPU_USAGE">
               <CONDITION>
                    <RELATION operator="LESS_THAN">50</RELATION>
                    <CONFIG_VALUE>BEST_COMPRESSION</CONFIG_VALUE>
               </CONDITION>
               <CONDITION>
                    <RELATION operator="MORE_OR_EQUAL">50</RELATION>
                    <RELATION operator="LESS_THAN">65</RELATION>
                    <CONFIG_VALUE>DEFAULT_COMPRESSION</CONFIG_VALUE>
               </CONDITION>
               <CONDITION>
                    <RELATION operator="MORE_OR_EQUAL">65</RELATION>
                    <RELATION operator="LESS_THAN">75</RELATION>
               <CONFIG_VALUE>LOW_COMPRESSION</CONFIG_VALUE>
               </CONDITION>
               <CONDITION>
                    <RELATION operator="MORE_OR_EQUAL">75</RELATION>
                    <CONFIG_VALUE>NO_COMPRESSION</CONFIG_VALUE>
            </CONDITION>
               </CONDITION_ATTRIBUTE>
    </ENVIRONMENT>
    ...
    ...
    ...
    <ENVIRONMENT config_option="IMAGE_SIZE">
            <CONDITION_ATTRIBUTE value="WIDTH_PIXELS">
               <CONDITION>
                    <RELATION operator="LESS_OR_EQUAL">320</RELATION>
                    <CONFIG_VALUE>1/2</CONFIG_VALUE>
               </CONDITION>
               <CONDITION>
                    <RELATION operator="LESS_OR_EQUAL">480</RELATION>
                    <RELATION operator="MORE_THAN">320</RELATION>
                    <CONFIG_VALUE>2/3</CONFIG_VALUE>
               </CONDITION>
               <CONDITION>
                    <RELATION operator="LESS_OR_EQUAL">640</RELATION>
                    <RELATION operator="MORE_THAN">480</RELATION>
                    <CONFIG_VALUE>3/4</CONFIG_VALUE>
               </CONDITION>
               <CONDITION>
                    <RELATION operator="MORE_THAN">640</RELATION>
                    <CONFIG_VALUE>1</CONFIG_VALUE>
               </CONDITION>
            </CONDITION_ATTRIBUTE>
    </ENVIRONMENT>
    ...
    ...
    ...
 </RECONFIGURATION>
```

Fig. 4. A Segment of the XML Configuration File

Fig. 4 shows examples of adaptations rules that are used to compose the services used in a meta-search application. For example, the adaptation rules for CPU usage can be interpreted as follow: If cpu_usage < 50 then perform best_compression; If cpu_usage

> = 50 and cpu_usage < 65 then perform default_compression; If cpu_usage > = 65 and cpu_usage < 75 then perform low_compression; If cpu_usage > = 75 then perform no_compression.

To implement the adaptation components, service provision in the wireless environment must take into account the changing operating environment based on the adaptation rules defined in the configuration file. As a result, after the service composition process is established on the WebPADS platform, the whole service composition and the individual mobilets must be able to re-configure automatically to adapt to changes in the operating environment in real-time. Furthermore, the dynamic reconfiguration of mobilet services aims at maintaining WebPADS to operate at an optimum setting based on the constrained environment.

