ARCHITECTURAL CONSIDERATIONS FOR CONTEXT AWARE APPLICATIONS
IN A MOBILE CLOUD COMPUTING ENVIRONMENT

A Thesis in
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by
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ABSTRACT

There have been significant recent changes in three areas related to mobile application technology: 1) Mobile devices have become more powerful and equipped with increasingly useful sensors; 2) Mobile device networks have improved in both bandwidth and reliability; and 3) New “apps” and usage patterns have resulted in greater amounts of data that are closely linked to the user and the activities that they use their device for.

A new class of applications such as Google Now[1], seek to behave as “virtual agents” to assist the user based on a large variety of fused data. Unfortunately, these applications are largely “closed source” and little of the basic research is made public.

This thesis explores the state of the art of this new class of applications with a special emphasis on questions such as:

1) What types of problems are best suited to this class of application (e.g. lost traveler abroad, assistive technology, etc.)?
2) When is it beneficial to perform processing on the device itself vs. connecting to the “cloud” or server?
3) What are the privacy concerns related to this type of information gathering and fusion?

The contributions of the thesis include:

1) A comprehensive literature review of the current state of the art and related technologies under development.
2) Design of a framework describing how relevant technologies interconnect
3) Design and implementing a software prototype to explore the effects of “on device” versus “in cloud” computation (see item 2 above).
4) Analysis of the implemented prototype and discussion of future implications.
# TABLE OF CONTENTS

LIST OF FIGURES .............................................................................................................. vi

ACKNOWLEDGEMENT ........................................................................................................ vii

Chapter 1 INTRODUCTION ................................................................................................. 1

Chapter 2 LITERATURE REVIEW ....................................................................................... 7

2.1. Smart Environment and its Components ................................................................. 7
2.2 A Multi-Disciplinarian Background ......................................................................... 9
  2.2.1 Ubiquitous Computing ...................................................................................... 9
  2.2.2 Location Based Computing ............................................................................ 10
  2.2.3 Mobile Computing ......................................................................................... 11
  2.2.4 Mobile Cloud Computing ............................................................................. 12
2.3 Context Aware Computing- Definition of context .................................................. 13
  2.3.1 Components of Context Aware Cycle ............................................................ 14
  2.3.2 Types of Context .......................................................................................... 15
2.4 Emerging Technologies ............................................................................................ 16
  2.4.1 Service Oriented Architecture (SOA) .............................................................. 16
  2.4.2 Middleware .................................................................................................... 17
  2.4.3 Web-services ................................................................................................ 18
  2.4.4 Wearable Computing .................................................................................... 19
  2.4.5 Internet of Things ......................................................................................... 21
2.5 Existing Applications ................................................................................................. 21

2.6 Summary .................................................................................................................... 22

Chapter 3 PROPOSED FRAMEWORK ............................................................................... 23

3.1 Diane Cook's Information framework for Smart Environment .................................. 23
3.2 Proposed Framework ............................................................................................... 25
3.3 Decision Component ............................................................................................... 29
3.4 Information Component ......................................................................................... 30
3.5 Summary .................................................................................................................. 33

Chapter 4 SYSTEM IMPLEMENTATION .......................................................................... 34

4.1 Factors of Division of Application Processing ....................................................... 34
4.2 Procedure of Implementation ............................................................................... 35
4.3 Technologies Used .................................................................................................. 38
  4.3.1 Java Servlets ................................................................................................. 38
  4.3.2 Forecast API ................................................................................................. 39
4.4 Implementation Details .......................................................................................... 40

Chapter 5 DISCUSSION ...................................................................................................... 43
Chapter 6 CONCLUSION AND FUTURE WORK...............................................................45

6.1 Conclusion ............................................................................................................45
6.2 Future Work..........................................................................................................46

BIBLIOGRAPHY........................................................................................................48
LIST OF FIGURES

Figure 1-1: Dynamic Application Processing Scenario .................................................5
Figure 2-1-1: Components of a Smart Environment[2] ......................................................8
Figure 2-2-3-1: A Mobile Environment[21] ................................................................12
Figure 2-4-2-1: Service Oriented Context Aware Middleware Architecture[34] ..............18
Figure 2-4-4-1: Evolution of Wearable Computing[48] ....................................................20
Figure 3-1-1: Components of a Smart Environment[2] ....................................................24
Figure 3-2-1: Framework for Managing Context in Mobile Cloud Computing ............27
Figure 4-2-1: Processing Scenario-Travel Route Decision Problem ............................36
Figure 4-3-1-1: Clients talking to Java Servlets in servers[67] ........................................39
Figure 4-4-1: Opening Screen of the Application ............................................................40
Figure 4-4-2: Quick Solution for the best route to travel .............................................41
Figure 4-4-3: Thorough Solution for the best route to travel ......................................42
Figure 5-1: Comparative Analysis of the time taken for displaying results ................43
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Chapter 1
INTRODUCTION

Since inception, mobile - mobile technologies and the manner in which they are used have undergone significant changes. Given that wireless standards have seen a constant growth supporting higher speeds of data communication for mobile devices, desktop systems and servers, it is not surprising that the applications that the mobile devices support have grown from enhanced quality of voice calls to the Global Positioning System (GPS) navigation system to instant messaging services to mobile internet browsing. Mobile devices are now used for daily activities such as - mail, schedule, location based services, news, social media, entertainment, health and emergency management. This has led to close interaction of the users with the mobiles which in-turn has dramatically affected their lives by influencing their day-to-day decisions. The mobile phones today are "smart" in the kind of data they present to the mobile user taking advantage of the embedded sensors and the ability to exchange data.

According to D. J. Cook [2], a smart environment is one that is able to acquire and apply knowledge about the environment and its inhabitants to improve their experience in that environment. Advances in smart technologies in the field of mobile devices and communications along with trending software agents and middleware technologies has further led to the emergence of ubiquitous and pervasive computing. The area of research that allows small devices to be invisibly ingrained in our everyday human surroundings and therefore provide and easy and omnipresent access to a computing environment is called Ubiquitous Computing [3]. Aided by advanced sensors, devices and wireless networking, ubiquitous computing aims to bring when you want, where you want, what you want and how you want kind of services to the end users. As an extension a new paradigm of ubiquitous computing
emerged where the environment leaned towards being aware of the situation it is placed in. This class of applications that has the ability to discover and react to the changes in the context in which they are situated are called Context Aware Applications [4] accessing public and private information to deliver smarter services to consumers. It was considered an emerging paradigm to free everyday users from manually configuring and instructing computer systems, which enables them to anticipate users' needs and act in advance.

Mobile devices are both personal and ubiquitous as a computing platform. The owners tend to compile all private information and personalize the appearance of information on the mobile devices making them well suited for context-aware computing. Mobile cloud computing has further provided users an exquisite platform to make of use context aware computing on the go. Many of the smart applications are now looking at cloud-computing as an enabler to exploit raw computing power, memory and storage resources to overcome the resource limitations of mobile devices [5]. With the management of context, its associated attributes and their inferences becoming fairly complex, cloud services offer help by taking over the computationally intensive tasks and performing the computations just once irrespective of the number of users.

