Optimal Cloud-Path Selection in Mobile Cloud Offloading Systems Based on QoS Criteria

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ABSTRACT

Recently, there emerge a variety of clouds in sky and thus, several similar cloud services (from different cloud venders) can be provided to a mobile end device. The goal of cloud-path selection is to find an optimal cloud-path pair between the mobile device and a cloud among a certain class of clouds that provide the same service, in order to carry out the offloaded computation tasks. It is easy to choose the optimal cloud-path to save execution time incurred by offloading program to cloud when considering only one factor. However, there are many Quality of Service (QoS)-based criteria such as performance, bandwidth, financial, security and availability that need to be considered when making final decisions. In this paper, a multiple criteria decision analysis approach based on the analytic hierarchy process (AHP) and the technique for order preference by similarity to ideal solution (TOPSIS) in a fuzzy environment is proposed to decide which cloud is the most suitable one for offloading. The AHP is used to determine the weights of the criteria for cloud-path selection, while fuzzy TOPSIS is to obtain the final ranking of alternative clouds. The numerical analysis is performed to evaluate the model. Furthermore, a method based on historical data of the mobile device's experiences is used to evaluate the importance weights of the alternative cloud service, when it is challenge to measure and acquire the parameters of criteria timely in practical systems.

Keywords: *Analytic Hierarchy Process (AHP), Cloud Computing, Offloading, Quality of Service (QoS)-Based Criteria, Selection, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)*

INTRODUCTION

Along with the development of cloud computing (Fox et al., 2009), offloading has become an increasingly attractive way to extend the battery life and reduce execution time on mobile devices. But there are a large number of clouds appearing in sky with different service models, pricing schemes and performance levels, and offloading the same program to different clouds may perform different amounts of computing within the same duration due to the cloud's speeds, and may cost different communication time due to bandwidth and cloud's availability. Therefore, given the diversity of cloud service offerings, an important challenge for customers is to discover who the "right" cloud providers are that can satisfy their requirements. However,

DOI: 10.4018/ijghpc.2013100103

previous work focuses on pure cloud service selection without taking the mobile environment into consideration. New challenges of cloud service selection are raised when combing the cloud computing with mobile systems. And thus an optimal cloud-path selection method is needed when choosing the best suited cloud provider for their applications.

The selection process can be a hard task since a variety of data needs to be analyzed and many factors should be considered. Service selection, whether single or multi-criteria, falls with the preview of decision making since the mobile device has to make a decision to select a service from amongst candidate cloud services. AHP and fuzzy TOPSIS are ideal ways to do multiple-criteria decision-making (MCDM) (Dağdeviren, Yavuz & Kılınç, 2009).

Accordingly, the main contributions of this study are three-fold. Firstly, we present the architecture and algorithms of optimal cloud selection based on one criterion at each time. Secondly, a decision hierarchy and a framework of cloud-path selection are proposed and further three steps of cloud service selection: matching, ranking and selection are analyzed. Thirdly, in order to make decision when considering multiple criteria simultaneously, we combine the methods of AHP and fuzzy TOPSIS.

This paper is an extended version of the conference paper (Wu, Wang & Wolter, 2012), presented at IEEE CloudCom 2012. In this paper, we propose a methodology that combing AHP and fuzzy TOPSIS for multi-criteria based cloud-path selection in mobile cloud offloading systems. This method aims to select the service that best matches the mobile user's requirements from amongst available cloud services. It is proved to be an effective and synthesized way through numerical analysis.

LITERATURE REVIEW

Cloud service selection is a highly significant research issue but it has not been fully investigated and little literature has been published in this area since cloud computing itself is still in its early stages. In this section, we give a brief overview of the related framework in cloud service selection.

The diversity in cloud computing offering makes it difficult to compare one cloud service against others. To help cloud users in selecting a cloud provider, CloudCmp (Li, Yang, Kandula & Zhang, 2010a, 2010b) has been proposed to compare the performance of public cloud services such as Amazon EC2, Windows Azure and Google AppEngine. A set of benchmarking tools are used in CloudCmp to compare the common services (such as elastic computing cluster, persistent storage, intra-cloud and wide area network) and the benchmarking results are then used to predict the performance and costs of application when deployed on a cloud provider.

CloudRank (Zheng, Zhang & Lyu, 2010) is a collaborative QoS-driven ranking framework for cloud components to predict the quality ranking of cloud components without requiring additional real-world component invocations from the intended user. By taking advantage of the past component usage experiences of different component users, it identifies and aggregates the preferences between pair of components to produce a ranking of the components through a proposed greed method.

Multi-Criteria Comparison Method for Cloud Computing ($(MC^2)^2$) (Menzel, Schönherr & Tai, 2011) offers a multi-criteria-based decision framework that can be applied to cloud computing scenarios. $(MC2)^2$ framework aims to choose the most suitable one when filtering out all infeasible alternatives by evaluating and ranking candidate cloud services using multiple criteria derived from a comprehensive criteria catalog. As a recommendation multi-criteria decision making process, the analytic network process (ANP) employs pair-wise comparisons and normalization to assign values to quantitative and qualitative criteria on a ratio scale.

Heterogeneous sets of criteria and complex dependencies between infrastructure services and software images should be considered, when selecting Cloud services. CloudGenius (Menzel, and Ranjan, 2012) is a framework that applies the AHP method and $(MC^2)^2$ framework to automate the decision-making process based on a model, factors and QoS parameters specifically for web server migration to the cloud. The final ranking is from the feasible combinations of VM and service that are sorted with values which calculated by weighted parameters. For the selection and combination, CloudGenius constructs a formal model to describe requirements, non- and numerical attributes.

Another AHP based ranking mechanism is called SMICloud (Garg, Versteeg & Buyya, 2011). It defines key performance and cost metrics for QoS attributes in Service Measurement Index (SMI) framework, which was proposed by Cloud Service Measurement Index Consortium (CSMIC) (C.S.M.I.C, 2011) for cloud computing service. To help rank such multi-attribute analysis techniques, an AHP-based ranking method is applied to compute the relative values of various cloud services according to the quality of service requirements of the customer and features of cloud services. The value of each attribute is classified with boolean, numeric, unordered set and range type.

