mCloud: A Context-aware Offloading Framework for Heterogeneous Mobile Cloud

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Abstract—Mobile cloud computing (MCC) has become a significant paradigm for bringing the benefits of cloud computing to mobile devices’ proximity. Service availability along with performance enhancement and energy efficiency are primary targets in MCC. This paper proposes a code offloading framework, called mCloud, which consists of mobile devices, nearby cloudlets and public cloud services, to improve the performance and availability of the MCC services. The effect of the mobile device context (e.g., network conditions) on offloading decisions is studied by proposing a context-aware offloading decision algorithm aiming to provide code offloading decisions at runtime on selecting wireless medium and appropriate cloud resources for offloading. We also investigate failure detection and recovery policies for our mCloud system. We explain in details the design and implementation of the mCloud prototype framework. We conduct real experiments on the implemented system to evaluate the performance of the algorithm. Results indicate the system and embedded decision algorithm are able to provide decisions on selecting wireless medium and cloud resources based on different context of the mobile devices, and achieve significant reduction on makespan and energy, with the improved service availability when compared with existing offloading schemes.

Index Terms—Mobile cloud computing, code offloading framework, context-awareness.

1 INTRODUCTION

For the past decade, the popularity of mobile devices, such as smartphones and tablets, has been increasing rapidly among users because of the advanced functions provided by the enhanced mobile device with faster CPU, substantial memory, and multiple sensors. However, the upgrade in hardware results in higher energy consumption, which leads to a major concern of the insufficient battery lifetime on mobile devices. Furthermore, mobile device users expect improved performance from their mobile devices, which reflects on more endurable battery and shorter processing time of all services provided by the devices. To overcome this obstacle between the user demand and available mobile devices, mobile cloud computing [1] is introduced.

Mobile cloud computing (MCC) provides services by bringing abundant resources in cloud computing [2] to the proximity of mobile devices to improve the mobile applications performance and conserve the battery lifetime. One of the techniques adopted in mobile cloud computing is code offloading [3]. It identifies the computation intensive code of a mobile program, and offloads the task to a cloud service via wireless networks. In the concept of code offloading, cloud resources used for offloading have many different types. First and the most common resource is public cloud services, such as Amazon, Google, and Microsoft Azure, which provide pay-as-you-go services over the Internet. Second, a nearby server named cloudlet [4] is considered as a cloud resource with fast network connection as well as powerful processors. Cloudlet serves as a middle layer between mobile devices and public cloud services to reduce the network delay and accelerates the computing. Last but not the least, a local mobile device ad-hoc network forming a device cloud [5] is another potential cloud resource, especially when there is no access to the Internet.

Code offloading in MCC has been comprehensively studied during the past few years [6], [7], [8], [9], [10], [11]. These works mainly focus on the code partitioning and offloading techniques, assuming a stable network connection and sufficient bandwidth. However, the assumption is rather unrealistic. As in reality, the context of a mobile device, e.g., network conditions and locations, changes continuously as it moves throughout the day. For example, the network connection can be unavailable or the signal strength is low. Since a mobile device usually has multiple wireless mediums, such as WiFi, cellular networks and Bluetooth, and each connection performs differently in terms of speed and energy consumption, the strategy of utilizing wireless interfaces can significantly impact the performance of the mobile cloud system as well as the user experience. Moreover, as we described above, there are multiple options of cloud resources that can be selected for code offloading under different conditions. As an example, in case the Internet connection is inaccessible, a group of mobile device users can still configure a code offloading service by setting up a wireless mobile ad-hoc network. Alternatively, a mobile device user can also connect to a nearby cloudlet to outsource the computation intensive mobile tasks when it is infeasible to use mobile data. The heterogeneity of MCC has not been rigorously studied in the literature as previous works only target the public cloud service.

To tackle the issues mentioned above and improve the service performance in mobile cloud computing, we pro-
pose a context-aware MCC system, called mCloud, that takes the advantages of the changing context of a mobile device and multiple cloud resources to provide an adaptive and seamless mobile code offloading service. The objective of mCloud is to derive offloading decisions under the context of the mobile device and cloud resources to provide better performance and less battery consumption. This paper is a significant extension of our previous work [12]. The new contributions reported in this paper are as follows.

- The related work is updated with some state-of-the-art works for mobile cloud code offloading.
- We redesign the system architecture by investigating and adding the failure detection and recovery module, based on the nature of mobile cloud environment and our proposed framework.
- The process of realizing mCloud offloading framework has been explained in a new design and implementation section. This includes the necessary technologies and approaches adopted in the system.
- The Performance Evaluation section is updated with new set of experiments. The new experiments, which incorporated our updated algorithms (equipped with failure recovery feature), consider multiple mobile cloud resource availability scenarios to capture the dynamic changes in the mobile cloud environment. In addition, these experiments are also conducted under several network condition scenarios to consider the unstable nature of the mobile cloud network. Moreover, the new experiments used heterogeneous pool of public cloud, cloudlet and MANET resources.

The remainder of this paper is organized as follows. We first discuss existing offloading approaches and frameworks for MCC in Section 2, and present an insight of mCloud architecture in Section 3. Then we introduce the system models and propose the context-aware offloading algorithm in Section 4. The approaches for system implementation are introduced in Section 5, followed by a discussion on the system evaluation and numerical results in Section 6. Finally in Section 7, we conclude and propose the future work.

2 RELATED WORK

Frameworks and architectures for code offloading in MCC have been comprehensively studied in previous works.

Flinn et al. [13] proposed a remote execution system called Spectra that provides offloading through a set of predefined APIs via Remote Procedure Call. Similarly, Chroma [14] handles offloading with an approach called tactics, which are defined as modules of remote calls specified by developers. The application consists of different combinations of the tactics. Both of the proposed systems need developers to specify the offloading codes statically, which is considered non-trivial and lack of flexibility. Hence, dynamic offloading schemes have emerged. Cuervo et al. [3] proposed a code offloading framework called MAUI that provides method level, energy-aware mobile application offloading for .NET applications. MAUI enables developers to annotate methods and fetches information from a set of profilers to make decisions dynamically on whether to offload. ThinkAir [8] enables Android mobile applications to offload the computation intensive jobs to their mobile clones running on the public cloud on the method level. Flores et al. [15] presented an evidence-based offloading framework EMCO that extracts knowledge from code offloading traces by applying machine learning algorithms to enhance the decision making process. However it is still in its prototype that needs to be comprehensively studied. These works have focused on offloading to public cloud or a server nearby, which may not be reliable under condition changes, such as cloud availability or connection losses.