However most of the context specific tasks are sensed and processed on the device and there are certain obstacles with respect to deciding when the information processing must be conducted on the device and when it makes sense to upload all the sensed data to the cloud and completely process it there. This thesis addresses this question by implementing a web-based model to run on the device vs. on the cloud, details of which are covered in-depth in the later section. The remainder of this section discusses the applications of context aware mobile cloud computing that have been studied in the past, research issues associated with it and describes a formal definition of the problem. Context aware computing was previously studied for several applications, which laid down the foundation were: (History)
- The first application was *The Active Badge Location System* [6] at Olivetti Research Ltd (ORL)\(^1\) which was used to find the location of the people in an office environment.
- *The PARCTAB Ubiquitous Computing Environment* [7] system is based on palm-sized wireless PARCTAB computers and an infrared communication system that links them to each other. These tabs were among the first to be used for different kinds of communication purposes in an office setup.
- "Activity based information retrieval", involves storage and retrieval of information which is stored along with the context at a given time. This is useful for keeping a record of located objects and the persons encountered and places mostly visited during a course of time[8].
- *An indoor wireless system for personalized shopping assistance*, [9] was developed so that a mobile device can guide the shoppers through the general store, help locate items, provide details, and do comparative analysis price analysis.
- Cyberguide [10] provides information services to a tourist about his/her current location for e.g. finding directions, retrieve background information and leave comments on the interactive map. The travel details are compiled automatically using the history of where the tourist has travelled over time and it is used by the system to make suggestions on places of interest to visit.

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\(^{1}\) Now a part of AT & T Laboratories Cambridge
• **Mobisaic Web Browser** [11] is an information system for a mobile wireless computing environment that extends standard web browsers to react to dynamic contextual information by incorporating Dynamic URLs and Active Documents.

• The TEA (Technology for Enabling Awareness) group proposed a real-time architecture for context aware-applications on notepads and mobile phones, which change profiles based on the activity of the user.

Based on the previous applications and the direction in which context-awareness in mobile cloud computing is shifting, the research issues that are associated with it can broadly be classified into:

1. Approach of building the context aware system: depends on requirements specific to a given case and the conditions such as the computing resources available (limiting mobile computing capability vs. higher performance cloud or desktop systems), number of users, location of sensors (local or remote).

2. Methods in which context specific data is acquired: **Direct Sensor Access** for devices with sensors locally built in, **Middleware infrastructure** which separates the application logic from adaptation logic and **Context Server** allows multiple users to access remote data sources[12].

3. Choice of **Context Models** for making the process of the interaction between multiple processes and components smooth[12].

4. Defining application processing - Dynamic partitioning of applications between the device and the cloud, improving the performance by delegating a part of the application to a resource rich cloud infrastructure[13].

This work deals with the second and fourth issues of choice of context-specific data acquisition method and dynamic application processing infrastructure between the cloud and the device. As a specific application, we consider the following scenario:
Travel Route - Decision Problem - Consider a person who has to travel from city X to city Y refer (Figure 1-1). There are two possible routes to reach the city Y. The first route passes through city A followed by city B to reach the destination Y, the modes of travel being flight from city X to A, flight from city A to B and concluding with a car drive to reach the destination Y from B. The second route passes through city C to reach destination Y, the modes of travel being car drive from city X to city C and flight from C to destination Y.

Figure 1-1: Dynamic Application Processing Scenario

The aim is to be able to decide the route to be taken for travel and it is modeled as follows:

1. On-Device Processing (Local Processing) - The decision to take a particular route is based on the primary factors distance and speed and processing is entirely done on the mobile device. This model basically depicts a scenario where time constraint is more important than accuracy constraint.
2. *Cloud/Client-Server Processing* (Remote Processing) - The decision to take a particular route factors in traffic, weather and precipitation other than distance and speed itself. Here the data processing and computation takes place in the Cloud. This model depicts a scenario where accuracy constraint is more important than the time constraint.

3. *Hybrid Computing* - The decision to take a particular route is processed partly on the mobile device and partly on the cloud with help of human integration for accurate route decision.

The focus of this research is on two fundamental areas (i) presenting a framework for context-aware mobile computing where different technologies are interconnected and (ii) to decipher the full potential of mobile cloud-computing by striking a balance between mobile applications (offline/on-device) and web applications (online/cloud) while dynamically shifting the computing and processing tasks between mobile and cloud. The contributions in this thesis include: 1) conduct of a literature review (Chapter 2), 2) discussion of various technologies that interconnect while designing a context aware application. (Chapter 2), 3) development of a framework for context aware applications in a mobile cloud computing environment (Chapter 3), 3) discussion of factors to be considered while dividing application processing between mobile and cloud (Chapter 4) and 4) implementation of web-based prototype to demonstrate the division of application processing (Chapter 4). The last chapter discusses potential extensions to this research (Chapter 5).
Chapter 2

LITERATURE REVIEW

As outlined in the previous chapter, the subjects that must be considered for adequately analyzing the context aware mobile cloud computing environment can be divided into three categories:

1.) Previous work that led context aware computing - Smart environment and its components, Ubiquitous Computing, Location Based Computing, Mobile Computing, Mobile Cloud Computing, Context Aware Computing; Definition of context and its classification;

2.) Reviewing the developing technologies associated with MCC(mobile cloud computing) environment - Service Oriented Architecture, Middleware, Web-services, Wearable Computing, Internet of Things;

3.) Reviewing Existing applications - Google Now, Siri and outlining the class of applications which it can be applied to. The rest of this section is organized to detail each subject and the work that has been done to address it.

Additionally, an existing design will be reviewed and extended as an hybrid information framework for context aware applications in a mobile cloud computing platform in the next chapter.

2.1. Smart Environment and its Components

D. J Cook and Das reviewed the smart environments that were trending in multiple disciplines such as mobile computing, middleware and agent-based software, pervasive computing and defined it as an "environment that is able to acquire and apply knowledge about the environment and its inhabitants in order to improve their experience in that environment". [2] The process of detecting a state of environment and its elements, analyzing the necessary inputs/outputs of the tasks and finally performing the necessary action was autonomous. This was considered to be the selling point of smart environments. Figure 2-1-1 describes the various components involved in a smart environment[2]. The
physical sensors send the information from the physical environment to the communication layer. Amongst the components of the Information, database stores the information received from the communication layer while the prediction, inhabitant modeling and data mining processed information from the sensors. This information is now available to the decision component.

While the perception of the environment is a bottom-up process, the action flows in the exact opposite manner. The decision is communicated to the information and communication layers and the action is taken by the physical sensors and triggers the perception of the new state of the environment. Context Aware applications started with the notion of a smart environment for mobiles.

Figure 2-1-1: Components of a Smart Environment[2]
2.2 A Multi-Disciplinarian Background

The framework for context-aware computing is a multi-disciplinary research area, which draws its goals from areas such as ubiquitous computing, location based computing, mobile computing and mobile cloud computing.