Overall, a summary of literature related with cloud service selection are given in Table 1.

Most of the previous work deals with pure cloud service selection without considering the mobile environment. When the cloud computing is combined with mobile systems, new challenges of cloud service selection are raised.

Finding an appropriate cloud-path pair has become increasingly important in mobile cloud environment. Existing methods of evaluation, however, do not take a broader range of criteria into account, such as network bandwidth and cloud availability. Since offloading the application into the cloud service depends closely on the network bandwidth between the mobile device and a cloud server and also the reachability of a cloud server, while the previous work of cloud service selection is not sufficient to manage such a new challenge. Therefore, we further explore the methods of cloud service selection in this paper as cloud-path selection for offloading in mobile cloud computing systems when taking the path-pair condition between the mobile device and cloud service into considering.

CLOUD-PATH SELECTION BASED ON ONE CRITERION

A. System Overview

In cloud offloading systems, in order to reduce total application execution time, we need to find an optimal cloud-path pair that from the mobile devices to the cloud to carry out the offloaded computation. The network bandwidth, the server's speedup, the link's failure rate and cloud's condition should be considered when selecting a server in cloud.

There are a variety of clouds appearing these days, for example, Amazon EC2, Microsoft Windows Azure, Google App Engine, IBM Blue Cloud and so on, but since they provide different kinds of cloud services that shall not

Table 1. An overview of cloud service selection literature

Frameworks	Themes	Methods
CloudCmp	Compare the performance of public cloud services	Cloud benchmarks
CloudRank	A collaborative QoS-driven ranking framework for cloud components	Greed method
$(MC^2)^2$	Cloud service recommender system based on multi-criteria comparison	MCDM and ANP
CloudGenius	Cloud infrastructure service and cloud VM image selection	AHP and $(MC^2)^2$ Process
SMICloud	Comparing and ranking cloud service based on SMI attributes	AHP and Relative Service Ranking Vector

be comparable. Here, we consider a certain class of clouds that provide the same service. A more suitable example will be the peer cloud storage services such as Dropbox, Box, Apple iCloud, MS Skydrive, Google Drive and so on.

The servers on clouds could also be different from each other, but basically the more resources they provide (larger speedup value F), the higher it costs. Therefore, we assume F is proportional to the cost per unit C, which means the larger F is, the more cost it would be, and thus we have

$$C_i = k_i F_i \tag{1}$$

where k_i is the scale factor for the i^{th} cloud, the speedup F_i indicates how powerful the i^{th} cloud server is in terms of execution speed comparing with the mobile device. Normally, F_i is much larger than 1 due to the servers are resource-rich while the mobile devices are resource-limited.

The diagram of cloud offloading systems is illustrated in Figure 1. There are M alternative clouds in the sky with a variety of speedup factors and economy costs. And bandwidth and link's failure rate are also different from each other. Therefore, an optimal cloud-path from the mobile device to cloud needs to be selected.

The time incurred by offloading is the sum of communication time and computing time spent on the server in cloud and it should be smaller than the execution time required by the mobile device in order to improve performance.

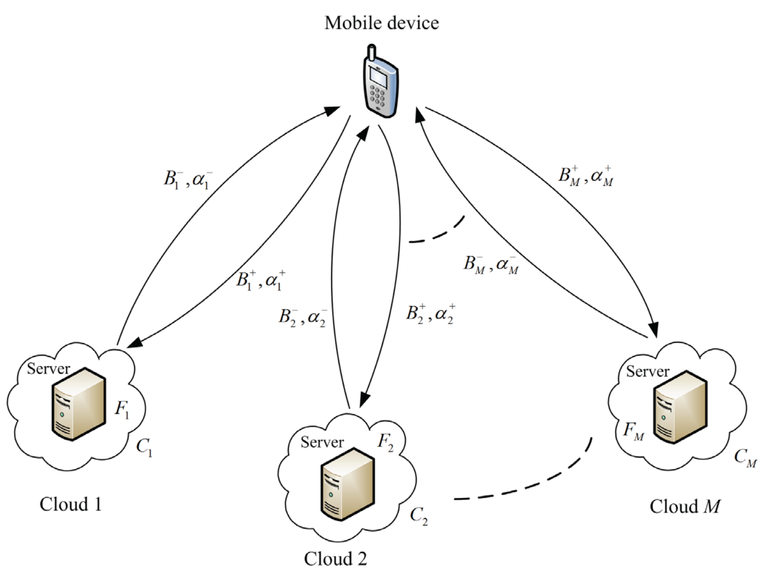
Therefore, for a certain cloud-path such as from the mobile device to cloud i, offloading program to the cloud server saves time only if it meets the following condition (Wu, Wang & Wolter, 2013)

$$t_m > t_s = \frac{t_m}{F_i} + (1+\alpha_i^+)\cdot\frac{D_i^+}{B_i^+} + (1+\alpha_i^-)\cdot\frac{D_i^-}{B_i^-} \tag{2}$$

where $i \in 1, 2, \cdots, M$, $\frac{t_m}{F_i}$ is the time spent on cloud,

$$(1+\alpha_i^+)\cdot\frac{D_i^+}{B_i^+} + (1+\alpha_i^-)\cdot\frac{D_i^-}{B_i^-}$$

Figure 1. Diagram of cloud offloading systems



is the communication time in serial when considering the link's failure, the parameters used in offloading process are given in Table 2. Note that bandwidth and link failure rate for the uplink and downlink can be different, *i.e.* $B_i^+ \neq B_i^-$ and $\alpha_i^+ \neq \alpha_i^-$.