Later, several works are proposed considering other types of resources for offloading. Bahl et al. [16] discussed the idea of accelerating the mobile cloud processing time by adding a middle layer called Cloudlet. Rahimi et al. [17] proposed a three-tier offloading framework consisting of mobile device, local cloud, and public cloud, with the consideration of mobile device mobility. Xia et al. [18] proposed an online location-aware algorithm in a two-tier MCC environment consisting of local cloudlet and remote cloud service. The objective of the proposed system is to provide equal energy consumption proportion on each local cloudlet. Chen et al. [19] proposed an architecture consisting of wearable devices, mobile devices and cloud for code offloading. It realized the opportunity to run heavy computation applications on wearable devices, by offloading part of the workload onto mobile devices or remote cloud. These existing works investigate the benefits of introducing other types of computing resources than cloud into MCC. However, they have not investigated the impact of wireless medium selection on the offloading performance.

Furthermore, the accuracy of the offloading decision making algorithm can significantly affect the Quality-of-Service of an MCC system. Chen et al. [20] proposed a semi-markovian decision process based approach to decide which part of the program to be offloaded in order to optimize the execution time and energy consumption. The simulation assumes a stable network condition that is rather infeasible in practice. Chen [21] formulated the decision making problem as an offloading game, and provided an offloading scheme that can achieve a Nash equilibrium of the game. Hung et al. [22] proposed a decision making approach by caching the previous offloading plan in the profiles to reduce the decision making overhead. Lin et al. [23] proposed a location based context-aware decision engine for code offloading. The decision engine takes into consideration the geographical location and the time-of-the-day as the history data to make the offloading decisions. All these works have only considered public cloud as their offloading location, and are lack of comprehensive studies on multiple criteria in the device context.

In summary, comparing to existing works, we aim to improve the MCC’s performance and service availability in an unstable mobile cloud environment by proposing a new framework that considers different offloading destinations (cloudlets, mobile ad-hoc cloud, and cloud resources) and wireless channels (WiFi, 3G, Bluetooth, WiFi-direct). We also proposed a multi-criteria offloading decision making algorithm. This brings the advantages of considering multiple criteria of energy consumption, execution time reduction,
Figure 1: Overview of mCloud Environment

resource availability, network conditions, and user preferences.

3 SYSTEM ARCHITECTURE

In this section, we give an insight of mCloud’s architecture to address the issue of context aware code offloading in a heterogeneous mobile cloud environment. We first describe an overview of the MCC environment that mCloud fits in. Then, the design of main components is presented in details.

3.1 System Overview

Figure 1 illustrates the overview of the proposed system for the heterogeneous mobile cloud environment. The device requesting the offloading service is regarded as a client. The proposed system leverages three types of mobile cloud resources, namely cloud, cloudlet, and mobile ad-hoc cloud.

First, cloud provides Infrastructure-as-a-Service with scalable computation and storage, which can be connected from mobile clients via WiFi or cellular network. It has the ability to host tasks requiring high computation and communication.

Second, a cloudlet is a local “datacenter in a box”, which resembles a cluster of multi-core processors and a high-bandwidth WLAN connection with considerable low power consumption [4]. A task with limited delay-resistance is well-suited in cloudlets.

Third, a mobile ad-hoc cloud that is formed by a group of mobile devices in the client’s proximity via short-range communication technologies, e.g. Bluetooth and WiFi Direct.

Due to mobility of the devices, the mobile ad-hoc cloud can be unstable. To ensure the stability of the mobile ad-hoc cloud in the mCloud framework, we adopt a one-hop topology for the mobile ad-hoc network. Moreover, we introduce a fault recovery policy for detecting failures and recovering tasks to obtain the consistency of the results.

3.2 Framework Components

The main components of the mCloud framework belong to two parts: client part and cloud server part. As depicted in Figure 2, there are five main components on the client side: Context Monitor, Decision Module, Task Manager, Communication Manager and Failure Recovery. On the cloud server side, main components include Communication Handler, Task Manager and corresponding mobile cloud infrastructures.

3.2.1 Context Monitor

The Context Monitor offers the context-awareness for the system by profiling multiple context parameters at runtime, and assists the Decision Engine when needed. Since the context of the mobile device has significant effect on the decision making accuracy, the system provides three relevant profilers: a program profiler, a device profiler, and a network monitor. However, profiling incurs additional runtime overhead and extra energy consumption. To avoid the high overhead, the profilers adopt the on-demand monitoring strategy, which only fetches context data when the offloadable methods are invoked.

a) Program Profiler: The program profiler tracks the execution of a program on the method level. The attributes being monitored include:

- the overall instructions executed,
- the execution time,
- the memory allocated,
- the number of calls of this method,
- the type of mobile cloud infrastructure resource for the execution (e.g. local, cloud, cloudlet),
- the data size of inputs.
The profile is updated at every invocation, and stored in the Context Profile database. Later the program profile is passed to Cost Estimation module to estimate the execution cost (i.e. running time, energy consumption) for decision making. The details of cost models are discussed in Section 4.2.

b) Device Profiler: The hardware profiles collected by the profiler represent the operating conditions of the mobile device being monitored. Same as the program profile, the device profile is fed into Decision Engine when needed to assist the cost estimation. The profile includes:

- the average CPU frequency,
- the average CPU usage,
- the maximum CPU frequency,
- and battery level.

c) Network Monitor: The network monitor collects the network information of the mobile device asynchronously at runtime so that it can record any change in the context. The profile is passed to cost estimation models when needed. The following network conditions are monitored:

- cell connection state and its bandwidth,
- WiFi connection state and its bandwidth,
- Bluetooth state,
- the congestion level of the connection (RTT) to VMs on the cloud,
- and the signal strength of cell and WiFi connection.

3.2.2 Decision Module

This component has the responsibility to decide whether and how to offload the mobile task, and dispatch the task to the appropriate mobile cloud infrastructure (i.e. cloud, cloudlet, or MANET) based on the current context. It consists of two main modules: Cost Estimation and Decision Engine. Based on the context profiles, Cost Estimation provides a set of cost estimation models that calculate the execution time of each offloadable task running on three types of mobile cloud infrastructure respectively, with the corresponding energy consumption on the client. Decision Engine then applies the cost estimations to the proposed context-aware decision making algorithm to provide the offloading decisions. We give a detailed discussion on the cost models and decision making algorithm in Section 4.

3.2.3 Task Manager

This component works as a middle layer between Decision Module and Communication Manager. It receives the decision, i.e. method name, offloading location, and network interface, from the upper layer. Then the Manager collects the related information, such as the method inputs, libraries for running the offloaded task, and network address of the offloading location. Last, it persists them into a format called Task Specs and passes the information to Communication Manager. When receiving the task results, Task Manager stores them in the device database.