2.2.1 Ubiquitous Computing

"The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable." Mark Weiser was the first to foresee the usage of portable computing devices. He called this type of computing where small devices are invisibly ingrained in our everyday human surroundings and therefore provide an easy and omnipresent access to a computing environment as Ubiquitous Computing [3]. The idea was to present applications to the end user which demanded less concentration from the user but yet seamlessly produce the desired results by imbibing intelligence of highly connected computer systems through casual interaction. A number of research projects were developed in Xerox PARC with this vision. The PARCTAB system[7] the pioneer, was based on palm-sized wireless PARCTAB computers and an infrared communication system that links them to each other. The device was designed to provide a real-time tracking mechanism of location, operational status messages of system elements and use context to deliver messages that aided the communication of individuals. Dey and Abowd[14] presented a conceptual framework for the support of rapid development context aware applications by developing a toolkit which was useful to handle the raw-sensed context implicitly which consequently determined the next state of the application.

[15]–[17] are the most recent works related to advances in ubiquitous computing. Thus the idea of devices being integrated in individuals lives which seamlessly helps them to get around their daily activities tended towards learning and being situationally aware, responsive and intuitive.
2.2.2 Location Based Computing

Location-based services are information services that make use of location at a given time to generate relevant information requested by the end user. The forerunner in the field of location based computing was *The Active Badge Location System* [6], the research conducted at Olivetti Research Ltd (ORL)\(^1\) which was used to find the location of the people within a building by means of their Active Badge. It served as an aid for the telephone receptionist dynamically updating the list of users' location and telephone numbers. This was done by means of infrared signals sent out by the active badges worn by an individual. The networked sensors detect these signals which determined the location. Location based services were used for stolen vehicle services as well as pagers programmed to transfer information about location based goods and services by International Teletrac Systems (later called PacTel Telecom). The first consumer LBS (Location based service) based mobile phone was *Palm VII* released in 1999[18]. The first LBS application was jointly shared by the Weather.com App and Traffic touch app which made use of zip-code level positioning information[19]. Schilit[4] in his work, reiterated the importance of location information and its contribution towards disseminating information to achieve a task. Evolution of location based services resulted in capturing location information in several methods, adopting several techniques.[20] The methods can be summarized as follows:

1.) *GPS based LBS* - Standard solution based on capturing exact location based on GPS.

2.) *GSM localization* - Location of the object/person is found out by determining the position of the mobile device relative to its cell site.

3.) *Near LBS (NLBS)* - Allows a person to capture information of his surrounding with the help of local range technologies like Bluetooth, Wireless Local Area Network (WLAN), Near Field Communication, which are used to match devices to nearby services.
4.) *Operator and GPS-Independent location service* - Provides access to geographical coordinates of mobile phone numbers through deep level telecom networks.

Location based services/location information thus persisted being integral towards the understanding of context.

**2.2.3 Mobile Computing**

Powerful mobiles and development of fast reliable networks has converged to make mobile computing as a very strong emergent paradigm in the field of communication and services. It does not require users to be stationary in a specific position of the network and allows mobility of the users. An architecture for general mobile computing environment was suggested by Daniel[21]. It consisted of two entities- mobile units and fixed hosts called mobile support stations. These fixed hosts communicate with mobile hosts within a particular networking range called cell through a wireless interface (refer to Figure 2-2-3-1). The features that change more frequently in a mobile environment when compared to fixed desktops are communication characteristics, connectivity and configuration of peripherals[4]. These features actually play in the favor of mobile computing environments as against traditional desktops. Communication asymmetry and power limitations of mobile devices result in broadcasting data to a larger set of clients, called data dissemination. This feature results in no waiting period for users and this form of notification to the clients is called push-based notification[21]. Portable devices, mobility, data dissemination and easy to use interfaces for the clients made mobile computing suitable candidates to model context based information in a dynamic environment.
2.2.4 Mobile Cloud Computing

Mobile Cloud computing has been one of the most researched areas over the past few years. Cloud serves as a computing environment, which provides application services through the Internet. Cloud computing was recognized as a complimentary service to the resource constrained mobile environment, by extending its capabilities through ubiquitous access of network in an on-demand fashion and also releasing them through minimal management efforts[22]. Mobile Cloud Computing environment takes advantage of the cloud's plentiful resources to acquire, assimilate and dispatch necessary data/services to the mobile devices. Despite this luxury, it is known that most of the context specific tasks
are sensed by the mobile device. Here communication of the sensed data is an issue since it rapidly uses up the battery power of the mobile device. Consequently, the full potential of a mobile cloud computing environment can be realized only when there is a balance achieved between applications which completely run on mobile devices called native applications[13] and applications which completely run on the cloud. There is a need for a decision mechanism which would analyze what part of the application would be delegated to the cloud while the mobile device continues to analyze the user input. This thesis presents a solution to modeling applications that run on mobile devices under certain cases, run on cloud in some other cases through analysis of Quality of Service (QoS) and Quality of Experience (QoE).

**2.3 Context Aware Computing - the challenge of defining "context"**

Schilit[4] defined context aware computing as the ability of a mobile user's application to discover and react to the changes in the context in which they are situated. Context Awareness is an intrinsic element of smart environments[23]. Context was first defined by Schilit[4] as location, identities of people in the environment, objects and state of these objects. Chen[24] termed context as the set of environmental states and settings that either determines an application's behavior or in which application event occurs and is interesting to the user. Dey's[23] definition of context is the most cited and elaborate one which defined context as any information that can be used to characterize the situation of entities(i.e. person, place or object) that are considered relevant to the interaction between user and application, including the user and the application themselves. Context here is typically location, identity and state of people, groups and computational and physical objects. Chaari[25] defined context in terms of dynamic application behavior as a set of external parameters that can influence the behavior of application by defining new views on its data and its available services. These parameters may be dynamic and may change during the execution. These are some of the prominent and most cited definitions of context, although it is not an exhaustive listing. Listing all of the definitions is beyond the scope of this thesis. However, it is clear though that context refers to any information that would aid the processing of the
mobile application under a given circumstance to make intelligent autonomous decisions. For the purpose of this thesis we will stick to this idea.

Let us consider a real world example to understand what elements qualify as contextual information. Consider the travel route decision problem discussed in the introduction chapter. For example, a person traveling from one city to another, the elements that can aid in the decision making of the route to be taken are:

- Time of travel
- Weather conditions throughout the possible routes
- Traffic updates
- Mode of travel

These can be considered as contextual information for the scenario considered.

2.3.1 Components of Context Aware Cycle

Context Aware applications are discussed to be a three step process[4]:

- **Discovery** - This involves learning about entities that are relevant to the given task and also learning their state throughout the application process. This means that the application has to explore the environment in order to receive inputs to work with not just on the device which it is residing but also learn about the network and computational resources available in its environment.

- **Selection** - Given the vast amount of information available in the environment. The application must be able to separate the necessary information from the irrelevant with regards to the given task. This is an elaborate procedure as it has to learn which device or which sensor is providing the correct information. Modeling this information in terms of type, location and other factors is also a primary concern.
• *Use* - The information which was discovered and selected now may or may not be used by the application in order to produce the necessary result, change the state of the environment or save it for a later usage in the application processing.