If economy cost is taken into consideration, the best cloud-path pair is selected when it meets the following condition:

$$min\left[k_i \cdot \frac{t_m}{C_i} + (1+\alpha_i^+)\cdot\frac{D_i^+}{B_i^+} + (1+\alpha_i^-)\cdot\frac{D_i^-}{B_i^-} \right] \quad i \in 1,2,\cdots,M \tag{3}$$

There are many principles (Ou, Yang and Hu, 2007) to determine the optimal cloud-path pair, such as

- **Random:** Select the cloud-path pair randomly.
- **Bandwidth:** Choose the cloud-path pair with the highest bandwidth.
- **Link's Failure Rate:** Select the cloud-path pair with the lowest link failure rate.
- **Speedup Factor:** Select the cloud-path pair with the highest speedup factor.
- **Cost:** Select the cloud-path pair with the lowest economy cost.

B. Simulation and Performance Evaluation

In this section, we implement the above algorithms to make cloud-path decisions and compare the numerical results.

Following parameters are used: the bandwidth B_i is uniformly chosen from [32, 256] *kbps* and the link's failure rate α_i is uniformly chosen from [0.01, 0.2]. Note that the bandwidth and link's failure for uplink and downlink can be different. The exchanged data for uplink and downlink are fixed as $D_i^+ = 2000kb$ and $D_i^- = 1500kb$, respectively.

Table 2. Parameters of offloading

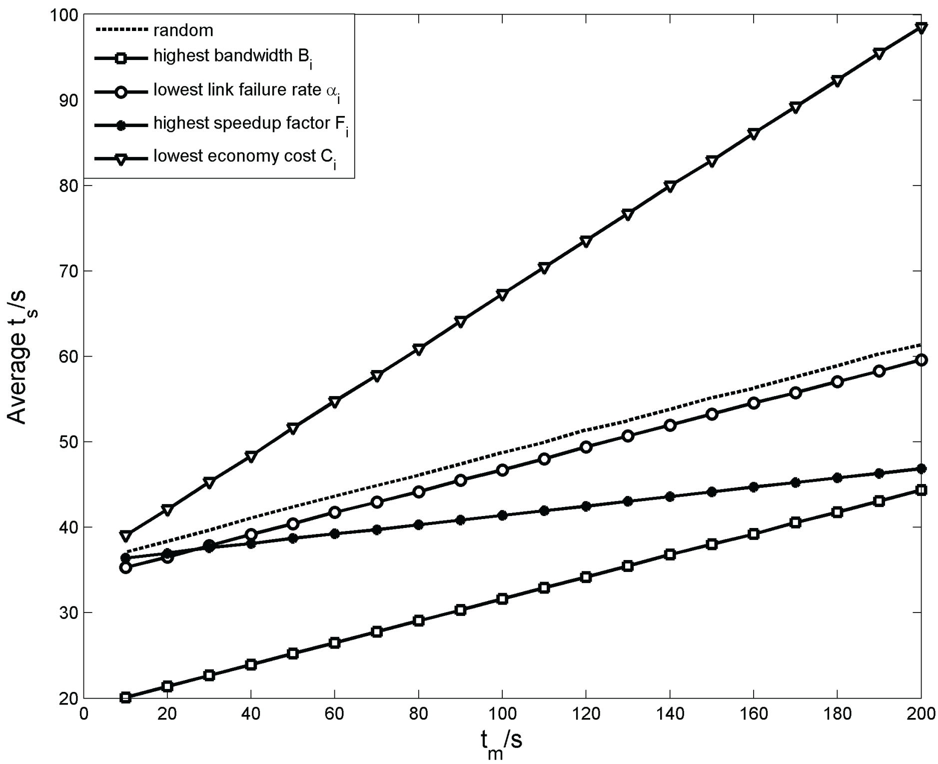
Symbol	Meaning
B_i^+	uplink bandwidth
B_i^-	downlink bandwidth
D_i^+	uplink exchanged data
D_i^-	downlink exchanged data
t_m	execution time on the mobile device
t_s	execution time incurred by offloading
α_i^+	uplink's failure rate
α_i^-	downlink's failure rate
F_i	speedup factor
C_i	economy cost

For convenience, we assume k_i is a constant and set as 1. The speedup factor F_i is uniformly chosen from [2, 20]. The baseline execution time is varying from 10*s* to 200*s*. And the number of alternative clouds is 10. The simulation is run 10, 000 times to reduce random chance.

The average time t_s obtained by the five cloud-selection algorithms are depicted in Figure 2. It can be seen that the random algorithm costs much more time than the algorithms of highest bandwidth, lowest link failure rate and highest speedup factor due to it does not consider any network or cloud condition. The lowest economy cost algorithm gets the biggest t_s among the five cases due to it is the cost criteria while the highest bandwidth, lowest link's failure rate and highest speedup factor are benefit criteria. Besides, according to the improvement of average time t_s, we can rank the priority of importance for the three benefit criteria mentioned above as *bandwidth* > *speedup factor* > *link's failure rate*.

Except based on time saving, cloud servers can also be ranked according to energy savings for mobile devices because battery consumption is another primary aspect that must be considered when making offloading decisions. For example, Kumar, Nimmagadda and Lu (2009) ranked servers based on energy savings for computation offloading.

Figure 2. Average t_s under different cloud-path selection algorithms



CLOUD-PATH SELECTION BASED ON MULTI-CRITERIA

A. Service Measurement Criteria

From above analysis, it can be found that our analysis is also limited in one criterion when making decision in selecting an optimal cloud-path, without considering other factors at the same time.

However, there are many criteria needed to be considered simultaneously. Here, we employ some of QoS criteria from CSMIC, which is designed to become a standard method to help organizations measure relative index for comparing different cloud services.

- **Financial:** How much it costs for the same amount of computing? It various in different cloud services. As shown in Table 3, we present the comparison results between AWS, Azure and AppEngine. It can be found that the price various a lot from instance types and different cloud providers. For the mobile cloud service providers, how to build an economic service provisioning scheme is critical, particularly when the mobile cloud resource is restricted (Liang, Huang and Peng 2012). It can be measured by *VM cost*, *data cost*, *storage cost* and *communication cost*. For example, if a VM is priced at p for *cpu* (cpu unit), *net* (network), *data* for data and *RAM* for RAM, then the cost of VM is calculated as (Garg, Versteeg, & Buyya, 2011)

$$\text{VM cost} = \frac{p}{cpu^a \cdot net^b \cdot data^c \cdot RAM^d} \tag{4}$$

where $a, b, c,$ and d are weights for each resource attribute and $a+b+c+d=1$.