3.2.4 Communication Manager

The communication manager on both client and server side handles connections between client mobile device and the remote execution in either mobile ad-hoc cloud or remote cloud VMs. It consists of a mobile cloud infrastructure discovery service and a communication handler. Once the decision engine generates the offloading decision, the communication manager takes over the task and executes based on the offloading decisions. Moreover, the Communication Manager corporates with Failure Recovery service to detect failures and start the recovery process.

a) Discovery Service: This module is responsible for discovering the mobile cloud infrastructure resources, i.e. the available mobile devices in the MANET, cloudlets, and cloud VMs. The service updates the information of the detected resources, such as network congestion level, IP address, computation capacity, etc., and stores the information in Device Profiler. Particularly, for the mobile ad-hoc cloud, the Discovery Service detects the available mobile devices in the proximity, forms an mobile ad-hoc cloud, and maintains the network at runtime. Nevertheless, the discovery via network interfaces can potentially incur additional overhead and energy consumption. To avoid the high detection overhead, the Discovery Service applies the periodic detection strategy, which asynchronously searches for the available devices in certain intervals periodically. We present the detailed implementation of the Discovery Service in Section 5.3.

b) Communication Handler: The Handler operates on both client and mobile cloud infrastructures to handle the communications and data transfer generated in between, which include mobile cloud infrastructure detection, offloading code, state synchronization between client and servers, failure detection, etc. In particular, when offloading a mobile task, the Communication Handler on the client serializes the code, related input, and the information of libraries needed to execute the code into the offloading package. Then it dispatches the package to the address provided by Task Manager. On the server side, the Handler unpacks the package and starts to synchronize the missing libraries described in the package with the client device. Once all the states are synchronised, it passes the deserialized code to the mobile cloud infrastructure for execution, and returns the result to client device upon completion.

3.2.5 Failure Recovery

It works with Decision Module and Communication Manager to detect the failures and recover the system. The details regarding the types of failures handled by Failure Recovery service, and the detection algorithm are presented in Section 4.4.

4 COST ESTIMATION MODEL AND ALGORITHM

We first introduce the system model and the problem formulation. Then we present the details of our cost estimation model and the context-aware offloading algorithm.

4.1 System Model and Problem Formulation

The system considers a heterogeneous mobile cloud environment, consisting of a mobile ad-hoc cloud, the nearby cloudlets and remote public cloud. There are a set of mobile device users that run applications seeking opportunities to offload tasks to the mobile cloud infrastructure.
As described in Section 3, the client connects to cloudlet and cloud via WiFi, and to cloud via WiFi or cellular network. On

### 4.1.3 Cloud and cloudlet modelling

Both cloud and cloudlet, we deploy single-core VMs as the offloading solution. VMs within a cloudlet or cloud are considered homogeneous, while they are heterogeneous across clouds and cloudlets in terms of computation capacity and network delay. Then we model VMs on cloud and cloudlet as follows.

\[ v_i = (\mu_i, r_i, \theta_i) \]  

where \( \mu_i \) is the CPU speed, \( r_i \) is the network delay from the client to VM, and \( \theta_i \) is the average CPU usage.

The heterogeneity of VMs between cloudlet and cloud reflects on the different \( \mu, r \) values in the model.

#### 4.1.4 Problem formulation

Having presented the models of the system, we formulate the decision making problem as to find a solution of selecting where to execute the task and how to offload so that the overall execution time and energy consumption is the lowest among all the cloud resources in the mobile cloud infrastructure based on the current context of the client device. Specifically, given a set of tasks \( T \), a set of cloudlets \( CL \), and a mobile ad-hoc cloud with \( h \) mobile devices \( M \), then the overall cost of executing a set of \( n \) tasks is

\[ C_{total} = \sum_{i=1}^{n} \Delta C(t_i, l_i, w_{m_i}) \]  

where \( \Delta C \) denotes execution cost of running task \( t_i \), including execution time and energy consumption. \( l_i \) represents the execution location for task \( t_i \), which includes local, mobile ad-hoc cloud \( M \), cloudlet \( CL \), or cloud \( C \). \( w_{m_i} \) is the wireless medium used to offload \( t_i \), including Bluetooth, WiFi, and cellular network. Thus, the problem is to provide an offloading decision \( \langle l_i, w_{m_i} \rangle \) for \( \forall t_i \in T \) to minimize the overall cost.

**Table 1: Notations**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>( t )</td>
<td>the mobile task being considered to offload</td>
</tr>
<tr>
<td>( s )</td>
<td>the data size of the offloadable task ( t ) that need to be transferred during offloading, in byte</td>
</tr>
<tr>
<td>( w )</td>
<td>the number of instructions for task ( t ) to complete</td>
</tr>
<tr>
<td>( M )</td>
<td>a set of mobile device as a mobile ad-hoc cloud</td>
</tr>
<tr>
<td>( m_k )</td>
<td>mobile device ( k ) in the mobile ad-hoc cloud</td>
</tr>
<tr>
<td>( \mu )</td>
<td>the average CPU speed of the mobile devices or VMs</td>
</tr>
<tr>
<td>( \tau_n )</td>
<td>link delay between client and local mobile device cloud</td>
</tr>
<tr>
<td>( \theta )</td>
<td>the average CPU usage</td>
</tr>
<tr>
<td>( r_i )</td>
<td>data transferring time for task ( i )</td>
</tr>
<tr>
<td>( w_{m_i} )</td>
<td>the wireless medium used for task offloading</td>
</tr>
<tr>
<td>( l_i )</td>
<td>the execution location of task ( i )</td>
</tr>
<tr>
<td>( \omega_{1,2} )</td>
<td>weight factors used in the general cost model to adjust the user preference</td>
</tr>
<tr>
<td>( \beta_d )</td>
<td>coefficient of channel energy consumption reflecting on execution performance</td>
</tr>
<tr>
<td>( B_{channel} )</td>
<td>the bandwidth of the wireless medium, namely WiFi, 3G, and Bluetooth, in MB/s</td>
</tr>
<tr>
<td>( C(t_i) )</td>
<td>general overall cost of task ( i )</td>
</tr>
<tr>
<td>( D(t_i) )</td>
<td>execution time of task ( i ) running on cloud resource</td>
</tr>
<tr>
<td>( E(t_i) )</td>
<td>energy consumption of offloading task ( i )</td>
</tr>
<tr>
<td>( \epsilon_{channel} )</td>
<td>the energy consumption of task ( i ) under certain bandwidth</td>
</tr>
<tr>
<td>( \epsilon_{tail} )</td>
<td>the estimated channel energy consumption per time unit</td>
</tr>
<tr>
<td>(\epsilon_{tail} )</td>
<td>wireless medium tail time energy per time unit</td>
</tr>
<tr>
<td>( T )</td>
<td>the wireless channel active tail time</td>
</tr>
</tbody>
</table>

1. Our system considers the Android Dalvik bytecode instructions.
4.2 Cost Estimation Models

The cost model consists of two parts, namely the task execution time denoted by \(D\), and the wireless channel energy consumption denoted by \(E\). Then the general model for overall cost of executing tasks \(t_i\) is as follows:

\[
C(t_i) = \alpha_1 * D(t_i) + \alpha_2 * \rho_d * E(t_i)
\]

(5)

\[
\alpha_1 + \alpha_2 = 1, \alpha_1, \alpha_2 \geq 0
\]

(6)

where \(\alpha_1\) and \(\alpha_2\) are weight factors to adjust the portion of time and energy consumption in the overall cost. \(\alpha_1\) and \(\alpha_2\) are considered to capture user preferences on the factors. If the user is not expert, methodologies like AHP can be used to generate the factors from linguistic values provided by users. The value of execution time and energy consumption in the cost model are normalized in a 0-100 scale with the upper and lower bound data profiled from real application results. We adopted \(\rho_d\) in our model to represent the effort of hardware settings (DVFS levels and wireless channel rate) on the device performance [20]. \(\rho_d\) will be set on a 0-1 scale based on the processor DVFS level and wireless channel rate.