To illustrate the concept of dynamic service reconfiguration [17], two examples are given in the following discussions. Fig. 5 shows the adaptation of the WebPADS system to the changes in bandwidth. In step 1, two pairs of mobilets provide HTTP services running in the service composition that operates over a wireless link of 100kbps. In step 2, the bandwidth of the wireless link drops to 10kbps, which leads to the user experiencing significant delays in Web access. This change is detected by the WebPADS system, which decides to modify the service composition to adapt to the bandwidth change. During step 3, to adapt to the decrease in bandwidth, an image transcoding mobilet is inserted into the service composition. By introducing a transcoding service, the data volume of all images going through the service composition is reduced to achieve a much faster transfer time over the wireless link, which in turn reduces the delay experienced by the user.

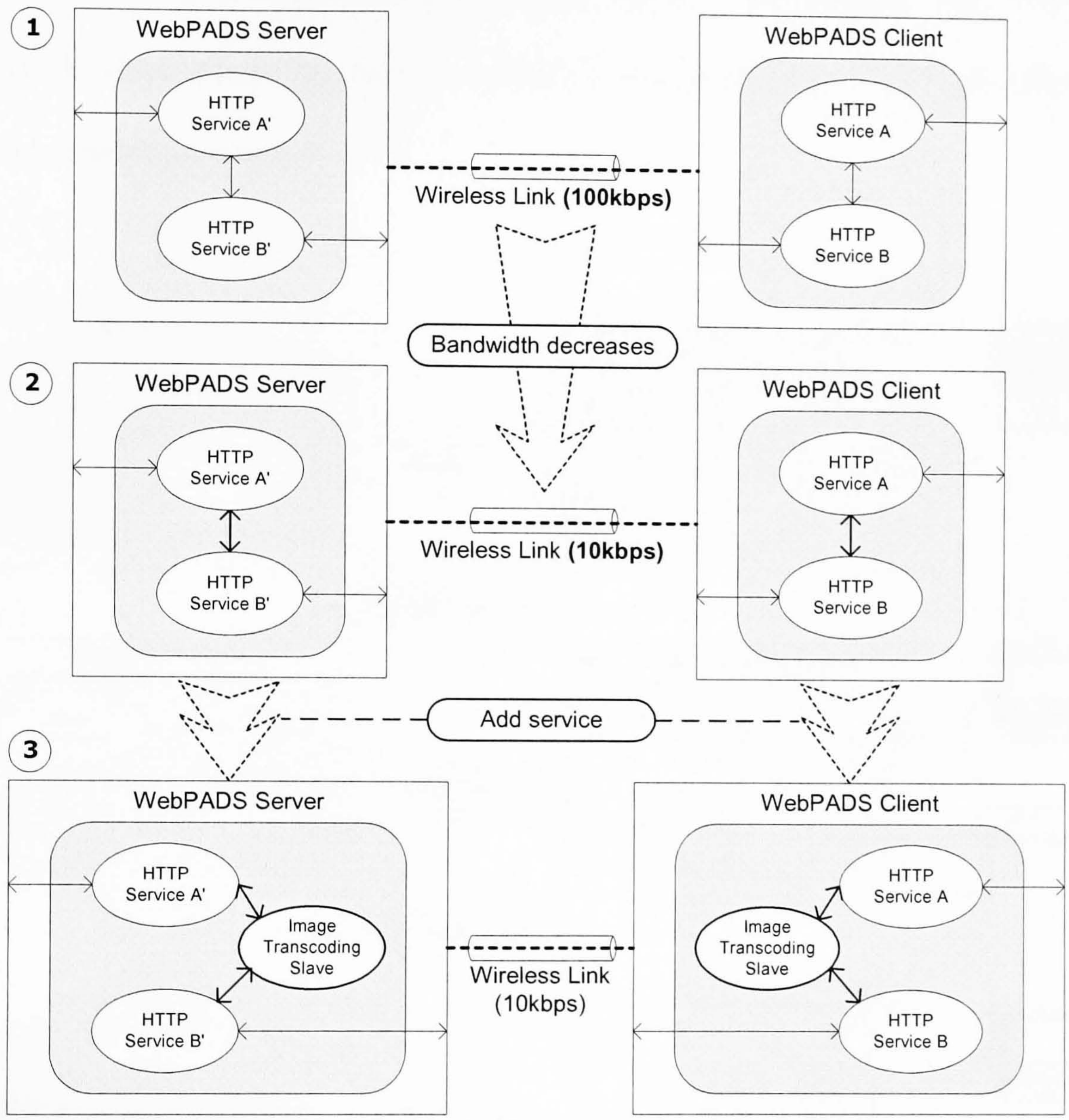

Fig. 5. Adaptation to Bandwidth Change

Fig. 6 shows another example of dynamic reconfiguration. In step 1, the WebPADS client is running on a personal digital assistant (PDA), which has a low-resolution display. A pair of page reformatting mobilets is running in the service composition to rearrange the page contents to improve the content layouts displayed on the PDA. In step 2, the PDA user moves to his office and connects the PDA to a high resolution monitor using an adapter so that the display resolution now becomes much larger. The change in the display capability is detected by the WebPADS system, which then decides to modify the service composition to adapt to the changes. During step 3, the page reformatting mobilet pair is removed, so that the original page format is preserved, which allows the user to exploit the higher resolution facilities offered by the high resolution monitor.

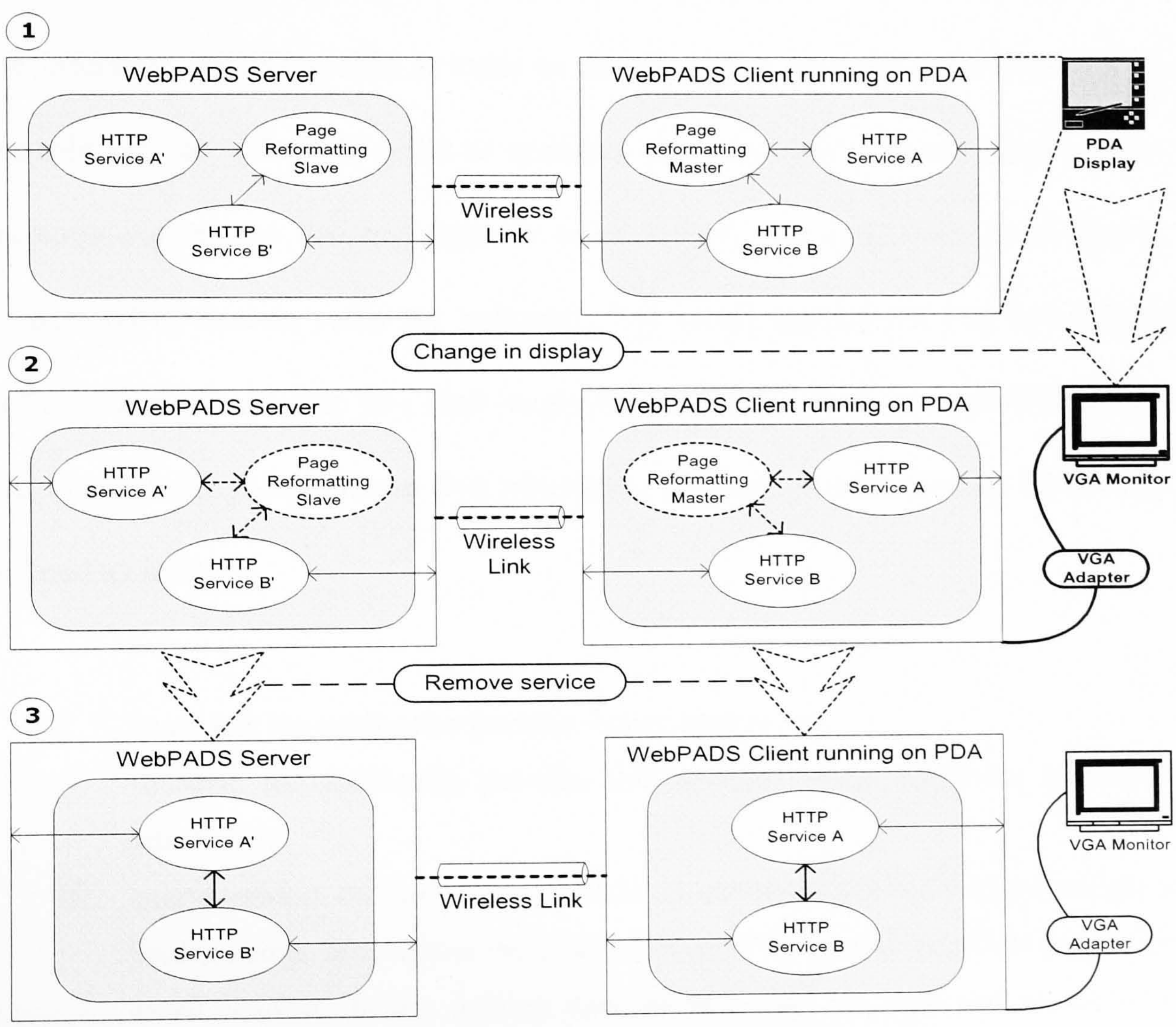

Fig. 6. Adaptation to Changes in Display Resolution

4.3. Fuzzy-based Service Adaptation Modelling

To demonstrate the effectiveness of Fuzzy-based Service Adaptation Modelling (FSAM) [2], a mobile email service application is used as an example in the following discussions. The mobile email service application is a context-aware application running on mobile platforms. It enables users to receive and send emails, by providing different levels of email services in the mobile platform. In particular, due to the spatial and temporal variations of wireless communication and computing resources, the inference engine is able to react to the changing contexts and deliver the most suitable service policy. In order to maintain an acceptable user experience when the resource constraints become tight or even severe, the adaptation mechanisms are predefined by certain rules (or policies). The email application has five adaptation policies corresponding to five QoS levels: headMail, fullMail, encryptedMail, bigMail and encryptedBigMail. These five adaptation policies provide service levels that are defined as follows:

I. headMail: the application provides email headers only.
II. fullMail: the application provides full contents for the email but without email attachments.
III. encryptedMail: the application provides an encrypted and compressed version of the mail contents, but without email attachments (This version improves the security of email contents. It also reduces data transmission overheads and associated costs through compression and decompression algorithms).