Building on the "Use" aspect, Naqvi[26] identified ways in which this context information can be used:

i. *Contextual Information Display* - The context is presented to the user on his/her mobile device.

ii. *Contextual Augmentation* - This will associate metadata associated with the captured context.

iii. *Context Mediation* - Here context is acquired with the motive to mediate it to parts of the application that are in need of it.

iv. *Context-aware Configuration* - Defines actions to be taken, given information associated to the context.

v. *Context-triggered Actions* - Certain context behavior is displayed if all the contextual conditions of a defined use-case are met.

### 2.3.2 Types of Context

The initial categorization of context was given as where you are, who you are with and what resources are nearby[4]. Ryan et al suggested categorization of context based on *location, identity, environment and time*. Dey[23] corrected this categorization by introducing activity in place of environment. He categorized context on the basis of location, time, activity and identity. He supported his proposal by stating that *environment* being a synonym of context, did not add any additional information to the existing context. While activity answers the primary question of what is occurring in the current circumstance. Location, time, activity and identity answered all questions related to who, what, when and where of the initial proposition by Schilit. He further defined a two-tier classification system for context
and called them *Primary and Secondary* contexts. Four primary contextual information is defined at the first level as location, time, activity and identity and secondary context was any information corresponding to the environment that could be indexed by primary context. For example, phone numbers associated with individuals could be indexed by identity. Hence phone number is the secondary context in this case. Thus the major pieces of information of the environment that aided the application processing were categorized.

**2.4 Emerging Technologies**

**2.4.1 Service Oriented Architecture (SOA)**

Traditional applications were relieved from having to develop components that solely serve their own purpose with the introduction of Service Oriented Architecture (SOA) by Schulte and Natis [27]. This architecture consisted of loosely coupled individual services with specific functionalities and could communicate with each other over the network to serve the purpose of applications with greater functionalities. In short, services are observed as plug-in components to accomplish the given task at hand. As noted earlier, wireless communications and mobility have taken the driver's seat accelerating the usage of smart applications on mobile devices. The development of these applications has undergone rapid change from being native applications to applications distributed partly on cloud and mobile with the help of the mobile cloud computing paradigm. These applications have therefore resorted to a service oriented approach of having loosely coupled services distributed on mobile and cloud. As context aware computing becomes increasingly prevalent on the mobile cloud computing platform, the intricacy and complexity that comes with effective utilization and management of context requires an investment in the blueprint of where and how the services distributed between the device and the cloud as they impose new integration and interoperability requirements. Hong et al[28] identified the quality of SOA that could be implemented in a context aware framework which was independence from hardware, operating system and programming language where sensors, services and devices can be changed, all other things
remaining constant and dynamically even as applications and sensor services continue to run. With the aim to develop mobile applications in a cloud computing environment which automatically provides timely notifications to their users by analyzing their situation and adapting to the new situation as it changed and to do this without the dedicated involvement from the user, Jason[29] proposed the use of context obtained from sensors of the mobile device and offloaded responsibilities to the cloud with the use of REST web-services in a service oriented fashion.[30] [31] are the most recent examples for the adaptation of services oriented methods in context aware computing. Thus context management is leveraged using Service Oriented Architecture in a mobile cloud computing framework. The role of Service Oriented Middleware is discussed in the next section.

2.4.2 Middleware

One of the first occurrences of the term "Middleware" was in a report [32] written by Pressman and Wadekar in 1969. Middleware in the simplest form can be described as the software that acts as a bridge between the operating system and application, especially among networked clients or a distributed system[33]. In the field of context aware applications, heterogeneity exists in the form of technologies, communication methods adopted, data representation and also it must be noted that the application processing occurs at different levels. This consequently led to a new class of applications inside context aware applications called context aware middleware solutions. In addition to the functionalities provided by the generic middleware, it handled context management and served as an active recipient to the changes occurring in the environment, capturing contextual information from heterogeneous sources. Some of the context aware middleware solutions are SOCAM - Service Oriented Context Aware Middleware [34] modeled context aware systems as set of services that perform context acquisition, context discovery, context interpretation and context dissemination(Refer Fig 2-4-1-1). CARISMA - Context Aware Reflective middleware System Mobile Applications[35] enhances context aware application development by making them adaptive using the reflection paradigm. CAPNET [36] is a
context aware middleware for mobile multimedia applications. [37] Re-iterated the concept of context aware middleware platforms as an answer to challenges associated with service discovery, mobility, environmental changes and context retrieval. [38] Overcame these challenges. Thus an effective middleware is a powerful tool to mask heterogeneous elements interacting in context aware applications and service provisioning. Context Aware middleware solutions has explicitly emerged as a distinct research area.

**Figure 2-4-2-1**: Service Oriented Context Aware Middleware Architecture[34]

### 2.4.3 Web-services

Web-service is defined as a method of communication between two electronic devices over the World Wide Web. With the adoption of Service Oriented Approach for context aware applications, web-services in this field came into limelight for managing context and its processing. Web-services are realized in a standard format of which XML (Extensible Markup Language) based languages and JSON (JavaScript Object Notation) are most widely used. A context aware service is considered as a smart web service defined as “a web service that can understand situational context and can share that context with other
services” [39]. Service discovery in [40], context management in [41], ESCAPE framework for teamwork and disaster management [42] and more recently [31][43][17] demonstrate the development of adaptable context aware web-services for context sharing.

2.4.4 Wearable Computing

Wearable computers, also called body borne computers are generally worn over/under/ in clothing, useful for complex computational support [44] more than just hardware coded logic. Wearable computers have found their application in service management, health care monitoring systems, smart phones and electronic textiles to name a few. ISWC (International Symposium of Wearable Computing) is conference dedicated to discussions/applications of wearable computing. Figure 2-4-4-1 gives an overview of the history of wearable technology. The last five years have seen a particular movement of wearable computing goals towards ubiquitous/context aware computing. Devices like Nike Fuel Band [45], Google Glass[46] and for that matter the most recent innovation Samsung's Galaxy Gear[47] are built to work with Smart Phones capturing and learning the context through user activities exploiting the added advantage of constant interaction of the computer and the user serving as a prosthetic. This technology is still at a nascent stage, researchers are exploring the various functionalities that promote ubiquitous use of such devices.
A BRIEF HISTORY OF WEARABLE TECHNOLOGY

INNOVATIONS

1975
Pulsar Calculator Watch
Monterey Watch Company introduces first calculator watch.

1979
Sony Walkman
Introduced a new portable way of listening to music.

1984
Casio Databank
CD-40 one of the first digital watches created that allowed the user to store information.

1987
Digital Hearing Aid
Hollon introduces the first body-worn digital hearing aid.

1993
Apple Newton PDA
One of Apple’s first attempts at reinventing personal computing.

1998
First BlackBerry Launched
The first BlackBerry device was an email pager.

2000
First Bluetooth Headset Shipped

2001
Apple iPod

2003
Viatron C-series
The world’s first fully digital pedometer.

2004
Motorola RAZR
Sold more than 100 million units, becoming the best-selling clamshell phone in the world to date.

2004
GoPro Camera
GoPro creates a personal camera that is wearable and mountable.

2006
Nike+ iPod Kit
The device measures and records the distance and pace of a walk or run.

2007
Apple iPhone

2008
Fitbit
Designed to be clipped onto clothing, it tracks steps, calories burned, activity intensity, and sleep.

2011
Jawbone Up

2012
Nike FuelBand

2012
Pebble Watch

2013
Nissan Nismo Smartwatch
Connects to a sports car to provide data on its performance in real time.

2013
Misfit Shine

2013
Google Glass
Head-mounted display that presents smartphone-like information hands-free.

2013
Samsung Galaxy Gear
Samsung announces their first foray into wearable tech with the Galaxy smartphone.

Figure 2-4-4-1: Evolution of Wearable Computing[48]
2.4.5 Internet of Things (IoT)