Given the general cost model in Equation 5, we describe the specific cost models for each type of the mobile cloud infrastructure resource.

4.2.1 Mobile ad-hoc cloud cost model

First, we model the execution time \(D\) for tasks running in the mobile ad-hoc cloud. Given a set of independent tasks \(T = \{t_i \mid 1 \leq i \leq n \}\) and a set of heterogeneous mobile devices \(M = \{m_k \mid 1 \leq k \leq h\}\), execution time \(D\) can be obtained by calculating the earliest finishing time (EFT) among all tasks mapped to the mobile ad-hoc cloud. This independent task scheduling problem is proved to be NP-complete [25]. Therefore the use of heuristics is a suitable approach. For mapping independent tasks to heterogeneous machines, Min-Min heuristic takes less processing time with the result as good as other heuristics [26]. Thus we adopt Min-Min in our cost model.

The Min-min heuristic maps unassigned tasks to available machines. It firstly calculates minimum completion times (MCT):

\[
MCT(t_i, m_k) = \left\{\text{min}_{1 \leq k \leq h} \{CT(t_i, m_k)\}\right\}, \forall t_i \in T
\]

(7)

where \(CT(t_i, m_k)\) is the completion time for task \(t_i\) on device \(m_k\). Then task \(t_i\) with MCT is selected and assigned to machine \(m_k\), and \(t_i\) is removed from \(T\), and the iterations repeat until all tasks are mapped (i.e., \(T\) is empty).

In the next step, we model the energy consumption \(E\) of the client device. Based on the results from Min-Min, we calculate the device communication energy cost for transferring data to the MANET and receiving the results.

Let \(B_{\text{channel}}\) denote the channel data rate. \(t_i = \{s_i, w_i\}\) represents the task, where \(s_i\) is the data need to be transferred and \(w_i\) is the workload. The channel energy consumption for transferring data is given as:

\[
\Delta E_{\text{channel}}(s_i, B_{\text{channel}}) = \beta_{\text{channel}} * \left(\frac{s_i}{B_{\text{channel}}} + \frac{s_{\text{result}}}{B_{\text{channel}}}\right) + \beta_{\text{tail}} * T_{\text{tail}}
\]

(8)

where \(\beta_{\text{channel}}\) is the power consumption rate related to the transferring time and \(\beta_{\text{tail}}\) is the wireless channel tail time power consumption rate.

Let \(M\) denote the set of mobile devices in the mobile ad-hoc cloud. \(\mu_k\) is the CPU speed of device \(m_k\) that selected by the MinMin algorithm and \(\theta_k\) is the average CPU usage. Then the overall execution cost is as follows:

\[
C_{t_i} = \alpha_1 \left(\frac{w_i}{\mu_k \cdot \theta_k} + \frac{s_i + s_{\text{result}}}{B_{\text{channel}}}\right) + \alpha_2 \cdot \rho_d * \Delta E_{\text{channel}}(s_i, B_{\text{channel}})
\]

(9)

4.2.2 Cloud and cloudlet cost models

Let \(t_i = \{w_i, s_i\}\) denote a mobile task. There are \(m\) VMs available on cloud or cloudlet. \(\mu_{VM}\) denotes the computing capacity, \(\theta_{VM}\) denotes the average usage of the VM, and \(l_{VM}\) denotes the network latency of the VM. Note that the tasks can be partitioned into subtasks, and VMs on cloud or cloudlet are homogeneous. Hence each task can be evenly partitioned and processed among the machines based on the number of available VMs. Then the cost of running task \(t_i\) can be modelled as follows.

\[
C_{t_i} = \alpha_1 \left(\frac{w_i}{m \cdot \mu_{VM} \cdot \theta_{VM}} + \frac{s_i + s_{\text{result}}}{B_{\text{channel}}} + l_{VM}\right) + \alpha_2 \cdot \rho_d \cdot \Delta E_{\text{channel}}(s_i, B_{\text{channel}})
\]

(10)

This cost model is utilized to estimate the task execution cost on cloud and cloudlet VMs by alternating the parameters \(\mu_{VM}, \theta_{VM}, l_{VM}\).

4.2.3 Local execution cost

For local cost estimation, we use a history data strategy to reduce the overhead. The local execution time of a method and energy consumption incurred by the device is stored in the database and applied later to the general cost model in Equation 5 for comparison. The estimation costs are then used as the input of the decision making algorithm.

4.3 Context-aware Decision Making Algorithm

Having shown how to estimate the task execution time and energy consumption with the cost models, we present the algorithm in this section. In order to obtain the lowest execution cost for the offloadable tasks under the context, based on Equation 9 and 10, the context-aware decision algorithm considers a set of context parameters, multiple wireless medium and mobile cloud infrastructure resources to decide which one is optimal to select the task to offload, which wireless medium is used for offloading and which resources to use as the offloading location.

4.3.1 Wireless medium selection

Most existing offloading frameworks in the literature only consider network speed and energy consumption when they make offloading decisions. Unlike those, mCloud focuses on utilizing multiple types of mobile cloud resources (i.e. cloud, cloudlet and mobile ad-hoc cloud) and wireless mediums based on device context to improve the offloading service availability and performance. Multiple criteria regarding device context including resource availability, wireless medium availability, network congestion, cost, energy consumption, etc. have been considered for making
offloading decisions in mCloud. Therefore, we need a multicriteria decision making approach (MCDM) in the proposed framework.

Among MCDMs, we apply Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [27] for wireless medium selection considering abovementioned criteria. TOPSIS offers lightweight processing and shorter response time comparing to other MCDMs [28]. It helps reduce the overhead of the proposed offloading decision making algorithm, considering it is running on mobile devices. Moreover, TOPSIS can be easily modified to consider more criteria if necessary, and the complexity remains the same regardless of the number of criteria. In mCloud, the decision making algorithm considers six criteria related to performance when selecting the wireless interface:

- energy cost of the channel,
- the link speed of the channel,
- the availability of the interface,
- monetary cost (i.e. cost when using mobile data),
- the congestion level of the channel (RTT),
- and the link quality of the channel (signal strength).

Table 2: IMPORTANCE SCALE AND DEFINITION

<table>
<thead>
<tr>
<th>Definition</th>
<th>Intensity of importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equally important</td>
<td>1</td>
</tr>
<tr>
<td>Moderately more important</td>
<td>3</td>
</tr>
<tr>
<td>Strongly more important</td>
<td>5</td>
</tr>
<tr>
<td>Very strongly more important</td>
<td>7</td>
</tr>
<tr>
<td>Extremely more important</td>
<td>9</td>
</tr>
<tr>
<td>Intermediate</td>
<td>2,4,6,8</td>
</tr>
</tbody>
</table>

Note that for the monetary cost, the algorithm only considers the cost generated by using the mobile data. Other cost such as cloud VM reservation is negligible from the mobile device’s perspective as a mobile task generally occupies a negligible time comparing to the cloud VM lifetime.