- **Performance:** Does it do what we need? As for its sub-criteria, *speed*, *accuracy* and *service response time* should be considered. The criterion *speed* means how fast a server on cloud for computing is and it can be measured though speedup factor F, which compares the execution speed of a cloud to that of the mobile device. *Accuracy* (or *trust*) is the degree of closeness to user expected actual value or result generated by using the cloud service (Kumar, Nimmagadda & Lu, 2009). It can be expressed as a mathematical formula

$$accuracy(\%) = \frac{1}{m} \times \sum_{i=0}^{m} p(a,b) \tag{5}$$

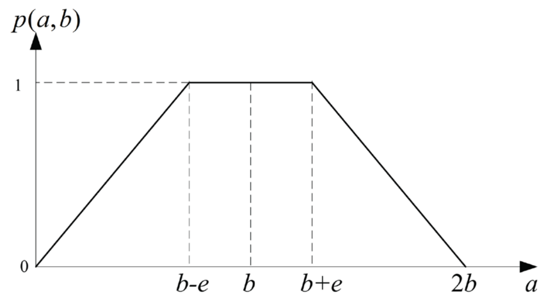
where m is number of checkpoints, a, b are observed and expected number of executions, respectively and p returns a percentage as shown in Figure 3.

Security: Is the service safe and privacy well protected? Commonly, this criterion is subjectively evaluated regarding many aspects. First of all, shifting all data and computing resources to the cloud is dangerous, for example, tracking individuals through location-based navigation data offloaded to the cloud. Besides,

Table 3. Price of public cloud service

Cloud Provider	Instance Type	CPU/Number of Cores	Price/Hr
AWS	Small Medium Large Extra large	1 2 4 8	$0.091 $0.182 $0.364 $0.728
Azure	Small Medium Large	1 2 4	$0.12 $0.24 $0.48
AppEngine	Default	N/A	$0.08

Figure 3. Mathematical model of function p(a,b)



security and privacy settings depend on the cloud providers since the data is stored and managed in the cloud (Kumar & Lu, 2010). Securing offloads adds non-trivial latency and energy overhead. Thus, careful choices must be made in deciding whether to encrypt communication and whether specific compute resources should be used. However, the QoS value of *security* is difficult to measure, but specific criteria that are measurable should be used when possible. Furthermore, *security* is also multi-dimensional in nature and it includes many attributes like *data integrity*, *data privacy* and *data loss*.

Besides, when cloud computing is combined with mobile systems, the following two criteria should be taking into consideration.

- **Bandwidth:** How fast is the data transmitted? It depends on the wireless link between the mobile devices and cloud service. When the wireless connection is excellent, a large amount of application execution and data should be offloaded to the cloud, but when it is poor, only a small amount of application execution and data can be offloaded during limited time (Wolski, Gurun, Krintz & Nurmi, 2008). Different network types and conditions have a large impact on the communication time cost and energy consumption. 3G wireless networks supporting 2M*bps* peak stationary and 384K*bps* peak mobile bandwidth are widely used, and there are Wi-Fi hotspots at home, at universities and cafes. 3G technology can provide a near-ubiquitous coverage while it consumes more energy than Wi-Fi because of communication latencies and is sensitive to location. The network condition can also change with location (Chun & Maniatis, 2010). While for stable and high-speed network, the program should be executed in the cloud server, however, the program should better be executed locally on the mobile device in the situations of unreliable and weak connectivity.
- **Availability:** Is it able to connect or use the cloud service? It is related with link's failure and cloud's unavailability during the whole offloading process. Cloud service may not be available in some cases and the network distance to the cloud also affects the performance of the program. Mobile cloud computing is difficult in locations such as the basement of a building, interior of a tunnel, or subway, where the wireless network bandwidth is so small that the cloud computing is not possible (Kumar & Lu, 2010). Dependence on a distant cloud could lead to problems when service outages occur. Failures may occur due to the mobile nature of mobile devices and unstable connectivity of wireless links, which render a less predictability of the performance of a program running under the control of offloading systems (Ou, Yang, Liotta & Hu, 2007). The most simple representation for availability is as a ratio of the expected value of the uptime of a system to the aggregate of the expected values of up and down time, or

$$A = \frac{E[Uptime]}{E[Uptime] + E[Downtime]} \quad (6)$$

where *Downtime* is the duration when the cloud service is not available while *Uptime* is the duration when the cloud service is available.

B. Decision Hierarchy of Cloud-Path Selection

The decision hierarchy for the problem of cloud-path selection is formed as Figure 4, when all the above service measurement criteria and sub-criteria are included.

There are three hierarchies listed in Figure 4. The first level is called target hierarchy, meaning what the object is. Here, it aims to find the best cloud service from amongst available cloud services which satisfy the essential requirements of the mobile device. The second level is called criteria hierarchy, and there are five criteria: *performance*, *security*, *bandwidth*, *availability* and *security* to be considered for this problem of cloud-path selection. The criteria can be classified into two categories: subjective criteria and objective criteria. The former is defined in linguistic/qualitative terms while the latter has monetary/quantitative definition. Figure 4 represents that root criteria can be made up of sub-criteria. The bottom level is named decision hierarchy, in which we can make the final decision in choosing one of the alternative clouds based on the analysis in criteria hierarchy.

C. Steps of Cloud Service Selection

As shown in Figure 5, there are three basic steps to be taken in the process of cloud service selection: matching, ranking and selecting.