IV. bigMail: the application provides full contents for the email with all the attached documents and files.
V. encryptedBigMail: the application provides an encrypted version of the full contents for the email with all the attached documents and files.

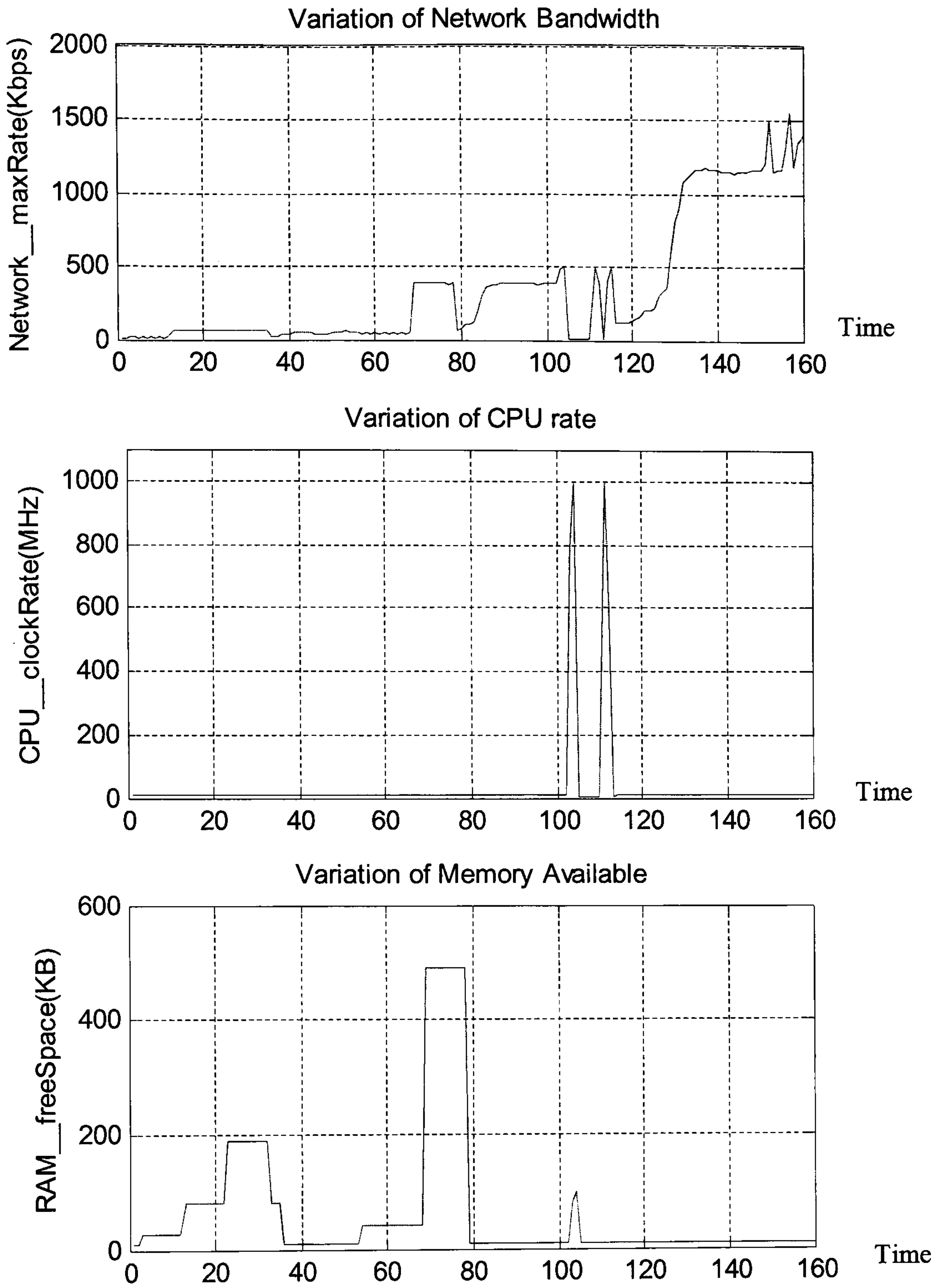

Fig. 7. Variations of Context Parameter Values

The email application provides different service levels according to variations in the contextual parameters: Network_maxRate, CPU_clockRate, and RAM_freeSpace. Fig. 7 shows the variations corresponding to the contextual parameters Network_maxRate, CPU_clockRate, and RAM_freeSpace. The detailed definitions of Policies, Context, Context Situation, Linguistic Values, Membership Functions, Standard Reference Depositories and Fitness Functions are defined as follows:

Policies: P_1 = {headMail, fullMail, encryptedMail, bigMail, encryptedBigMail}, which denotes the policies corresponding to the services provided at different QoS levels.

Context: C = {Network_maxRate, CPU_clockRate, RAM_freeSpace}

Linguistic Values: LV = {low, high}

Context Situation: $SI(t)$, $SI(t)$ is the 3-tuple vector to represent the fuzzified context.

$$SI(t) = \{(\text{Network\_maxRate, high}, \mu_{\text{Network\_maxRate high}}(\text{value\_of(Network\_maxRate, t)})), \\ (\text{CPU\_clockRate, high}, \mu_{\text{CPU\_clockRate high}}(\text{value\_of (CPU\_clockRate, t)})), \\ (\text{RAM\_freeSpace, high}, \mu_{\text{RAM\_freeSpace high}}(\text{value\_of (RAM\_freeSpace, t)}))\}$$

The graphs of the membership functions for network bandwidth, CPU clock rate and RAM free space are described in Fig. 8. The corresponding formulas for the membership functions for Network_maxRate, CPU_clockRate, and RAM_freeSpace are defined by the formulas (1), (2), and (3).