For the alternatives, the algorithm considers Bluetooth, WiFi, and 3G in this system, but more interfaces can be added if new techniques emerge. Then the process of wireless interface selection is as follows.

First, the relative weights for criteria being considered in TOPSIS are obtained by using analytic hierarchy process (AHP) [29]. The pairwise comparison results are presented in a matrix.

\[
A = \begin{bmatrix}
a_{11} & a_{12} & \cdots & a_{16} \\
a_{21} & a_{22} & \cdots & a_{26} \\
\vdots & \vdots & \ddots & \vdots \\
a_{61} & a_{62} & \cdots & a_{66}
\end{bmatrix}, \quad a_{nn} = 1, a_{mn} = \frac{1}{a_{nm}} \tag{11}
\]

The pairwise comparisons of six criteria are generated based on the standardized comparison scale of nine levels shown in Table 2. Then TOPSIS uses matrix \(A\) to calculate the weights of the criteria by obtaining the eigenvector \(\omega\) related to the largest eigenvalue \(\lambda_{max}\).

\[
A\omega = \lambda_{max}\omega \tag{12}
\]

Since the output of AHP is strictly related to the consistency of the pairwise comparisons, it is necessary to calculate the consistency index [30]:

\[
CI = \frac{\lambda_{max} - n}{(n-1)} \tag{13}
\]

\[
CR = \frac{CI}{(n-1) + \text{RandomIndex}}
\]

CR, which is the consistency ratio of CI, should be less than 0.1 to have a valid relative weight output.

After the weights are generated, a evolution matrix consisting of three alternatives and six criteria is created, denoted by \(M = (x_{mn})_{3\times 6}\). The values of the criteria are collected at runtime by the Context Monitor, and normalized using Equation 14.

\[
N_{M_{mn}} = \frac{M_{mn}}{\sum_{n=1}^{6} M_{mn}^2} \tag{14}
\]

Then the weights obtained from AHP method are applied to the normalized matrix \(N = (t_{mn})_{3\times 6}\).

\[
M_w = \omega_n \ast N
\]

where \(\omega_n\) represents the weight. The best solution and the worst solution are then calculated from the weighted matrix \(M_w, \) denoted by \(S^+ = \{\min(t_{mn}|m = 1 \ldots 6)\} \in J^+\}, \{\max(t_{mn}|m = 1 \ldots 6)\} \in J^\} \) and \(S^- = \{\min(t_{mn}|m = 1 \ldots 6)\} \in J^\} \) respectively, where \(J^+\) is the positive criteria to the cost and \(J^-\) is the negative criteria to the cost.

At last, the wireless medium is selected by calculating the Euclidean distance between each alternative and the best and worst solution \(D^+_m\) and \(D^-_m\) respectively. And ranking the alternatives by applying a closeness score to the best solution,

\[
D^+_m = \sqrt{\sum_{n=1}^{6} (t_{mn} - t^*_m)^2}
\]

\[
D^-_m = \sqrt{\sum_{n=1}^{6} (t_{mn} - t^-_m)^2}
\]

Then rank the alternatives by applying a closeness score \(R_m\) to the best solution. The alternative with the highest \(R_m\) is selected as the output of the wireless selection algorithm.

\[
R_m = \frac{D^+_m}{D^+_m + D^-_m} \tag{17}
\]

However, one drawback of TOPSIS is its sensitiveness to rank reversal, thus in our system, if a new alternative appears, the algorithm will be triggered to generate the new weights and related matrix.

4.3.2 Decision making

The context-aware decision making algorithm is composed of two main phases, which are summarized in Algorithm 1. The first phase is estimation phase (step 2-11), during which the context parameters such as context profiles and wireless interface states are collected from the corresponding modules. Then the cost estimation models executes the calculation cost for each offloading request. In the selection phase (step 12-40), the algorithm gives offloading decision based
on the available wireless interfaces and the cost estimations. In case there are multiple wireless interfaces available, the algorithm applies TOPSIS model to select the best interface under current context such as data rate, workload size to obtain the best data transfer performance as well as minimum energy consumption. Based on the wireless interface selection result, the algorithm selects the offloading location that has the lowest execution cost. Finally, the algorithm returns the decision pair of \((\text{offload location, wireless medium})\).

The complexity of the proposed algorithm is \(O(MN\log N)\), where \(M\) is the number of devices in mobile ad-hoc cloud and \(N\) is the number of tasks. The first phase of the proposed algorithm uses an improved MinMin (in terms of time complexity) [31] (step 7). Each machine maintains a sorted queue of completion time of all tasks on the machine. It takes \(O(MN\log N)\) to construct the queues. In addition, the scheduling takes \(O(MN)\) to compare the head of each queue at each scheduling iteration. Thus, the overall complexity is \(O(MN\log N)\). Next, for cloud and cloudlet cost estimation (step 9-10), the time complexity is \(O(N)\). Therefore, the time complexity of the first phase in the proposed algorithm is \(O(MN\log N + N) = O(MN\log N)\). The second phase of the algorithm generates the offloading decision with the time complexity of \(O(1)\). Therefore, the time complexity for the proposed algorithm is \(O(MN\log N)\).

### 4.4 Failure Recovery

The mobility of mobile devices can incur node failures in the proposed mobile cloud environment, especially the mobile ad-hoc cloud. Although mCloud only considers a one-hop network topology, it is necessary to ensure the consistency of results once the failure occurs. Therefore, we apply a pair of failure detection and recovery policy. The failures considered by the policy include remote nodes crash, remote nodes out of communication range, and message omissions.

#### 4.4.1 Failure detection

The system adopts checkpointing to detect remote node crash and communication lost in Algorithm 2.

The discovery service inside communication manager periodically broadcasts messages to the remote nodes within the system at each checkpoint and waits for the confirmation message returned by the remote nodes. The discovery service updates a vector that stores the number of confirmation message received from each available node. Then at the end of each checkpoint period, the discovery service calculates the gap between the number of messages received for each node and its own counter. Nodes with same number as the counter or within the distance of \(\lambda_d\) are considered as working, and are tagged as CONNECTED. Nodes that the gap is larger than \(\lambda_d\) are then considered failure, and are tagged as FAILURE. Since we only consider one-hop network between the hosting device, MANET devices and cloud VMs, the delivery of the message is not affected by the route change. The failure is mostly likely node crash or dropping out of communication range. In this case, we set \(\lambda_d\) to 3. In case mCloud adopts more complicated network topology in the future, we can adjust the number to fulfill the failure detection requirement.