The "Internet of Things" [49] term reflects the ideology that all computers/devices should be able sense/process/analyze/broadcast/manage information about themselves in an environment which allows for interaction with other devices, humans in the network through technologies such as Radio Frequency Identification (RFID), sensor technology, Internet Protocol (IP) based infrastructure in a smart and autonomous fashion. There are many applications of this concept like *Embedded intelligence* which leverages collection and analysis of digital traces left by people when interacting with smart devices, to learn about environmental activities and social connections [50], *Ambient Intelligence* coupled with *Autonomous* control [51]. The concept that when an object can represent itself digitally it can be controlled from anywhere opens up new possibilities which brings together people, process, data and things to make networked connections which Cisco Systems Inc., coined as Internet of Everything (IoE) [52]. Although there are several benefits, there are also challenges associated with power consumption, low-cost smart sensing system development, security issues and scalability [53].

2.5 Existing Applications

Among the existing applications *Google Now* [1] and Apple *SIRI* [54] have stood out as intelligent personal agents which uses a natural language user interface to answer questions, make recommendations and perform actions by delegating requests to a set of web services. The additional functionality provided by Google Now is that it provides the user with information that it predicts might be useful for him/her. It does so by recognizing the repeated actions of the user (common locations, calendar appointments, queries searched, Gmail appointments) and displays information in the form of "cards". Although these
applications are powerful in-terms of the information they dispense, the methodology adopted is not available for researchers. Through this thesis a framework for this class of applications is proposed by including the human cognition as an added incentive to aid machine/device information processing.

2.6 Summary

The above review provides an understanding of the evolution of the technologies for ubiquitous environment. It is observed that there is a growing trend towards incorporating devices and smart services in our daily lives to enable communication not just with the end users who are requesting services but also amongst various devices. The goal is to put forth a complete solution by learning prior activities of the user even when some information is unable to be captured at the time of information gathering, there by promoting an autonomous intelligent environment. Bringing together a novel combination of these technologies as plug-in components a novel dynamic information architecture is proposed in the next chapter which addresses context awareness in a powerful mobile cloud computing platform.
CHAPTER 3

PROPOSED FRAMEWORK

This section describes highlights of Cook and Das's Information Framework for Cross Domain (mobile computing, artificial intelligence and sensor networks) Smart Environment and discusses how it to can be extended to provide the proposed Framework for Managing Context in Mobile Cloud Computing.

3.1 Diane Cook's Information Framework for Smart Environment

The motivation for the proposed framework is Cook's design of smart environment and its components[2] which was briefly described in chapter 2. Cook's design for a smart environment was based on information management and processing through distributed wireless sensor networks for development of an intelligent and automated environment. Empowered by wireless mobile communications/computing as well as situation-aware computing, pervasive computing aims to provide a where you want, when you want and how you want approach to the service layers (refer Figure 3-1-1).

Some of the highlights of Cook's framework are:

- The perception of the state of the environment and flow of decision back to the environment is described as an evolving cycle consisting of Physical, Communication, Information and Decision components.
- The importance of existence of an intelligent agent that can reason about the environment through the information received through the physical components and execute necessary action.
- A model of the ubiquitous nature through converting information into meaningful representations that is stored in the database which could be retrieved as and when required. They indicated the
need for development of automated machine-to-machine interaction without the explicit control of the user.

- The need for effective interfaces which are not only transparent between disparate entities in the environment but also scale well to a large number of users.

- A focus on the development of effective middleware strategies that could mask the effects of location and mobility of the end users, when retrieving results from the decision making component. Please refer Figure 3-1-1.

![Diagram of a Smart Environment](image)

**Figure 3-1-1: Components of a Smart Environment[2]**

Having said this, there are certain limitations to the framework. They are:
Physical sensors are limited when it comes to energy, communication, computation and storage which thereby leads to uncertainty in the sensed data.

A single intelligent agent would not suffice for modeling complex context learning situation. Disparate entities to overcome these short-comings are not discussed.

The model is missing a resource-rich component that can be used to scale to massive data load that could occur at a given time. The data offloading concept which can drastically reduce the overhead on the system as well as the response time to the user is not discussed.

The elements which belong to the four distinct components of their framework are weakly described for the current generation of smart environment.

Storing information in a database for retrieval at a later time is an outdated concept when it comes to online context learning of inhabitant's interests as the amount of data that would go into this database is still an unsolved challenge to the "Big Data" community.

The approach does not involve the use of mobile technology, although they are essentially suitable candidates for the described scenario.

Hence there is a need to update this framework to bring into play multiple intelligent agents to handle data dynamically—keeping in mind the user's request, the time to respond and accuracy vs. time constraint to suit the current trends of user requests in a context-aware computing environment.

3.2 Proposed Framework

For context-aware computing in a mobile cloud computing scenario, there is a need for restructuring the existing framework by shifting the focus towards acquiring information about the environment through a mobile device. The limitations in Cook's framework of a smart environment are overcome by presenting a framework that could handle information processing dynamically by
choosing between mobile device, cloud and hybrid computing for the purpose of information processing. Following are the major changes made to Cook's framework:

- Decision Component: Modified this layer to include Human Cognition, Machine Application and Hybrid Computing: combination of both.
- Information Component: Modified this layer to include Hard and Soft Fusion and Multi Agent Systems.
- Communication Component: Modified this layer to include Mobile, Cloud, High Performance Computing/Grid and Human Integration.
- Physical component: Unlike the traditional sensors that make the wireless sensor network. Physical Sensors in this framework come from those on a generic mobile device. They are Accelerometer, Gyroscope, Barometer, Thermometer, Photometer, Magnetometer etc. Refer to Figure 3-2-1.
- Context-Aware Middle ware and Web-services for communication amongst all participating entities (mobile/cloud/human/grid).

This design helps to overcome the shortcomings of existing smart environment in the following manner:

- Limitations of computation, energy, communication and storage are overcome by proposing a hybrid system of mobile device used in conjunction with cloud systems in place of multiple physical sensors.
Uncertainty in continuous acquirement of state of the environment and dispatching the necessary actions to be taken is modeled in the form of multiple software agents responsible for specific tasks.

- Autonomous nature of the smart environment is incorporated through context modeling. Through context model, the interaction between external interfaces is determined. When information acquired from the environment is stored as context models, a structured storage aids re-usability of data as against traditional storage in the database where the information needs to be queried as and when ever it is required, leading to overhead.
- Inclusion of human cognition and interaction aids the results from the machine application to be drawn towards a personal solution catered to a specific individual under a given scenario.