- **Matching:** The role of matching step is to find a list of available cloud services that are functionally matched with a service request by the mobile user. On the mobile device side, upon receipt of an offloading request, the *service request module* invokes the *cloud discover module* to find appropriate cloud services according to the component of *Service Level Agreement (SLA) management* that keeps track of SLAs of customers with cloud providers and their fulfillment history. The candidate cloud services are registered based on the collected information in the *cloud register module*.
- **Ranking:** The ranking step which is the focus in this paper is to evaluate and rank the available cloud services according to QoS values and ranking of services based on the results of criteria and sub-criteria calculation. The *criteria calculator module* depends on the components of *qualitative*

Figure 4. The decision hierarchy of cloud-path selection

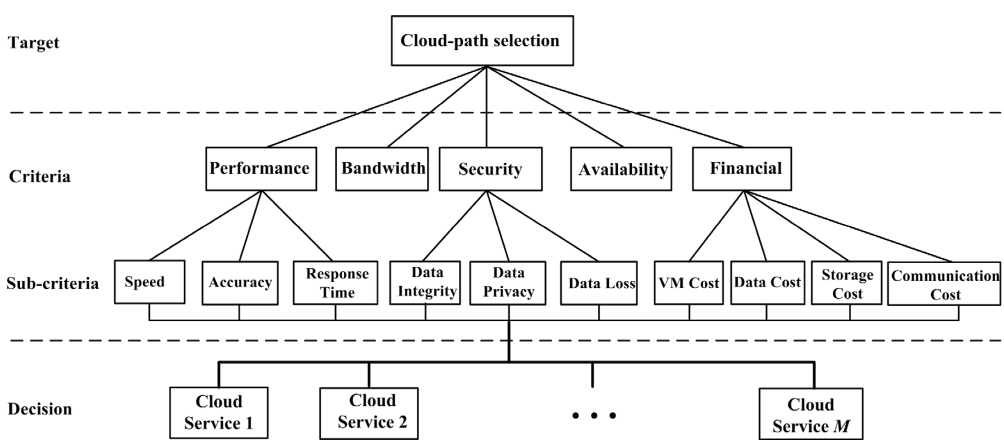
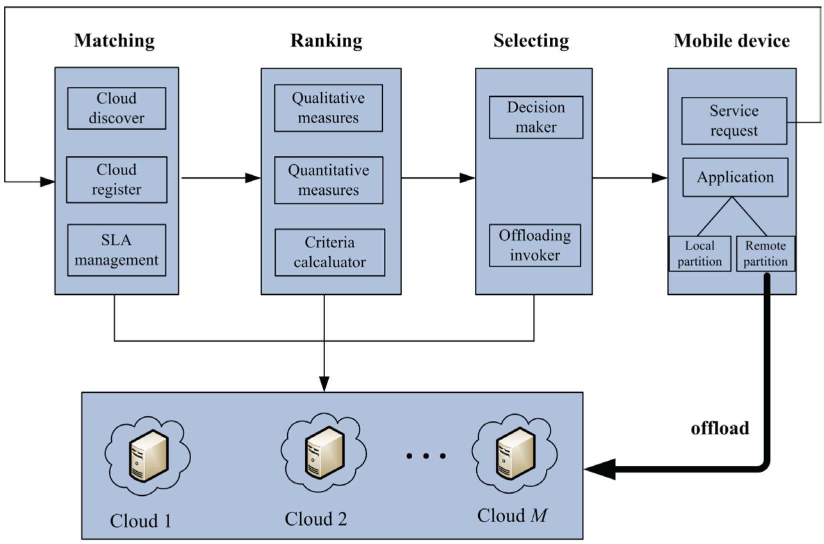


Figure 5. Framework of cloud service selection



measurements and *quantitative measurements*. Qualitative criteria are those that cannot be quantified and are mostly inferred based on previous user's experiences, and the *qualitative measures module* systematically measures the quality of a cloud service, *e.g. security*. Quantitative criteria are those that be measured by using software and hardware monitoring tools, and the *quantitative measures module* measures the quantity of some criteria, *e.g. bandwidth*, *VM cost* and *speed*. The ranking step can be described as follows (Tran, Tsuji and Masuda, 2009)

$$\text{RankedAvailableCloudServiceList} = f_{rank}\left(\text{AvailableCloudServiceList, ServiceRequest}\right) = \left\{CS_n \middle| \forall i, j \text{ and } i \le j\text{: } rank(CS_i) \ge rank(CS_j)\right\} \quad (7)$$

$$\text{AvailableCloudServiceList} = \left\{CS_n \middle| functionalMatched\left(CS_n, SR\right)\right\} \quad (8)$$

where CS_n, *SR*=(*FunctionalDescription*, *QoSValues*), CS_n is the n^{th} cloud service and *SR* is the service request by the mobile device, *QoSValues* are based on criteria to evaluate cloud service ranking. *FunctionalDescription* describes a cloud service's functionality such as software as a service (SaaS), platform as a service (PaaS), infrastructure as a service (IaaS) or date as a service (DaaS), which are necessary for the matching step. *Functionalmatched* compares the cloud service with mobile user's request service, if they are matched, then we put such cloud service into the list of available cloud services. The ranked list of cloud services is then used for the next step.

- **Selecting:** In the selecting step, the *decision maker module* is invoked to choose the optimal cloud-path according to the ranked list of cloud services. And then the *offloading invoker module* is triggered to partition the application into local partition and remote partition, and the remote partition is then offloaded to the selected cloud service.

METHODS OF COMBING AHP AND FUZZY TOPSIS

To rank the cloud-path pairs, the methods of AHP and fuzzy TOPSIS are combined in this paper. AHP is employed to obtain weights of the criteria for cloud-path selection, while fuzzy TOPSIS is used to determine the priorities of the alternative clouds in decision-making process (Dagdeviren, Yavuz & Kilin, 2009). The processes are described in detail in the following.

A. The AHP Method

AHP is a process for determining the relative importance of a set of alternatives in a multi-criteria decision problem. It converts the evaluations to numerical values that can be processed and compared and derives a numerical weight or priority for each element of the hierarchy.