<table>
<thead>
<tr>
<th>Algorithm 1 Context-aware decision algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: procedure \text{GET}\text{DECISION}(context,tasks)</td>
</tr>
<tr>
<td>2: para[] ← context</td>
</tr>
<tr>
<td>3: task[] ← tasks</td>
</tr>
<tr>
<td>4: programProfile ← get method profile</td>
</tr>
<tr>
<td>5: start discovery service and gather resources profiles</td>
</tr>
<tr>
<td>6: local_cost ← estimate execution cost on client device</td>
</tr>
<tr>
<td>7: manet_cost ← estimate execution cost on mobile device</td>
</tr>
<tr>
<td>8: cloud using MinMin heuristic</td>
</tr>
<tr>
<td>9: cloudlet_cost ← estimate execution cost on cloudlet</td>
</tr>
<tr>
<td>10: cloud_cost ← estimate execution cost on public cloud</td>
</tr>
<tr>
<td>11: check network interface state</td>
</tr>
<tr>
<td>12: if only cell network is available then</td>
</tr>
<tr>
<td>13: check cloud availability</td>
</tr>
<tr>
<td>14: if cloud is available then</td>
</tr>
<tr>
<td>15: decision ← minCost(local, cloud)</td>
</tr>
<tr>
<td>16: return decision</td>
</tr>
<tr>
<td>17: else</td>
</tr>
<tr>
<td>18: return decision(local_execution, null)</td>
</tr>
<tr>
<td>19: else if only WiFi is available then</td>
</tr>
<tr>
<td>20: check cloud, cloudlet and manet availability</td>
</tr>
<tr>
<td>21: decision ← minCost(local, cloud, manet, cloudlet)</td>
</tr>
<tr>
<td>22: return decision</td>
</tr>
<tr>
<td>23: else if only Bluetooth is available then</td>
</tr>
<tr>
<td>24: check manet availability</td>
</tr>
<tr>
<td>25: if manet is available then</td>
</tr>
<tr>
<td>26: decision ← minCost(local, manet)</td>
</tr>
<tr>
<td>27: return decision</td>
</tr>
<tr>
<td>28: else</td>
</tr>
<tr>
<td>29: return decision(local_execution, null)</td>
</tr>
<tr>
<td>30: else</td>
</tr>
<tr>
<td>31: interface ← TOPSIS(context)</td>
</tr>
<tr>
<td>32: if interface is Wifi then</td>
</tr>
<tr>
<td>33: decision ← minCost(local, cloud, manet)</td>
</tr>
<tr>
<td>34: if interface is 3G then</td>
</tr>
<tr>
<td>35: decision ← minCost(local, cloud)</td>
</tr>
<tr>
<td>36: if interface is Bluetooth then</td>
</tr>
<tr>
<td>37: if manet is available then</td>
</tr>
<tr>
<td>38: decision ← minCost(local, manet)</td>
</tr>
<tr>
<td>39: else</td>
</tr>
<tr>
<td>40: return decision(local_execution, null)</td>
</tr>
</tbody>
</table>

Moreover, the detecting policy puts the target time on completing the offloading tasks. The target time is related to the estimated execution time provided by the cost models inside decision engine. When the time of checkpoint looping is beyond the target time, the discovery service considers a failure happened in the node that has not returned the result, and proceeds the failure recovery on the tasks from that node.

#### 4.4.2 Recovery

When failures happen, the discovery service fetches the current running states of the tasks on each node at each checkpoint during failure detection. The information includes task ID, the point of failure, and the partial result obtained. If the failure is confirmed by the detection policy, the Discovery Service sends a recovery request to the decision engine. Then the Decision Engine packs all the information of the failed task and choose another available cloud resource node for further execution. If there are no suitable nodes under the current context, the task is then executed locally on the device itself.
5 System Design and Implementation

The implementation of our prototype framework is built based on ThinkAir [8]. The system is implemented on Android operating system. We apply VM migration technology using Java Reflection [32] as our offloading method in mCloud to minimize the modifications of the existing or developing mobile applications. The system and programming APIs are implemented as a library for the Android application developers. Android x86 system [33] is deployed on the cloud and cloudlet VMs. In this section, we explain in details the design and implementation of mCloud and programming APIs.

5.1 Android x86

In order to leverage the cloud resources, the framework needs to offload the mobile tasks from the ARM-based system application to an x86-based cloud VM. Android x86 is an open-source project to port Android operating system to an x86 or AMD host. It provides major functions of an Android device on desktop system like Windows. As a result, our proposed framework can fit into most of the existing and developing Android applications and cloud services without modifications on the program. We deployed the Android x86 system on Virtualbox virtual machines running on commercial public cloud services.

5.2 Offloading method

We use Java reflection as mCloud’s offloading method. Java reflection allows the program to inspect the available Java classes, methods, interfaces and their properties within the system or itself at runtime [34]. We can manipulate programs with certain classes, retrieve related properties like parameter types and fields, and invoke the methods of other programs remotely. Our proposed mCloud framework implements the offloading and remote execution by using Java reflection and Java annotations.

5.3 Execution environment

The execution dataflow is depicted in Figure 3. Five main components are implemented, namely Context Monitor, Decision Engine, Task Manager, Communication Manager, and Discovery Service. These components constitute the execution environment for the code offloading tasks.

5.3.1 Discovery service

The Discovery Service starts when the application is opened on the device. It detects two different types of resources: the available Android x86 VMs in the remote, and mobile devices in the proximity. The Service first contacts a root server on the cloud VM and retrieves a list of available Android x86 VMs and their IP addresses on the public cloud and local cloudlets. Meanwhile, the Discovery Service starts an new thread in the background, which establishes a WiFi hotspot to let the mobile devices nearby connect to the client.
device. Then the Service can simply ping within a certain IP address range to detect the available mobile devices. The benefit of this approach is that in most cases when the public cloud services are not available, for example at a disaster recovery site, using hotspots to form an ad-hoc network is stable and easy to establish.

The service will search devices in periodical searching strategy to keep the available mobile device list updated. Additionally, the Service also considers Bluetooth connection in Discovery Service. It will activate the Bluetooth module on the client device when the service starts at the beginning and initialize a Bluetooth discovery session that detects other Bluetooth capable devices in the range. The hosting mobile device then gets a list of bonded devices and other available devices for connection. All the information of the mobile devices discovered by the system will be stored for the further decision engine evaluation.

5.3.2 Context Monitor

Device profiler, network profiler and program profiler are implemented in the Context Monitor. The Context Monitor is designed to collect context data in an on-demand monitoring strategy in order to reduce the overhead. Hence, the profilers are implemented with BroadcastReceiver 3 to receive the context data only when the context changes. Listing 2 shows an example of the network profiler. The profiler in the example will detect the current active network connection type when it is changed.

5.3.3 Communication Manager

The communication manager extracts the information of the IP address of the offloading location, offloading task ID, method name, input parameters, and wireless medium type being used generated by task manager. Then it starts a new asyncTask 4 in the background to initialize the connection to the selected cloud resource. The communication manager detects if connected cloud resource has the application files and relevant libraries, and sends missing files. Then the Manager waits until the asyncTask collects the results.