- The inclusion of the resource rich cloud is useful under circumstances where the computation is intensive and it would take a long time when computed on the mobile device. The information processing is then offloaded to the cloud. While the user receives certain push notifications for some additional details, the cloud presents the solution to the user. This masks the delay that would have been experienced by the user had there been no intermediate tasks to keep him busy. This overcomes the limitations of energy consumption on any physical sensor or mobile device for that matter.

- As discussed in the introductory chapter, the usage of mobile devices has proliferated exponentially. Therefore the use of mobiles as the primary information retrieving device is an advantage as it is portable and there is no cost associated with establishing additional sensors around the inhabitant's environment.

- The mobility of the user does not hinder the delivery of context aware services. This is taken care of by the context aware middleware.

Recall that Cook's Information Framework consisted of four major components: Physical, Communication, Information and Decision. Although Communication and Physical components are necessary to understand the complete functioning of the context aware applications, for the purpose of this thesis- focus is laid on the elements that make the Decision and Information components for the following reasons ( -- points out the component to which functionality belongs) :

1. The novelty in this framework comes with the inclusion of the Human Cognition to the context aware applications which come into play when cloud services are invoked. --Decision Component
2. It is necessary to understand how the human cognition influences and aids in the decision process by the machine application and how it interacts with the machine application in the case of hybrid computing. -- *Decision Component*

3. From learning state of the environment, processing information and dispatching necessary actions, all complex tasks are modeled as software agents. -- *Multi Agent Systems in Information Component*

4. Data mining and prediction of the future activities of the inhabitants, which is the heart of the context aware computing goals is also modeled in the information component of the framework. -- *Information Component*

5. Autonomous nature of the smart environment is incorporated through context modeling. Through context model, the interaction between external interfaces is determined. -- *Information Component*

The next two sections provide a deeper insight of the elements present in the Decision and Information components of the architectural framework.

### 3.3 Decision

The Decision Component in the framework is responsible for logical conclusion of the information received from the environment, in the form of necessary actions which are observed on the display of the mobile devices. This consists of three main components which are described below:

- **Machine Application**: Machine application refers to the application logic that runs on the mobile device of the consumer or in the cloud. The information which is captured by the physical sensors of the mobile device is combined with the information received from the cloud and algorithmically solved to achieve the task at hand when the information processing occurs in the
cloud. When time is a constraint, information received from the sensors is processed locally on the device to attain fast results.

- **Human Cognition:** Cognition can be described as the faculty of processing information by applying knowledge, reasoning, calculating and problem solving. It is a known fact that human's are gifted with a faculty of cognition which can be considered as a natural state. Within the framework of context aware applications, human cognition can be considered as one of the inputs that could aid analysis of the information received from the environment and help produce necessary steps of actions. When accuracy of the generated actions is greater than the time taken to present the actions to the user, information is offloaded to the cloud for further processing. Here human entered inputs are also factored in for information processing and generation of results.

- **Hybrid Computing:** Hybrid Computing is basically the combination of *Machine Application* and *Human Cognition*. In situations where the data received from the mobile sensors is large/continuous and time to generate actions for the user is reasonable (not too long or short), the generation of actions can be divided amongst the machine application and cloud computing system with human entered inputs. This would be effective when the data received from the mobile sensors is complex, resulting in complex action sequences.

### 3.4 Information

The information component of the framework is like the brain of the system. It is responsible for mining, processing, modeling of raw information received from the environment through mobile physical sensors. In addition, when cloud systems are in picture, information is received from the cloud which includes the information arising from human integration under special circumstances. In such
a case, it necessary to understand hard and soft information fusion. The main elements that make
Information component are Context Modeling, Multi Agent Systems, Data mining, Databases, Hard/Soft
Data Fusion and Prediction and are described as follows:

- **Context Modeling** - In context aware computing systems, a formal context model is essential as
it serves as a provision for needed information as well as to store and manage context itself. As
pointed by [55], advantages of context modeling in context aware computing are three fold: 
  *Knowledge Sharing*, *Logic Inference* and *Knowledge Reuse*. Given that we are dealing with
heterogeneous systems (mobile/cloud/grid) it is necessary to lay down a uniform understanding of
contextual information. Deduction of high-level context from raw information consistent across
different platforms and solving inconsistent context knowledge is possible through context
ontology. Storing and maintaining such data through the use of standards such as OWL (Web
Ontology Language) [56] promotes the re-use of contextual information without having to
collect all information from the environment at all times.

- **Multi Agent System**: An intelligent software agent can be described as a functional
system/computer program that is capable for performing tasks by learning/using information to
achieve goals. Coming together, several such intelligent agents solve complex problems
efficiently and form multi-agent system. Extensive work has been done for multi agent systems in
the field of context aware computing and even otherwise [57][58][59][60][61]. Within the
updated framework in this thesis, Multi Agent systems can be modeled as follows:

  1. Software agents can be used for making a decision of processing the information on
the mobile/cloud/hybrid.

  2. Software agents can be used for extracting the most useful contextual information
amongst the data recorded by sensors on the mobile device.
3. Dispatching necessary actions (final outcome) to the end users in a top-down fashion in an otherwise bottom-up framework.

4. Channelizing data amongst disparate devices based on the complexity of the situation.

5. Various elements in this information component can be considered as software agents accomplishing disparate tasks.

Therefore Multi-Agent Systems enhance modularization of the application by abstracting their complexity.

- **Hard/Soft Information Fusion:** An intriguing aspect in the field of multi-sensor data fusion that has gained focus in the recent times is the concept of human-centered information fusion [62]. It focuses on the engagement of human cognition to support computer programs, here humans serve as "soft sensors". This when combined with the information obtained from the physical sensors ("hard" sensors) are known to complement their collective findings and ultimately yield numerous benefits [61][63][64]. In the context of the updated framework of this thesis, human inputs support the information obtained from the mobile sensors when the cloud services are invoked. This feature provides the most accurate results to the end-user.

- **Data Mining/ Prediction/ Databases:** Data Mining refers to extracting useful information from available dataset and transforming it into an understandable structure which would be useful for further use [65]. The process of procurement of information from the mobile sensors to storing into Databases can be described as the following stages of data mining: Data Acquisition, Context Annotation, Context Modeling, Storage.

1. **Data Acquisition** - The mobile device under consideration is Android Mobile Device[66].

   Android sensor framework provides methods which enable the developer to determine
the list of sensors available on the device as well as their capabilities and attributes. By monitoring sensor events raw data can be acquired.

2. **Context Annotation** - Raw data acquired in the acquisition stage is annotated to belong to a specific category. For example: *Location, Time, Human Input, Weather.*

3. **Context modeling** - Interaction of the software agents to exchange the annotated elements between multiple systems(mobile/cloud/hybrid) can be described in the form of Web Ontology Language (OWL). At a high level, OWL uses classes and properties to describe the interaction.

4. **Storage** - Information about the environment is finally stored in the *Database* consistent with the context model which promotes re-use and *prediction* of future activities of users.