The results of the pairwise comparison on N criteria can be expressed in an evaluation matrix as:

$$\mathbf{A} = \left(a_{ij}\right)_{N\times N} = \begin{bmatrix} a_{11} & a_{12} \cdots a_{1N} \\ a_{21} & a_{22} \cdots a_{2N} \\ \vdots & \vdots \ddots \vdots \\ a_{N1} & a_{N2} \cdots a_{NN} \end{bmatrix}, \quad a_{ii} = 1, a_{ji} = 1 / a_{ij} \tag{9}$$

where element α_{ij} is based on a standardized comparison scale of nine levels as shown in Table 4 (Olson, 2004).

The relative weights are given by eigenvector ($\mathbf{w}$) corresponding to the largest eigenvalue ($\lambda_{\max}$) as:

$$\mathbf{Aw} = \lambda_{\max}\mathbf{w} \tag{10}$$

The output of AHP is strictly related to the consistency of the pairwise comparison. The consistency index (CI) is defined as follow:

$$\mathrm{CI} = \frac{\lambda_{\max} - N}{N - 1} \tag{11}$$

The final consistency ratio (CR) is calculated as:

$$\mathrm{CR}=\mathrm{CI}/\mathrm{RI} \tag{12}$$

where RI is the average random consistency index that is only relevant with the matrix order. And in order to meet the consistency, CR should be less than 0.1.

B. The Fuzzy TOPSIS Method

TOPSIS is widely used to solve decision problems in real situation. We use fuzzy TOPSIS here since it is intuitively easy for the decision-makers to use and calculate through a triangular fuzzy number and it is proved to be an effective way for formulating decision problems (Dağdeviren, Yavuz & Kılınç, 2009). The process steps of fuzzy TOPSIS can be outlined as follows (Olson, 2004)

Table 4. Importance scale and its definition

Definition	Intensity of Importance
Equally important	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Extremely more important	9
Intermediate	2, 4, 6, 8

- **Establish a decision matrix for the ranking:** The structure of the matrix can be expressed in the following:

$$X = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_M \end{array} \begin{array}{c} \begin{array}{cccccc} C_1 & C_2 & \cdots & C_j & \cdots & C_N \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} & \cdots & x_{1N} \\ x_{21} & x_{22} & \cdots & x_{2j} & \cdots & x_{2N} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} & \cdots & x_{iN} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{M1} & x_{M2} & \cdots & x_{Mj} & \cdots & x_{MN} \end{bmatrix} \end{array} \quad (13)$$

where C_j is the j^{th} criterion and A_i is the i^{th} candidate cloud service, N is the number of criteria and M is the number of alternatives. The triangular fuzzy number x_{ij} belong to [0, 1], and thus there is no need for normalization. The membership functions of linguistic values used in this paper are described in Figure 6, and the corresponding triangular fuzzy numbers are shown in Table 5.

- **Calculate the weighted normalized decision matrix by multiplying the normalized decision matrix by its weights from AHP method:** The weighted normalized value v_{ij} is calculated as

$$v_{ij} = x_{ij} \times w_j,\ i=1, 2, \cdots, M \quad j=1, 2, \cdots, N \quad (14)$$

where w_j represents the weight of the j^{th} criterion, which is obtained from the AHP method.

- **Determine the positive-ideal (A^+) and negative-ideal solutions (A^-), respectively:** Define:

$$A^+ = \{v_1^+, v_2^+, \cdots, v_N^+\} = \left\{\left(\max_j v_{ij} \,\middle|\, i \in I\right), \left(\min_j v_{ij} \,\middle|\, i \in I'\right)\right\} \quad (15)$$

$$A^- = \{v_1^-, v_2^-, \cdots, v_N^-\} = \left\{\left(\min_j v_{ij} \,\middle|\, i \in I\right), \left(\max_j v_{ij} \,\middle|\, i \in I'\right)\right\} \quad (16)$$

For normalized positive triangular numbers, we can define the fuzzy positive-ideal and negative-ideal solutions. As for benefit criterion, we have $v_j^+ = (1,\ 1,\ 1)$ and $v_j^- = (0,0,0)$, while for cost criterion, we have $v_j^+ = (0,\ 0,\ 0)$ and $v_j^- = (1,\ 1,\ 1)$.

- **Calculate the distance of each alternative from A^+ and A^- using the Euclidean distance, which are denoted by:** D_i^+ and D_i^-. Define

$$D_i^+ = \sum_{j=1}^{N} d(v_{ij}, v_j^+), \quad i=1, 2, \cdots, M \quad (17)$$

$$D_i^- = \sum_{j=1}^{N} d(v_{ij}, v_j^-), \quad i=1, 2, \cdots, M \quad (18)$$

where $d(v_{ij}, v_j^+)$ is to calculate the Euclidean distance between v_{ij} and v_j^+.

Figure 6. Membership functions of linguistic values

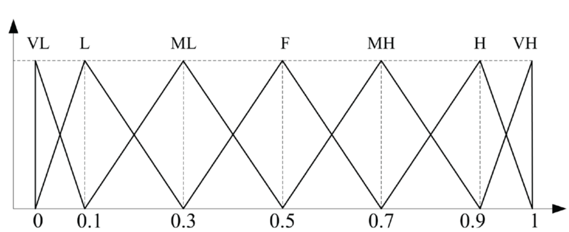


Table 5. Fuzzy membership functions

Linguistic values	Fuzzy ranges
Very low(VL)	(0, 0, 0.1)
Low(L)	(0, 0.1, 0.3)
Medium low(ML)	(0.1, 0.3, 0.5)
Fair(F)	(0.3, 0.5, 0.7)
Medium high(MH)	(0.5, 0.7, 0.9)
High(H)	(0.7, 0.9, 1)
Very high(VH)	(0.9, 1, 1)

- **Calculate the relative closeness to ideal solution, denoted as:** C_i^*. Define

$$C_i^* = \frac{D_i^-}{D_i^+ + D_i^-}, \quad i=1, 2, \cdots, M \tag{19}$$

- **Rank the alternatives according to:** C_i^* **in descending order.** The nearer the value C_i^* close to 1 means the better the performance of the alternatives.