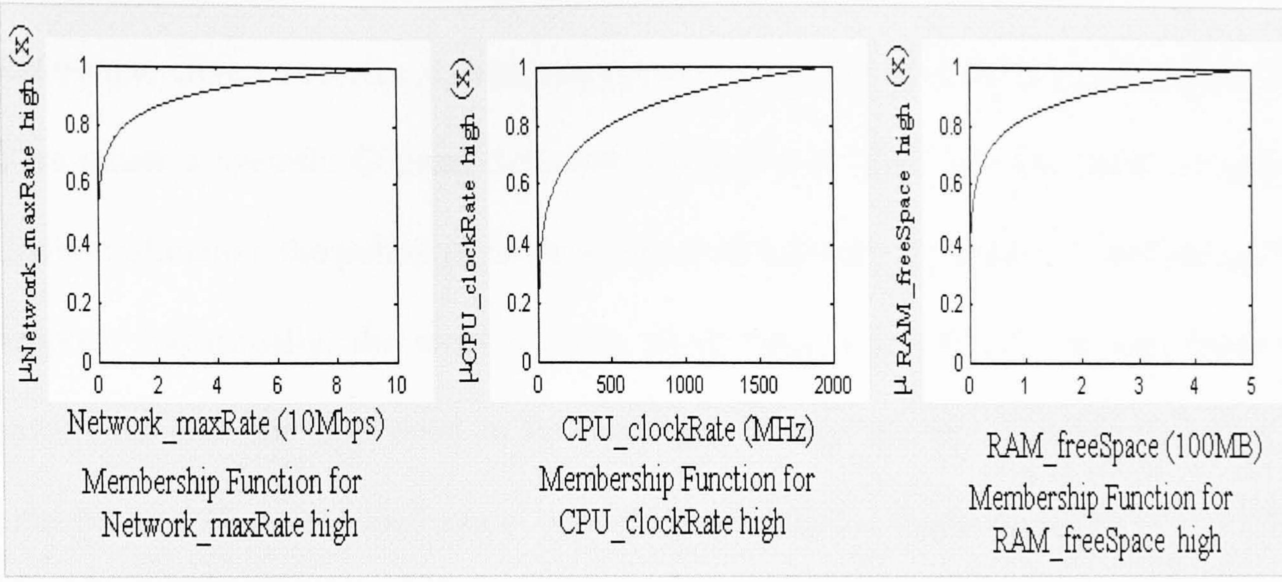

Fig. 8. The Membership Functions

The membership function for *Network_maxRate high*:

$$\begin{cases} 0 & B < 1Kbps \\ C_1 = \dfrac{\log_{10} B/1k}{5} & 1Kbps \leq B \leq 100\ Mbps \\ 1 & B > 100Mbps \end{cases} \qquad (1)$$

The membership function for *CPU_clockRate high*:

$$\begin{cases} 0 & F < 2MHz \\ C_2 = \dfrac{\log_{10} F/2M}{3} & 2MHz \leq F \leq 2GHz \\ 1 & F > 2GHz \end{cases} \qquad (2)$$

The membership function for *RAM_freeSpace high*:

$$\begin{cases} 0 & R < 50000B \\ C_4 = \dfrac{\log_{10} R/50k}{4} & 50000B \leq R \leq 500MB \\ 1 & R > 500MB \end{cases} \qquad (3)$$

The modelling approach to fuzzy based reasoning employs the concepts of ***Standard Reference.*** Given a service s_i, with respect to each policy p_i^j $(1 \le j \le m)$, we assume that there exists a specific Context Situation associated with p_i^j. On the basis of such a Context Situation, the policy p_i^j is the most suitable policy for service s_i and should be adopted. Intrinsically, the most suitable policy means a tradeoff between resource constraints and the QoS level to be delivered. A most suitable Context Situation is referred as a ***Standard Reference*** $SR(p_i^j)$. Given a set of linguistic values $LV = \{lv_1, lv_2, \ldots, lv_k\}$, $SR(p_i^j)$ can be represented by a set of 3-element tuples:

$$SR(p_i^j) = \{(c_i, lv_b, \mu_{c_i lv_b}(best\_value\_of(c_i)) \mid c_i \in C, i \in [1,n], lv_b \in LV, b \in [1,k]\} \quad (4)$$

The ***Standard Reference*** Context Situation corresponds to the best standard reference context parameters associated with each service policy. They are predefined according to the application requirements. For each of the five policies: headMail, fullMail, encryptedMail, bigMail and encryptedBigMail, a most suitable Context Situation is defined. The ***Standard Reference*** context situations for these five policies are listed in table 2.

	Network_maxRate (kbps)	**CPU_clockRate (MHz)**	**RAM_freeSpace (KB)**
headMail(p_1^1)	2	4	0.2
fullMail(p_1^2)	10	10	0.4
encryptedMail(p_1^3)	10	100	10
bigMail(p_1^4)	500	50	2
encryptedBigMail(p_1^5)	500	1000	100

Table 2. Standard Reference Context Situations

To define a ***Model Reference Depository***, it is necessary to substitute the corresponding values for network_maxRate, CPU_clockRate and RAM_freeSPACE in Table 2 to the membership functions (1), (2), and (3) respectively. Table 3 shows a segment of the ***Model Reference Depository*** corresponding to the five policies for email service.

	Network_maxRate High	**CPU_clockRate High**	**RAM_freeSpace High**
$SR(p_1^1)$	0.06	0.10	0.15
$SR(p_1^2)$	0.20	0.23	0.23
$SR(p_1^3)$	0.20	0.57	0.58
$SR(p_1^4)$	0.54	0.47	0.40
$SR(p_1^5)$	0.54	0.90	0.83

Table 3. Model Reference Depository

With the above information, the steps for developing the fuzzy-based service adaptation model (FSAM) are listed as follow:

(i) The predefined membership functions are used to map the current context into the Context Situation defined by the following formula:

$$\begin{aligned} SI(t) = \{ & (\text{Network\_maxRate, high, } \mu_{\text{Network\_maxRate high}} (\text{value\_of (Network\_maxRate, t)}), \\ & (\text{CPU\_clockRate, high, } \mu_{\text{CPU\_clockRate high}} (\text{value\_of (CPU\_clockRate, t)}), \\ & (\text{RAM\_freeSpace, high, } \mu_{\text{RAM\_freeSpace high}} (\text{value\_of (RAM\_freeSpace, t)})\} \qquad (5) \end{aligned}$$

(ii) The Fitness Function for FSAM is used to calculate the fitness degrees of the current context for each policy using the following formula:

FF(SI(current), $SR(p_i^j)$) =

$$\frac{1}{\sum_{i=1}^{size\_of(SR(p_i^j))} \left|\mu(best\_value\_of(c_i)) - \mu(value\_of(c_i, current))\right|^{l_i}} \quad (6)$$

where c_i represents the ith context information; *SI(current)* represents the current context; *size_of(SR(p_i^j))* represents the number of tuples in *SR(p_i^j)*; *μ(x)* is the membership function appearing in the *i-th* vector, and l_i is a positive integer.