5.3.4 Decision Engine

Upon receiving the offloading request, the Decision Engine first fetches all the information from Context Monitor and Discovery Service. Then it passes all the context parameters and available device information to the decision algorithm for evaluation. The decision is packed into an array as execution location, machine IP address, offloading method name, input parameters, and wireless channel for communication.

### Listing 2: Profiler implemented with BroadcastReceiver

```java
public void networkProfiler()
{
    networkStateReceiver = new BroadcastReceiver()
    {
        public void onReceive()
        {
            netInfo=connectivityManager.getActiveNetworkInfo();
            networkType = netInfo.getTypeName();
        }
    }
}
```

### Listing 3: An example of remote execution

```java
private void remoteExecution(InputStream objIn)
{
    name = objIn.readObject();
    parameters = objIn.readObject();
    //Get the class
    class = obj.getClass();
    //construct class in remote host
    constructor = class.getConstructor();
    instance = constructor.newInstance();
    //Get the offloading method
    runMethod = class.getDeclaredMethod(name, paraTypes);
    runMethod.setAccessible(true);
    //invoke the remote method with input parameters
    result = runMethod.invoke(class,parameters);
}
```

### Table 3: Experiment Scenarios

<table>
<thead>
<tr>
<th>No.</th>
<th>Application</th>
<th>Scenario</th>
<th>User Preference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Math application, face detection</td>
<td>stable device context, test performance against baselines</td>
<td>time_sensitive energy_sensitive time_energy</td>
</tr>
<tr>
<td>2</td>
<td>Math application</td>
<td>unstable mobile cloud resource availability, stable network</td>
<td>time_energy</td>
</tr>
<tr>
<td>3</td>
<td>Math application</td>
<td>stable mobile cloud resource availability, unstable network</td>
<td>time_energy</td>
</tr>
</tbody>
</table>

Once the Decision Engine makes the offloading decision, the framework starts the remote execution. Listing 3 gives an example of the remote execution. The remote cloud resource first unpacks and get the parameters regarding the execution environment, such as method name, input parameters, and return types. Then it use Java reflection to create a new instance of the offloaded class. Last, it invokes the annotated method to execute and return the results to the hosting mobile device. During the remote execution, the hosting mobile device is on hold until all the results are returned from the cloud resources.

### 6 Performance Evaluation

#### 6.1 Experiments Settings

To the best we know, there are no available standard testbeds that are suitable for the performance evaluation. Thus, to evaluate the effectiveness of mCloud and offloading scheme on different kinds of mobile applications, we implement two android applications. The applications represent two different types of tasks, one is small file size and have high computation, and the other one is big file size with high computation. For the first type, we implement an application that performs math operations based on the input data, and for the second type we implement a face detection application.

We deploy the applications on one HTC G17, one Samsung I997, and one Nexus 5, which form a device cloud for the experiments. One Android x86 clone are installed within VirtualBox on an Intel i5 laptop serving as cloudlet, the emulated CPU speed was adjusted from VirtualBox to match the
processing speed of cloudlet. Two Android x86 clones are set up in an Amazon EC2 t2.medium instance. Moreover, we use PowerTutor [35] to monitor the energy consumption of CPU and communication. Unrelated applications, background services (e.g. GPS, audio, etc.) and screen of the mobile devices are shut down during experiments.

The relative weights for criteria in TOPSIS model is generated based on the system priority. Due to the concern on the processing delay and energy consumption, we assume that the order of priority set for the six criteria under consideration is: resource availability > power consumption > bandwidth > channel congestion level > signal strength > monetary cost. Based on this assumption we calculate the weights from AHP and the results are shown in Table 4. The consistency ratio value is 0.052 (less than 0.1), thus the weights are valid.

We conducted three sets of experiments. A summary of the scenarios is listed in Table 3. In the first scenario, two applications are executed in a stable device context (i.e. all mobile cloud resources and wireless mediums are available and stable) to evaluate the performance of mCloud in terms of time and energy consumption, under three user preference policies. Then we compare them with the baselines of local_only. In the second scenario, we conduct experiments under multiple cases of mobile cloud resource availability, while in the third test scenario, mCloud is tested under unstable network conditions. These results are then compared with the existing work ThinkAir. In summary, the second and third set of experiments aim to demonstrate the advantages of mCloud in an unstable mobile cloud context.

### 6.2 Results and Analysis

We run the two implemented mobile applications with 500 input tasks respectively under three offloading policies, namely time_sensitive, energy_sensitive, and time_energy. Then the results are compared with the baselines that runs workload in offloading policy local_only. The characteristics of the generated workloads is listed in Table 5. Workload S_L and S_H are generated by the calculation application, and workload B_H is generated by the face detection application. Each measurement result is calculated by the average of 10 trails. Figure 4a and Figure 4b compare the execution time and energy consumption respectively of each workload under three offloading policies, which are time sensitive, energy sensitive and time energy combination. Table 6 lists the proportion of the tasks allocated to the multiple cloud resources in mCloud’s mobile cloud environment.

As shown in Figure 4a, for workload S_L, the execution time is reduced by around 55% under time_sensitive policy comparing to local_only policy. 75.4% of the tasks are scheduled by the decision engine to the cloudlet server (shown in Table 6) that has a much lower network latency than public cloud. In Figure 4b, the energy consumption for workload S_L is reduced by 55.6% under energy_sensitive policy, which has the best performance among all policies. 84.2% of the tasks are scheduled to the MANET due to the low energy consumption on data transferring via Bluetooth. For the time_energy policy, the result shows in Table 6 that 9.6% tasks are executed in local, 70.4% tasks in cloudlet, and 20% in public cloud, with the consideration of network condition and available cloud resources.

We can also observe similar results that, for workload S_H, mCloud gives the best performance by achieving 65% of time reduction under time_sensitive policy and 70% of energy reduction under energy_sensitive policy. For workload B_H, mCloud achieves 25% of time reduction and 30% of energy reduction on average. The experiment results show the mCloud is most beneficial to the tasks that have low data size and high computation.