CASE STUDY: OPTIAML CLOUD-PATH SELECTION USING THE METHODS OF AHP AND FUZZY TOPSIS

A. Calculate the Weights of Criteria

The priority of importance depends on what we care about most. For instance, if the offload data is neither privacy nor confidential, in this case, *security* is the least important factor among the five criteria.

For a cloud offloading system, *bandwidth* is considered as the most significant because it decides the extra communication cost between the mobile device and a cloud. Besides, *performance* is also important since it determines application's execution time and affects battery consumption of the mobile device. According to the simulation results for individual criterion depicted in Figure 2, we assume the priority of importance is ranked as: *bandwidth* > *performance* > *availability* > *security* > *financial* when choosing the optimal cloud-path pair. However, the priority of these five criteria can be various in other situations.

Employing the importance scale given in Table 4, we get the pairwise comparison matrix as shown in Table 6.

By using the AHP method, we calculate the weights of the criteria as shown in Table 7. The weights will be used in evaluation process.

Table 6. Pairwise comparison matrix for criteria

Criteria	*Bandwidth*	*Financial*	*Performance*	*Security*	*Availability*
bandwidth	1	9	3	7	5
financial	1/9	1	1/6	1/2	1/3
performance	1/3	6	1	4	3
security	1/7	2	1/4	1	1/2
availability	1/5	3	1/3	2	1

From Table 7, it can be seen that speed and bandwidth are determined as the most important criteria. Besides, the consistency ratio CR is 0.020 < 0.1 (criteria checking point). Thus, the weights are shown to be consistent which can be used in the decision-making process.

B. Select the Optimal Cloud-Path

In this problem of cloud-path selection, it is assumed that there are four candidate cloud services available. Besides, it can be seen that *financial* is a cost criterion whereas the others are benefit criteria. The results of fuzzy weighted decision matrix are given in Table 8.

The results of fuzzy TOPSIS analysis are summarized in Table 9. D_i^+ and D_i^- can be calculated by using Eq.(17) and Eq.(18). Based on C_i^* values, the ranking of the clouds in descending order are Cloud 2, Cloud 4, Cloud 3 and Cloud 1 as shown in Figure 7. And thus, cloud 2 with $C_2^* = 0.348$ is the optimal alternative among the four clouds. In other words, we should choose the path pair between the mobile device and cloud 2 to offload data when considering the five criteria, simultaneously.

According to the numerical analysis, the method of combing AHP and fuzzy TOPSIS seems to be an effective and synthesized way in solving cloud-path selection. However, the challenge we face today is that those parameters for decision making such as bandwidth, security, execution time for offloading and failure rate are a little hard to measure or acquire timely in practical systems. Therefore, the way that how to estimate and measure these parameters is further investigated in the following.

C. Qualitative and Quantitative Measurements of Criteria

For the objective criteria and sub-criteria listed in Figure 4, such as the criterion *bandwidth* and the sub-criteria of *performance*: *speed*, *accuracy* and *service response time*, the triangular fuzzy numbers can be used directly. Since it is difficult to measure or acquire in time, we use the historical data based on mobile user's experiences to construct the evaluation value, *e.g.*, the triangular fuzzy number return on assets can be expressed as

$$\left(\min_i\{h_i\}, (\Pi_{i=1}^t h_i)^{1/t}, \max\{h_i\}\right) \quad (20)$$

where $h_1, h_2, \cdots, h_t$, denote the return on assets of past *t* periods.

For example, the results of triangular fuzzy numbers are obtained in Table 10 according to Eq. (20) when three historical data are used. The weights of *security* and *bandwidth* are obtained from the AHP method as shown in Table 7. Similarly, we can get the weights of sub-criteria according to the AHP method.

We can also get the graded mean integration representation from Table 10. Let $A_i = (a_i, b_i, c_i),\ i = 1, 2, \cdots, n$, be *n* triangular fuzzy numbers. By the graded mean

Table 7. Results obtained from AHP

Criteria	Weights	λ_{max}, CI, RI	CR
Bandwidth	0.528	$\lambda_{max} = 5.089$ CI=0.022 RI=1.12	0.020
Financial	0.042		
Performance	0.252		
Security	0.068		
Availability	0.110		

Table 8. Weighted evaluation matrix for the alternative clouds

Cloud	*Bandwidth*	*Financial*	*Performance*	*Security*	*Availability*
Cloud 1	VL	H	MH	L	ML
Cloud 2	VH	H	VH	VL	L
Cloud 3	F	ML	H	H	MH
Cloud 4	MH	L	F	MH	VH
Cloud 1	(0, 0, 0.1)	(0.7, 0.9, 1)	(0.5, 0.7, 0.9)	(0, 0.1, 0.3)	(0.1, 0.3, 0.5)
Cloud 2	(0.9, 1, 1)	(0.7, 0.9, 1)	(0.9, 1, 1)	(0, 0, 0.1)	(0, 0.1, 0.3)
Cloud 3	(0.3, 0.5, 0.7)	(0.1, 0.3, 0.5)	(0.7, 0.9, 1)	(0.7, 0.9, 1)	(0.5, 0.7, 0.9)
Cloud 4	(0.5, 0.7, 0.9)	(0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.5, 0.7, 0.9)	(0.9, 1, 1)
Weights	0.528	0.042	0.252	0.068	0.110
Cloud 1	(0, 0, 0.053)	(0.029, 0.038, 0.042)	(0.126, 0.176, 0.227)	(0, 0.007, 0.020)	(0.011, 0.033, 0.055)
Cloud 2	(0.475, 0.528, 0.528)	(0.029, 0.038, 0.042)	(0.227, 0.252, 0.252)	(0, 0, 0.007)	(0, 0.011, 0.033)
Cloud 3	(0.158, 0.264, 0.370)	(0.004, 0.013, 0.021)	(0.176, 0.227, 0.252)	(0.048, 0.061, 0.068)	(0.055, 0.077, 0.099)
Cloud 4	(0.264, 0.370, 0.475)	(0, 0.004, 0.013)	(0.076, 0.126, 0.176)	(0.034, 0.048, 0.061)	(0.099, 0.110, 0.110)
A^+	v_1^+ =(1,1,1)	v_2^+ =(0,0,0)	v_3^+ =(1,1,1)	v_4^+ =(1,1,1)	v_5^+ =(1,1,1)
A^-	v_1^- =(0,0,0)	v_2^+ =(1,1,1)	v_1^+ =(0,0,0)	v_1^+ =(0,0,0)	v_1^+ =(0,0,0)