The fundamental question about which data should be used to generate the results is based on two factors. The first factor is, the time frame within which the user wants the results. And the second factor involves the privacy settings of the user. The data thus recorded can be used to learn the activities of the user while securing the privacy of the user. Thus *Prediction* of the future activities of the user can be modeled.

**3.5 Summary**

We have proposed a Hybrid Information Framework for context aware computing application as an extension of Cook's Information architecture for smart environments. The new framework involves the inclusion of hybrid decision making, powerful cloud systems and context modeling that can alleviate recursive/cumbersome patterns of knowledge discovery. This results in an intuitive environment. More over the privacy issues pertaining to sensitive information of users is accounted by adopting a user control strategy. Given such a framework, the next chapter discusses a prototypical implementation analyzing the division of application processing between mobile device and cloud.
Chapter 4

System Implementation

4.1 Factors For Division of Application Processing

A web-based model was implemented to illustrate the discussion of application processing between the mobile and cloud. To understand the basis of division of processing we consider the following examples:

1. *Is this my stop?* - Consider a train traveler querying his mobile phone if the next stop is the one where he should exit the train. Here time is a constraint and the mobile device should quickly generate a solution for the traveler. Also given that the train is in motion, it is likely that the device user may face network connection issues. This is a suitable candidate for modeling a solution based on local processing on the device.

2. *Planning vacation* - Consider a person who is at home and is planning a vacation at leisure. Here accuracy is a constraint. One would prefer a thorough plan of the places he/she could visit taking into account the weather, travel itinerary and traffic updates. Given sufficient time and good network coverage this is a suitable candidate for modeling a solution based on thorough (mobile + cloud) processing. Here user preference is uploaded to the cloud, triggering calls to weather and traffic API for gathering the relevant information. Processing and computation therefore occurs in the cloud.

It is clear that there are certain scenarios where processing information on the device is ideal vs. uploading information to the cloud. Another constraint that promotes the ideology -"Use the mobile as a standalone device in every situation where there is a scope" is, energy consumption due to communication of the sensed data to the cloud. With every update of the operating system that powers a
mobile device, users experience a decreased battery life. The applications which are constantly pulling data from the phone like Dropbox syncing, Google photos synchronization with cloud and other applications are partly responsible for exhausting the battery of the mobile device. Increasing availability of Long Term Evolution (LTE) (wireless communication for high-speed data) for phones will also drastically reduce the battery life of the mobile devices. Hence a mobile device application should be designed such that it makes the right judgment about application processing division. Therefore the factors that are identified to aid in the application processing division are Time, Accuracy, Energy Consumption and Communication.

4.2 Procedure of Implementation

The following approach was adopted to address the issues discussed above:

1. A specific scenario of Travel Route Decision Problem was selected to illustrate the concept of division of application processing.
2. A web-based prototype was developed as a proof-of-concept. The prototype involves the design and implementation of the options "Quick" and "Thorough" which modeled the Time and Accuracy constraints discussed in the section above.
3. A sample algorithm was implemented to quantify the measure of route to be taken for travel based on the Weighted Travel Score.

The approach is shown below:
Figure 4-2-1: Application Scenario - Travel Route Decision Problem

Figure 4-2-1 describes the scenario assumed for the demonstration purpose in this thesis. As discussed in the introduction chapter, in the Travel Route Decision Problem - a person has to travel from city X to city Y refer (Figure1-1). There are two possible routes to reach the city Y. The first route passes through city A followed by city B to reach the destination Y, the modes of travel being flight from city X to A, flight from A to B and concluding with a car drive to reach the destination Y from B. The second route passes through city C to reach destination Y, the modes of travel being car drive from city X to city C and flight from C to destination Y.

The aim is to be able to decide the route to be taken for travel and it is modeled as follows:

1. **On-Device Processing** (Local Processing) - The decision to take a particular route is based on the primary factors distance and speed and processing in entirely done on the mobile device. This model basically depicts a scenario where time constraint is more important than accuracy constraint.
2. **Cloud/Client-Server Processing** (Remote Processing) - The decision to take a particular route factors in weather and precipitation other than distance and speed itself. Here the data processing and computation takes place in the Cloud/Server. This model depicts a scenario where accuracy constraint is more important than the time constraint.

The process is as follows:

1. The web application asks the traveler for information about the **Source, Destination** and the mode of result (**Quick** or **Thorough**). The **Quick** option accounts for local processing based on pre-fetched travel itineraries. Second, the **Thorough** option accounts for computation on the cloud/server.

2. The result of the query is the best suitable route for travel which is computed based on a **Weighted Travel Score**.

3. For the **Quick** option, the **Weighted Travel Score** is a trivial solution based on distance between each leg of the route and the speed of the mode of travel. For the sake of simplicity, the possible modes of travel in this prototype are drive and flight.

   \[
   \text{Weighted Travel Score (WTS) [Estimated Travel Time] = Distance/Speed}
   \]

4. For the **Thorough** option, the **Weighted Travel Score** factors in weather information from **Forecast** API containing the wind speed and precipitation information pertaining the source, destination and the possible waypoints.

   \[
   \text{WTS = (Distance/Speed) \ast (Factor \ast Windspeed) \ast (Factor \ast Precipitation)}
   \]

Here when the mode of travel is flight, the wind speed has more weightage compared to precipitation. While the mode of travelling is driving, the opposite case occurs; with precipitation having more weightage over wind speed. The factor itself in each case varies from 0.01 to 0.9 depending on the mode of travel.
4.3 Technologies Used

Web application was chosen for the prototype because by nature it is a distributed application i.e. it is a program that runs on more than one computer and communicates through a network or server. Specifically, a web application is accessed with a web browser and is popular because of the ease of using the browser as a user client. They can also be accessed through mobile browser provided their design is responsive. HyperText Markup Language (HTML), Cascading Style Sheets (CSS) and JavaScript are additional scripting languages that are used with web application responsible for the user interface and functionality of the application. Java Language is used with web application in this implementation because of its versatility. The Java Technology used in this thesis' prototype is Java Servlet API running on Apache Tomcat Server.

4.3.1 Java Servlet API

According to [67], Java servlet lets you define HTTP specific classes. Servlets are protocol- and platform-independent server side components, written in Java, which dynamically extend Java enabled servers. They provide a general framework for services built using the request-response paradigm. In this prototype, a servlet is used to get the text input from an online form, process this information and print it back to the screen in an HTML page format. The servlet runs on the server side - without an application Graphical User Interface (GUI) or HTML user interface (UI) of its own. Figure 4-3-1-1 illustrates clients talking to java servlets in servers.
4.3.2 Forecast API

The Forecast API [68] lets you query for most locations on the globe, and returns:

- Current conditions
- Minute-by-minute forecasts out to 1 hour (where available)
- Hour-by-hour forecasts out to 48 hours
- Day-by-day forecasts out to 7 days

The API call `https://api.forecast.io/forecast/APIKEY/LATITUDE,LONGITUDE` returns the current forecast (for the next week). There are wrapper libraries available for this API that make it easy and quick to include it in our application. Information is presented as data point object, which represents the various weather phenomenon occurring at a specific instance of time.