In the above equation, the denominators are used for calculating the distance between *SI(current)* and *SR(p_i^j)*. When $l_i = 1$, the function uses Hamming distance; when $l_i = 2$, the function uses Euclidean distance. The Hamming distance and the Euclidean distance are classical methods for calculating the fuzzy distance between two statuses. Hamming distance is simple, but it has a disadvantage that when certain context information has a very outstanding value in the final policy choice, the calculation will be misguided by the outstanding value. Contrarily, the Euclidean distance can avoid the outstanding value problem to a certain extent, with the cost of a little more computing complication. When $l_i = 3$, we use l_i as a weight assigned to a context, which can be adjusted by individual applications.

(iii) After calculating the fitness degrees for the fitness functions, the policy p_i^s (where *s* corresponds to the policy with the maximum fitness degree value) will be the most suitable policy to be adopted for the current context situation:

For email service, the modelling approach defines the adaptation mechanisms by choosing the adaptation policy (p_1^s) with the maximum fitness function:

p_1^s where s corresponds to the policy with:

$$\text{Max } \{FF(SI(t), SR(P_1^1)), FF(SI(t),SR(P_1^2)), FF(SI(t),SR(P_1^3)), FF(SI(t),SR(P_1^4)) \\ FF(SI(t),SR(P_1^5))\}$$

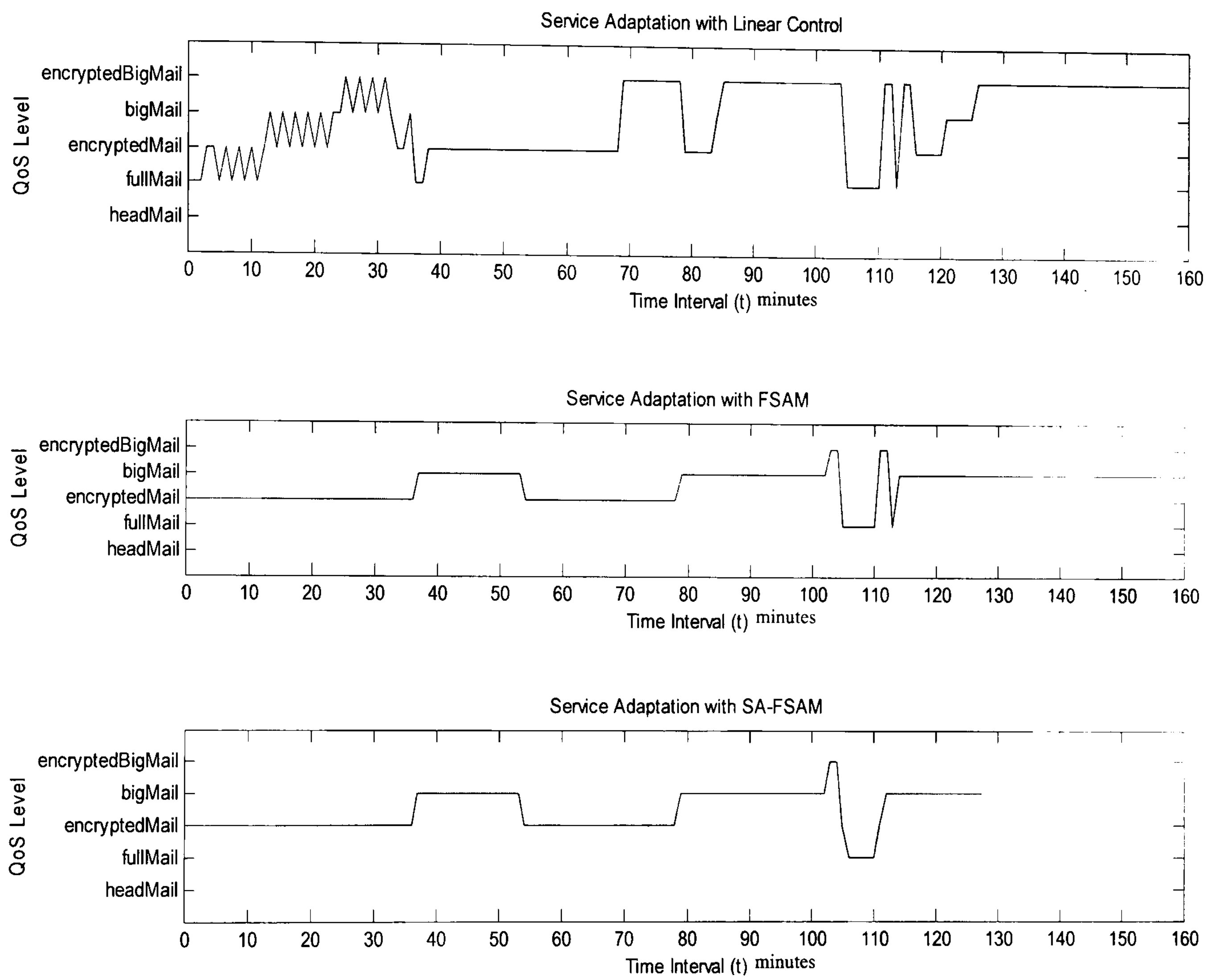

Fig. 9. The Mail Service Adaptation

Experimental results show that the FSAM approach provides stable adaptation experience for mobile users. It avoids frequent switches among different quality of service levels that cause negative user experience and inefficiency in resource utilization (as shown in Fig. 9). However, with large-granular fluctuation in contextual values (refer to time interval t = 104 to time interval t = 115 in Fig. 9), the large-granular fluctuations in service adaptation are not handled using the FSAM. An improved version of the inference engine employs the SA-FSAM and the MRAC approach [5], a closed-loop control enables the inference engine to detect the change adaptations that are greater than one QoS level, and adjust the radical changes with a modified Self-adaptive Fitness Function. The past adaptations in the previous two time intervals have a joint effect on the current adaptation decision to decide the adjustment effect. By including self-adaptation in a time series, the adaptations to those large-granular fluctuations become adjustable. It can be seen from Fig. 9 that for email service, the SA-FSAM eliminates the zigzag adaptations in the FSAM in the time internal t = 113. The SA-FSAM migrates smoothly to the next QoS level compared with the FSAM, avoiding frequent drastic changes in QoS levels resulting from adaptation decisions.