Table 9. Fuzzy TOPSIS results

Alternatives	D_i^+	D_i^-	C_i^*
Cloud 1	3.802	1.225	0.244
Cloud 2	3.267	1.743	0.348
Cloud 3	3.402	1.624	0.323
Cloud 4	3.365	1.662	0.331

Figure 7. Ranking the alternatives based on the fuzzy TOPSIS results

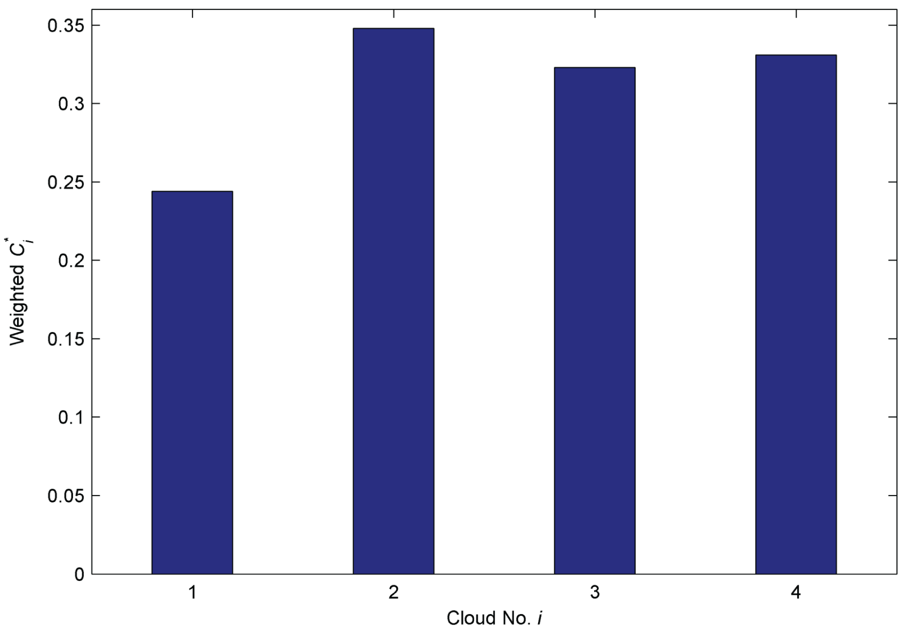


Table 10. Results of triangular fuzzy numbers

Criteria (Weights)	Sub-Criteria (Weights)	Historical Data				Triangular Fuzzy Numbers			
		Cloud 1	**Cloud 2**	**Cloud 3**	**Cloud 4**	**Cloud 1**	**Cloud 2**	**Cloud 3**	**Cloud 4**
Security (0.068)	*Accuracy* (0.3)	60% 70% 68%	95% 99% 97%	70% 75% 80%	80% 85% 90%	(60%, 65.85%, 70%)	(95%, 96.99%, 99%)	(70%, 74.89%, 80%)	(80%, 84.90%, 90%)
	Speed (0.6)	7 8 10	20 21 22	10 12 11	18 20 16	(7, 8.24, 10)	(20, 20.98, 22)	(10, 10.97, 12)	(16, 17.93, 20)
	Service response time (0.1)	400 320 440	20 30 50	80 100 120	300 280 320	(320, 383.31, 440)	(20, 31.07, 50)	(80, 98.65, 120)	(280, 299.55, 320)
Bandwidth (0.528)	*Network Bandwidth* (1)	32 40 46	200 256 300	80 90 120	180 160 170	(32, 38.90, 46)	(200, 248.58, 300)	(80, 95.24, 120)	(160, 169.80, 180)

integration representation method (Ding & Liang, 2005), the graded mean integration representation $P(A_i)$ of A_i is

$$P(A_i) = \frac{a_i + 4b_i + c_i}{6} \tag{21}$$

For the subjective criteria and sub-criteria, such as the sub-criteria of *security*: *data integrity*, *data privacy* and *data loss*, the triangular fuzzy numbers to evaluate the superiority of alternatives can be $S = \{VL, L, ML, F, MH, H, VH\}$, where *VL*= Very Low, *L*=Low, *ML*=Medium low, *F*=Fair, *MH*=Medium High, *L*=High, and *VH*=Very High. The fuzzy values are as shown in detail in Table 5.

Overall, both methods can be used to evaluate the importance weights of all criteria and sub-criteria as well as the fuzzy ratings of alternative cloud service, when it is still a challenge to measure or acquire the parameters of criteria timely in practical systems.

CONCLUSION

To sum up, we further explore the methods of optimal cloud-path selection for offloading in mobile cloud computing systems when taking the network bandwidth between the mobile device and cloud service and the availability of cloud service into considering, because the previous work of pure cloud service selection is not sufficient to manage the new challenge in mobile cloud environment. In this study, several alternative cloud services are considered and evaluated in terms of many different criteria such as *performance*, *bandwidth*, *security*, *financial* and *availability* in cloud-path selection problem.

We use a scheme that combing AHP and fuzzy TOPSIS methods, which considering the subjective judgments of evaluators and making final decision based on the results from multiple criteria analysis to select an optimal cloud-path in cloud offloading systems. And it is proved to be an effective and synthesized way through numerical analysis. Besides, both single and multiple criteria decision analysis approach are performed. Furthermore, the method based on historical data of mobile user's experiences is given, when it is difficult to obtain the QoS values of criteria and sub-criteria timely in real systems.

In short, cloud-path selection will be a crucial issue due to the development of mobile cloud computing. This paper aims in offering a solution to cloud-path choosing while multi-criteria are being considered, and the aim hits the trend of future realistic needs.

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