The properties that the data point objects may have are `time`, `summary`, `nearest storm distance`, `nearest storm bearing`, `precipitation intensity`, `wind speed`, `temperature minimum`, `temperature maximum`
and others. Amongst the numerous properties, this implementation utilizes the current wind speed and temperatures across possible routes for modeling an accurate solution.

In the next section, details of the implemented system are illustrated with screenshots of the applications.

4.4 IMPLEMENTATION DETAILS

Travel routes from three different sources to destinations are considered for the sake of implementation. Following figure 4-4-1-1 is the opening screen of the application where the user is given choice of source, destination and mode of result.

![Opening Screen of the Application](image)

Figure 4-4-1: Opening Screen of the Application

When quick solution is selected by the user, a WTS (Weighted Travel Score) is computed for each leg of each possible route from the source to destination. For the sake of simplicity, two possible
routes with two waypoints are considered from source to destination. The route with a lower WTS score is chosen as the favorable route and is displayed to the user. As mentioned before, Weighted Travel Score for the local processing scenario is the estimated time to destination and is given in terms of distance and mode of travel. Figure 4-4-2 illustrates the results displayed when the local processing option is chosen.

Weighted Travel Score (WTS) [Estimated Travel Time] = DISTANCE/SPEED

Desirable Route is:
- Source: State College
- Destination: Boston
- Mode: Quick
- RiL1 Weighted Travel Score: 0.6733
- RiL2 Weighted Travel Score: 3.0636
- RiL1 Weighted Travel Score: 3.509
- RiL2 Weighted Travel Score: 0.9013
- WTS for Route1: 4.6389
- WTS for Route2: 4.4124
- Result: Preferable choice: Route2
- Route was generated in: 4277 Nano secs.

Figure 4-4-2 - Quick solution for the best route to travel

When thorough solution is chosen by the user, the WTS is computed for each leg of each route factoring in wind speed and precipitation at source, waypoint and destination. The values for wind speed and precipitation are obtained by making calls to Forecast API for the most up-to-date information. As discussed before, wind speed is given more weightage when compared to precipitation if the mode of
travel is flight while the reverse happens when the mode of travel is drive. For high wind speed value the flight route is not considered and for high precipitation intensity value the drive route is not considered.

Figure 4-4-3 illustrates the results displayed when the mode of result is thorough.

\[ WTS = \frac{DISTANCE}{SPEED} \times (FACTOR \times WINDSPEED) \times (FACTOR \times PRECIPITATION) \]

Figure 4-4-3: Thorough solution for best route to travel
CHAPTER 5

Discussion

This chapter provides a discussion of the implementation results for the prototype of travel route decision discussed in chapter 3.

<table>
<thead>
<tr>
<th>Route</th>
<th>Thorough /Cloud</th>
<th>Quick / Local</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCE to BOS</td>
<td>1.927</td>
<td>0.00009408</td>
</tr>
<tr>
<td>SCE to ACY</td>
<td>2.421</td>
<td>0.00002138</td>
</tr>
<tr>
<td>BOS to ACY</td>
<td>1.931</td>
<td>0.00011547</td>
</tr>
</tbody>
</table>

Figure 5-1: Comparative Analysis of the time taken for displaying results

Observe the timing results in the above figure. We see that given a simplified case the time to result is more than 10,000 times faster for the Quick case when compared to the Thorough case. This reinforces the benefit of using the mobile device for standalone processing when fast computation time is the highest priority. The advantages of having local processing are not just quick results but also no network latency, since it is independent of calls to the Forecast API, requires lower processing power and can be computed on prespecified travel itineraries. The Thorough option has the advantage of learning the best route at any given time in the journey but this should be invoked only when it is known that the communication of the sensed data would not cost excessive battery power.
Offloading data to the cloud really depends on the computation being performed and the resources considered. An interesting case occurs when the routes considered have several thousand waypoints. Here it would take few days for the computation of the ideal route if the processing occurs on a local server. The timing would drastically reduce if High Performance Computing (HPC) can be achieved through Amazon Web Services.
Chapter 6

Conclusion and Future Work

6.1 Conclusion

This thesis first presents a conceptual analysis of topics that aid the understanding of context aware applications. Then it discusses various technologies that interconnect to form an ideal architecture for context aware applications in a mobile cloud computing environment. Finally a prototype system has been developed in this thesis to showcase the effects of division of application processing between local device and cloud.

The points which are emphasized in this thesis are - describing a class of applications that belong to the context-aware category and mechanism for distinction of application processing occurrence. Some of the applications that are context-aware considered in this thesis are described in terms of examples such as lost traveler, time to stop for a train/bus traveler and planning routes for vacation trips.

The assertion that mobile cloud computing environment can be effectively utilized only when there is a balance achieved between application which completely run on mobile devices and applications which completely run on the cloud is proved with the implementation of a prototype application where the division is based on time and accuracy constraints. The results generated support the idea of reducing data upload to the cloud when possible to improve processing speed, reduce dependency on connectivity and prevent battery energy exhaustion. However, cloud access is recommended when additional data sources are required for an adequate computation, or when access to high performance cloud computing outweighs the computational and network costs.
6.2 Future Work

There are certain limitations to the initial attempt of exploring interconnecting technologies in context aware applications. First, several elements are added to Diane Cook’s smart environment information framework in order to make it suitable for mobile cloud computing environments. But, elements like Human-in-the-loop, HPC and context-aware middleware are not implemented to evaluate the effectiveness of application processing division. Second, the algorithm to compute the Weighted Travel Score (WTS) is elementary and is intended as a surrogate for more complex and tested formula in a real world application. The method of computation of WTS would change significantly when accounting for the elements mentioned above. The focus in this thesis was more on the development of an information framework rather than implementing algorithms for learning the activities of the users. Some specific areas for future work are:

- This application can be combined with calendar appointments, news, social media and other applications contributing to traffic/severe climate information to enhance it as a multi-modal application.
- The best route calculation can be modeled as a calculus problem to retrieve the best results at any given point in the journey.
- Given the interest of the end user, the result data can be predicted as per his daily activities, although this would require consideration of maintaining adequate user privacy and security.
- The algorithm to compute Weighted Travel Score is based on the product of different parameters. In real world scenario, computation in this manner is not the most ideal way to go about things. Fuzzy logic based algorithms can be taken into consideration like Adaptive Neuro Fuzzy Inference System (ANFIS)[69].
It would be interesting to find out the effects of cycle computing in high performance cloud clusters given large amounts of data and how application processing division would occur in such circumstances.

Human-in-the-loop experiments can also be considered in some special circumstances. For example: An elderly individual is going across town for a doctor's appointment. It is not always possible for their family members to be with them in such circumstances. In order to ensure safe travelling be it crossing the road or driving a car, a family member who is receiving a live video stream of this activity via smart glasses with camera's would be able to give a better judgment on the proximity of the vehicles while crossing the road or directions in some situations.

Thus these are some of the areas that have been identified for future investigation. Exploring the above elements one would get an estimate of the numerous possibilities that can be accomplished through cloud and mobile technologies. Although mobile and cloud technologies have surprised us with their exponential growth and variety of disciplines in which they can be used, it is not an understatement to say that we still have a long way to go when it comes to the innovation with respect to these technologies.
BIBLIOGRAPHY