By focusing on the modelling aspects using the SA-FSAM that is implemented with MRAC techniques, application designers can focus on the adaptation model with reference to standard reference context situations for different mobile applications, and provide desirable system performance to meet the quality of service requirements.

4.4. Development and Modelling of Adaptive Applications

A modelling approach allows applications developers to focus on the high level objects and entities in Web-based applications. In addition, the middleware infrastructure also provides facilities for developing interactive Web-based hypertext interface elements. The middleware infrastructure has been designed to enable the development and modelling of interactive adaptive applications.

Model-Driven Frameworks - In [4, 9], a model-driven framework is implemented for the development of dynamic Web-based applications. The framework provides a modelling approach for designing Web-based interfaces and interaction elements that are essential for various context-aware applications. The framework generates Web-based user interfaces using an object-oriented hypermedia model. These Web-based user interface elements are essential for the development of context-aware applications that implement adaptations with Web contents, navigation elements and presentation properties (e.g. to provide adjustments on the screen and Web page appearance). In paper [18], a model-based design automation framework is described for automatic generation of user-interface elements in Web-based applications. These model-based frameworks are implemented to facilitate the development of context-aware hypertext systems.

Context-Aware Hypertext Systems - To provide adaptive applications that provide personalized contents, context-aware hypertext systems need to perform content adaptation at the user model level. In [10, 11, 6], adaptive learning applications are developed, incorporating user models in the content adaptation process. The system provides personalized Web contents based on the user model that incorporates user preference, progress and current status. Paper [10] focuses on descriptions of personalized features based on the user model, and paper [11] focuses on the descriptions of adaptation features based on the domain model using an ontology framework. The ontological approach provides a hierarchical description of context information and facilitates the representation of dependencies among context data [52].

To demonstrate the effectiveness of the adaptive infrastructure. paper [6] describes the implementation of a rule-based approach to implement an adaptive personalized e-learning system for content adaptation, navigation, and course sequencing.

Much research has been conducted on personalization of e-learning systems. Location awareness brings new opportunities and challenges. The widespread use of mobile devices and smart phones has offered new opportunities and challenges for developing context-aware mobile e-learning applications. These systems facilitate learning activities by integrating the learning contents with reference to the physical location by presenting appropriate information in context. In paper [19], a novel positional technique is developed to identify a learners' location using cellular ad hoc networks. The infrastructure and facilities developed in this research offer a rich platform for testing and implementing adaptive applications. To extend current systems to a ubiquitous learning environment, various e-learning applications need to be investigated. A number of edited research books in the e-learning area [21, 22, 23, 24, 25] have been published. These edited volumes include architectures of different e-learning systems, including content adaptation systems, personalized systems and location-aware e-learning systems.

5. Evaluations and Conclusion

5.1. Summary of the Research

This thesis includes 25 research publications that provide contributions relating to an adaptive infrastructure for development of context-aware applications. The statement of contributions from collaborators of the research is included in Appendix I and copies of the submitted paper publications are included in the attached volume. When the research publications are developed the earlier publications attracted more citations than the recent ones. However, the contributions in modelling of adaptive applications are more evident in the later papers than the earlier ones. This research does not concentrate on a single application or a single system. The models are developed and evolved over time and subsequently incorporated in the adaptive middleware infrastructure. The following shows a summary of the major research contributions that are implemented in the modelling and application development infrastructure:

- Middleware Infrastructure: A comprehensive adaptive middleware infrastructure that facilitates the development of adaptive components and applications (as shown in Fig. 2).
- WebPADS: A dynamic service reconfiguration model for adaptive Web access, providing facilities for dynamic service composition, active deployment of new mobile services, dynamic reconfiguration of services and service migration.
- FSAM: A fuzzy-based service adaptation model that is implemented as the core part of the service adaptation engine in the context-aware mobile computing middleware.
- SA-FSAM: A self-Adaptive fuzzy-based service adaptation model that implements elements of self-adaptively to improve the quality of

service by avoiding frequent changes in service adaptation resulted from drastic changes in context situations.

- Model Reference Adaptive Control: The SA-FSAM middleware employs a novel approach by incorporating Model Reference Adaptive Control (MRAC) techniques in control engineering. Based on historical adaptation information, the system is able to adjust the adaptation function and fine-tune decisions based on a Model Reference Depository.

- Context-aware Adaptive Applications: Individual applications are implemented in the top layer of the middleware (as shown in Fig 2). These applications are described in the refereed publications, providing evaluations to demonstrate the effectiveness of the approach.

5.2. Evaluation of the Adaptive Infrastructure

5.2.1. Evaluation of the WebPADS Platform

One of the desirable features of a mobile Web middleware is the need to support existing Web applications and interoperate over existing network infrastructure. As such, the HTTP/TCP/IP protocol stack was employed in WebPADS, but with enhancements that optimize the traffic on the wireless link. In addition to providing augmented services based on the client-proxy approach, the WebPADS supports ease of deployment across existing networking and Web infrastructure. The WebPADS platform actively deploys appropriate new services for the operating environment, and adapts to the environmental changes by dynamically adjusting service provision. Table 4 summarizes the characteristics of WebPADS system and other related works as compared to a set of characteristics benchmarks [3, 29].