Figure 5 and Figure 6 break down time and energy consumption of workload S_H and B_H respectively. For workload S_H in Figure 5a, the offloading overhead under

### Table 4: criteria weights for topsis

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Consumption</td>
<td>0.180</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>0.130</td>
<td></td>
</tr>
<tr>
<td>Cloud Resource Availability</td>
<td>0.514</td>
<td>0.052</td>
</tr>
<tr>
<td>Congestion Level</td>
<td>0.081</td>
<td></td>
</tr>
<tr>
<td>Signal Strength</td>
<td>0.062</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>0.033</td>
<td></td>
</tr>
</tbody>
</table>

### Table 5: workload for the experiments

<table>
<thead>
<tr>
<th>Workload</th>
<th>Average data size (byte)</th>
<th>Average Android bytecode instructions (MI)</th>
<th>Number of tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_L</td>
<td>725</td>
<td>5.8</td>
<td>500</td>
</tr>
<tr>
<td>S_H</td>
<td>650</td>
<td>24</td>
<td>500</td>
</tr>
<tr>
<td>B_H</td>
<td>3000</td>
<td>29.5</td>
<td>500</td>
</tr>
</tbody>
</table>

### Table 6: Proportion of tasks mapped in each location under different policies (T: time_sensitive, E: energy_sensitive, TE: time_energy)

<table>
<thead>
<tr>
<th>Workload</th>
<th>Policy</th>
<th>Local</th>
<th>Manet</th>
<th>Cloudlet</th>
<th>cloud</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_L</td>
<td>T</td>
<td>1</td>
<td>0</td>
<td>75.4</td>
<td>23.6</td>
</tr>
<tr>
<td>S_H</td>
<td>E</td>
<td>15.8</td>
<td>84.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>TE</td>
<td>9.6</td>
<td>0</td>
<td>70.4</td>
<td>20</td>
</tr>
<tr>
<td>B_H</td>
<td>T</td>
<td>41.2</td>
<td>58.8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>60.8</td>
<td>39.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>TE</td>
<td>33.5</td>
<td>12.6</td>
<td>53.9</td>
<td>0</td>
</tr>
</tbody>
</table>

---

5. Calculated by Equation 13
different policies is around 20% on average, while the offloading overhead of workload B_H in Figure 6a is much larger. The difference of offloading overhead between these two workloads is due to the time consumed in transferring the data. The energy consumption of communication is fairly small since the workload S_H includes tasks with small data sizes (Figure 5b). On the contrary, workload B_H contains tasks with large data sizes that increase the energy consumption of transferring the data (Figure 6b). The communication of workload S_H costs around 13.6% of the total energy consumption on average, while for workload B_H it costs more than 30% on average.

Figure 6a shows the overall time under time_sensitive is greater than energy_sensitive, while the execution time under time_sensitive is smaller. This is because the tasks under time_sensitive policy were scheduled among local and cloudlets via a WiFi public access point on our site with long latency, and tasks under energy_sensitive policy were scheduled among local and Manet via Bluetooth and WiFi-direct, which has almost no network latency. Consequently, for workload B_H that has large data size to transfer, although the task execution time is lower, more time spent on waiting for results and transmission under time_sensitive policy. The overall time will be shorter under time_sensitive when using a lower latency access point.

Furthermore, to explore the performance of mCloud in terms of execution time and energy consumption under unstable contexts, we conduct the experiment using workload S_H with different combinations of available cloud resources and network conditions under time and energy combined policy, and compare performance with ThinkAir.

First, we evaluate the performances in different available cloud resources conditions while the network condition is stable. The test cases are listed in Table 7.

<table>
<thead>
<tr>
<th>Case</th>
<th>Cloud VM</th>
<th>Cloudlet</th>
<th>MANET</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 7a and Figure 7b shows the execution time and overall energy consumption of the workload in each case for our proposed system and ThinkAir respectively. In Figure 7a, it shows that mCloud outperformed ThinkAir in terms of time saving in all the four cases. Especially in case 2 and case 4, due to the unavailability of public resources, ThinkAir chooses to run all the tasks locally on the device, while mCloud offloaded part of the tasks to the mobile clones on cloudlet and the nearby mobile device cloud, which conserved around one third of the time ThinkAir took for execution. The similar result can be observed for energy consumption of the two systems in Figure 7b. The results show that our proposed system can provide code offloading services when the mobile cloud environment is short of public cloud resources and help conserving execution time and battery, unlike many existing mobile cloud frameworks.

Second, we compare mCloud with ThinkAir under unstable network condition. The experiments are conducted by executing workload B_H under changing network context. We alter the bandwidth of Internet connection and 3G connection to stimulate the changing network condition in the real world. Table 8 lists the four test cases. The maximum bandwidth of our testing devices’ Wifi connection was 14.3 MBps, the average 3G connection speed was 3 MB/s. The Bluetooth speed was the same throughout the experiment. When the speed was set to 0, it represents the unavailability...
Table 8: Average Network Speed for Each Test Case

<table>
<thead>
<tr>
<th>Case</th>
<th>Wifi (MB/s)</th>
<th>3G (MB/s)</th>
<th>Bluetooth (MB/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.3</td>
<td>3.5</td>
<td>2.8</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>3.2</td>
<td>3.0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>2.2</td>
</tr>
<tr>
<td>4</td>
<td>1.7</td>
<td>3.3</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Figure 8: Performance under available resource changing conditions

of the corresponding wireless channel. In order to alter the bandwidth of the network, we set up a virtual access point on the laptop and connect DummyNet [36] to the virtual AP to manage the network bandwidth, latency, etc.

Case 1 represents the scenario where all the wireless channels are available and operating at full speed. Case 2 represents the scenario where WiFi connection is not available. Case 3 represents neither WiFi nor 3G is available. Case 4 represents the WiFi connection speed drops from full speed to low speed that is slower than 3G and Bluetooth.

Figure 8a and Figure 8b show the execution time and overall energy consumption of the workload in each case for our proposed system and ThinkAir respectively.

As illustrated in Figure 8a and Figure 8b, test case 1 shows that mCloud has close performance as ThinkAir in terms of execution time and energy consumption. For case 2, 3 and 4, mCloud has around 20% performance gain comparing to ThinkAir. For test case 2, when only mobile data and Bluetooth are available, mCloud schedules the offloading tasks to either MANET through Bluetooth or local due to the consideration of monetary cost. The result of test case 4 shows that when the network is unstable or slow, mCloud can save more execution time and energy than ThinkAir because of the multiple cloud resources and context being considered in mCloud.

### 7 Conclusions and Future Work

We proposed a context-aware offloading decision algorithm that takes into consideration context changes (e.g. network conditions and heterogeneous mobile cloud resource) to provide decisions on wireless medium and mobile cloud infrastructure resources to utilize at runtime. We also provide a general cost estimation model for mobile cloud infrastructure resources to estimate the task execution cost including execution time, energy consumption. The models can be easily modified for the new cloud resources. We then designed and implemented a prototype system considering three types of cloud resources (mobile device cloud, cloudlet and public clouds) and a decision engine that runs the proposed algorithm and related cost estimation models. We presented the evaluation of mCloud, and results showed that the system can provide offloading decisions based on the current context of mobile devices to lower the cost of execution time and energy.

We plan to extend the framework to give the cloud resources ability to intercommunicate with each other, with the handover strategy to perform the failure recovery based on the context changes, so that the current system can be more efficient and reliable.

Moreover, future works can investigate resource management strategies for offloading-as-services cloud providers. Having access to variety of task offloading traces for different cloud instances, providers can utilized machine learning approaches to extract specific offloading policies for offloading tasks in similar conditions.

In addition, the mobility of mobile devices can affect the performance of the mobile ad-hoc cloud. Specifically, the mobile device users may depart and arrive in different patterns and the topology of the mobile cloud environment may change as the result. Therefore, the effect of different user mobility models on system performance need to be investigated in the future.

### References