	i-mode	WAP	WBI	WebPADS
TCP/IP	Original TCP/IP	. WAP protocol stack	Original TCP/IP	Original TCP/IP
HTTP	Original HTTP	WML	Modified HTTP	Modified and Optimized HTTP stream
Support Generic Application	✗	✗	✓	✓
Client Proxy Approach	✗	✓	✗	✓
Wireless Awareness	✓	✓	✗	✓
Active Deployment	✓	✗	✓	✓
Dynamic Adaptation	✗	✗	✗	✓
Mobility Support	✓	✓	✗	✓

Table 4. Mobile Middleware Feature Comparison

5.2.2. Evaluation of Fuzzy-based Service Adaptation Modelling

This research aims at developing an adaptive modelling infrastructure and an application development middleware for context-aware mobile computing that supports fuzzy-based context composition and context reasoning. In typical mobile computing environments, the adaptation decisions based on the FSAM and SA-FSAM platforms need to consider the drastic changes in bandwidth and related parameters. Although higher bandwidth results in better quality of service (such as high quality video), it is undesirable to have frequent adaptations in real-time with significant number of switching among different QoS levels. The Self-Adaptive Fuzzy-based Service Adaptation Model (SA-FSAM) takes historical adaptation information into account, and utilizes a closed-loop control mechanism to fine-tune adaptation decisions. By combining control-theoretic and fuzzy-based approaches, the SA-FSAM model minimizes both small-granular oscillations and large-granular fluctuations, so that drastic changes in service adaptation decisions are minimized. The fuzzy-based approach was compared with a conventional threshold based linear approach [2, 5, 14]. The experimental results show that the Fuzzy-based approach effectively avoids drastic service adaptations resulting from drastic changes in context situations. The fuzzy-based approach in the SA-FSAM platform provides improved user experience for service adaptation and optimizes network resources in a mobile environment.

5.2.3. Research Contributions

This thesis presents a number of contributions to existing work in context-aware mobile computing. The first contribution is the development of a complete adaptive middleware infrastructure. The second contribution is the development of facilities for dynamic service composition and re-configuration. The third contribution is the introduction of the Fuzzy-based Service Adaptation model (FSAM) for service adaptation. The fourth contribution is the development of Model Reference Adaptive Control (MRAC) mechanisms to fine tune adaptation decisions. The 25 publications are research outputs that are generated from this research. They are categorized according to the classifications based on the nature of the contributions. A summary of the contributions of the submitted publications is listed in Table 5. It should also be noted that the more recent publications provide significant contributions to the modelling of adaptive applications.

	Areas of Contribution				
Paper	(I) Adaptive Middleware Infrastructures	(II) Dynamic Service Adaptation & Composition using WebPADS	(III) FSAM Inference Mechanism	(IV) MRAC Model Reference Adaptive Control	(V) Adaptive Mobile Application Development
1		✓			✓
2	✓		✓		
3	✓	✓			
4	✓				✓
5	✓			✓	✓
6					✓
7		✓			✓
8			✓		
9	✓				✓
10					✓
11					✓
12		✓			✓
13	✓				
14	✓		✓		
15	✓				
16	✓				
17	✓	✓			
18	✓				✓
19					✓
20					✓
21					✓
22					✓
23					✓
24					✓
25					✓

Table 5. The Nature of the Contributions for the Submitted Publications (Refer to the prior publication reference section for details of the submitted publications)

5.3. Conclusion

Various researches on context-aware computing have been carried out in the past few years. To overcome the new challenges and requirements for context-aware systems, many researchers have made efforts to design and implementation adaptive infrastructures that can effectively provide users with context-aware services. Most of the approaches for context-aware applications are usually developed for specific problem domains (e.g. multimedia applications) [47]. This research emphasizes on a generic adaptation model that can be applied to different applications. The modeling facilities are implemented in an adaptive middleware infrastructure that is able to gather, manage, evaluate and perform reasoning with context information.

The research models developed in this thesis are original, representing the state-of-the-art infrastructure for modelling and development of context-aware applications. In addition to the middleware approach, this research has developed research models for dynamic service reconfiguration (WebPADS) and fuzzy-based service adaptation (FSAM/SA-FSAM). The dynamic service reconfiguration model contributes to the development of adaptive services that can be composed dynamically and migrated to different network domains, and the FSAM/SA-FSAM model significantly contributions to the literature for reasoning under uncertainty. Compared with other approaches, the fuzzy-based solution shows a better tolerance for the variations of context, resulting in significant improvements in the effectiveness of service adaptation [2].

This research contributes to the development of a complete infrastructure for building context-aware applications. The infrastructure consists of a middleware for context-aware application development that is supported by a set of context information modelling and reasoning facilities. The details of the modelling and adaptive middleware infrastructure have been published in peer-review journals, book chapters and conference publications. The contribution to the advancement knowledge is evident from the 66 citations that have been generated from the publications listed in Table 1. The more recent publications further extend the modelling capabilities of the context-aware middleware infrastructure, and are expected to stimulate context modelling researches in the computing literature.

5.4. Future Directions of Research

The development of context-aware applications is complicated because adaptive systems are highly context dependent and are affected by their operating environments. Context information include physical context derived from context data that are collected from physical devices and high level cognitive context information that is derived from the cognitive elements of a user's context, including user preferences, tasks, emotional states, and situation monitoring. Physical context information is derived from a variety of sources. The context data collected from different sensors and failure prone devices differ in terms of information quality. Therefore the management of large amount of context information becomes an important research issue. On the other hand, high level cognitive context information is important for providing personalized context-aware computing services, because it focuses on the user's cognitive activities rather than extracting user's movements based on physical environments.

By employing a modelling approach, this research improves the maintainability and evolving capabilities of context-aware systems. The well-designed context information models developed in this thesis ease the development and deployment of future applications. However, there are a number of challenges that need to be addressed to reduce the complexity in the development of context-aware applications. These include several research areas covering cognitive modelling for user situations, context prediction, and context reasoning.

In order to develop personalized computing services according to different user situations, cognitive models are required to describe the user's situations based on the cognitive elements of a user's context. As situations are semantic abstractions from low-level context cues, human knowledge and interpretation of the world must be integrated into a model or situation representation. A future direction of research would be to develop high level context abstractions based on a specification process, where sensor perceptions are aggregated and associated to human-defined situations using machine learning techniques.

Another future direction of research would be to improve the quality of service adaptation using context prediction techniques. Since raw data of low-level context are gathered from different physical sensors, and the data type, formats, and abstract level from the sensors are different, the context-aware middleware need to manage numerous amounts of data in the context database effectively. In order to make the best use of historical context information, the context-aware middleware needs to offer proactive services by implementing a module for context prediction that utilizes the historical sensor data collected over time. It is anticipated that the information offered by context prediction facilities will further improve the stability of service adaptation in the model reference adaptive control process.

As the adaptive framework is designed for generic context-aware application development, it is important for the adaptive middleware infrastructure to provide reasoning capabilities with high expressive power. At present rule-based representations, fuzzy-based representations, and ontological model are implemented in the adaptive middleware infrastructure. These representations differ in terms of expressive power and reasoning capabilities. To support reasoning with high level context data, rule-based reasoning mechanisms are implemented in a restricted logic programming language. They lack the facilities to support formal definitions of the semantics and precise nature of context descriptions. Fuzzy-based approaches provide rich semantics for context description and reasoning for different context-aware applications, but they lack the support for hierarchical context descriptions and representation of dependencies among context data. On the other hand, ontological models have clear advantages regarding recognition of complex relationships and support for interoperability and heterogeneity. However, ontological models are generally unsuited to recognition of simpler context data. In order to trade off between expressiveness and complexity, the choice of a single context modelling approach may not always be satisfactory. The above considerations suggest that different modelling languages and tools need to be integrated with each other. A future direction of research is to combine different formalisms and techniques to develop a comprehensive hybrid approach that incorporates different models for development of context-aware applications.

6. Prior Publication References

(This section presents a list of my author and co-author publications, including six journals, five book chapters, nine conference publications and five edited books)

Journals

[1] R. Cheung. An Adaptation Control Model to Support Mobile Web Access, *International Journal of Control and Automation*, 1(*1*), pp. 9-16, 2008

[2] R. Cheung, G. Yao, J. Cao, A. Chan. A Fuzzy-based Service Adaptation Engine for Context-Aware Mobile Computing Middleware, *International Journal of Pervasive Computing and Communications*, 4(*2*), pp. 147-165, Sept 2008

[3] S.N. Chuang, A.T.S. Chan, J. Cao, R. Cheung. Actively Deployable Mobile Services for Adaptive Web Access, *IEEE Internet Computing*, pp. 26-33, March/Apr 2004

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Appendix I: Statement of Contributions from the Collaborators

Statement of Contributions

Date : 7th June, 2011

Confirmation on the percentage of contributions for the following publications:

(1). Ronnie Cheung, Gang Yao, Jiannong Cao, Alvin Chan. "A Fuzzy Service Adaptation Engine for Context-Aware Mobile Computing Middleware", International Journal of Pervasive Computing and Communications, pp147-165, Sept 2008

Percentage of Contribution for paper (1) :
Ronnie Cheung (45%) Gang Yao (10%) Jiannong Cao (25%) Alvin Chan (20%)

(2). Siu Nan Chuang, Alvin T.S. Chan, Jiannong Cao, Ronnie Cheung. "Actively Deployable Mobile Services for Adaptive Web Access", IEEE Internet Computing, pp26-33, March/Apr 2004

Percentage of Contribution for paper (2):
Ronnie Cheung (25%) Siu Nam Chuang (25%) Jiannong Cao (25%) Alvin T. S. Chan (25%)

(3). Ronnie Cheung, Jiannong Cao, Gang Yao, Alvin Chan, "A Fuzzy-based Service Adaptation Middleware for Context-aware Computing", Proceedings of the IFIP International Conference on Embedded and Ubiquitous Computing, Lecture Notes in Computer Science, Volume 4096, Springer, Korea, pp580-590 (Best Paper Award)

Percentage of Contribution for paper (3)
Ronnie Cheung (45%) Gang Yao (10%) Jiannong Cao (25%) Alvin Chan (20%)

(4). Siu Nam Chuang, Alvin T.S. Chan, Jiannong Cao, Ronnie Cheung. "Dynamic Service Reconfiguration for Wireless Web Access", Proceedings of the 12th International World Wide Web Conference [WWW2003], Budapest, Hungary, ACM Press, pp58-67, May 2003

Percentage of Contribution for paper (4)
Ronnie Cheung (25%) Siu Nam Chuang (25%) Jiannong Cao (25%) Alvin T. S. Chan (25%)

(5) Gang Yao and Ronnie Cheung, A Java-based Middleware for Enterprise Application Integration, Proceedings of the Second International Conference on Communications and Networking in China, Shanghai, China, Aug 2007

(6) Ronnie Cheung and Gang Yao, A Novel Positioning Technique for Cellular Ad Hoc Networks, Proceedings of the IASTED International Conference on Networks and Communication Systems, Thailand, pp.251-257, April 2007

Percentage of Contribution for paper (5) and (6)
Ronnie Cheung (70%) Gang Yao (30%)

Prof. Jiannong Cao, Chair Professor & Head of Department of Computing,
Hong Kong Polytechnic University

Alvin T.S. Chan,, Associate Professor, Department of Computing, Hong Kong Polytechnic University

Gang Yao, Research Associate, Department of Computing, Hong Kong Polytechnic University

Ronnie Cheung

Statement of Contributions

Date: 19th June, 2011

Confirmation on the percentage of contributions for the following publications:

R. Cheung, C. Wan, C. Cheng. An Ontology-based Framework for Personalized Adaptive Learning, Advances in Web-based Learning, Lecture Notes in Computer Science, vol. 6483, Springer, pp. 52-61, 2010

Percentage of Contribution for the above paper:
Ronnie Cheung (90%) Calvin Wan (5%) Calvin Cheng (5%)

Calvin Wan, SPEED, Hong Kong Polytechnic University

Calvin Cheng, SPEED, Hong Kong Polytechnic University

Ronnie Cheung

Statement of Contributions

Date: 20th July, 2011

Confirmation on the percentage of contributions for the following publications:

[1] R. Cheung, H. B. Kazemian. Model Reference Adaptive Control in Fuzzy-based Context-Aware Middleware, International Journal of Computational Intelligence Systems (submitted)

Percentage of Contribution for paper [1]:
Ronnie Cheung (90%) H. B. Kazemian (10%)

[2] R. Cheung, H. B. Kazemian. A Modeling Framework for Adaptive Content Presentation and Navigation, Journal of E-Technology (accepted for publication)

Percentage of Contribution for paper [2]:
Ronnie Cheung (90%) H. B. Kazemian (10%)

[3] R. Cheung, H. B. Kazemian. An Adaptive Framework for Personalized e-Learning, Communications in Computer and Information Science, vol. 136, Springer, pp. 293-306, 2011

Percentage of Contribution for paper [3]:
Ronnie Cheung (90%) H. B. Kazemian (10%)

[4] R. Cheung, H. B. Kazemian. Adaptive Service Composition for Meta-Searching in a Mobile Environment, to appear in Proceedings of the Workshop on the Applications of Soft Computing to Telecommunications in the 12th EANN / 7th AIAI Joint Conferences, Greece, Sept, 2011

Percentage of Contribution for paper [4]:
Ronnie Cheung (90%) H. B. Kazemian (10%)

H. B. Kazemian

Ronnie Cheung