Wang, X, Qu, D, Li, K, Cheng, H, Das, SK, Huang, M, Wang, R and Chen, S

A flexible and generalized framework for access network selection in heterogeneous wireless networks

A Flexible and Generalized Framework for Access Network Selection in Heterogeneous Wireless Networks

Xingwei Wang[1], Dapeng Qu[2*], Keqin Li[3], Hui Cheng[4], Sajal K. Das[5],
MinHuang[6], Renzheng Wang[6], Shuliu Chen[6]

[1]College of Software, Northeastern University, Shenyang, China
[2]School of Information, Liaoning University, Shenyang, China
[3]Department of Computer Science, State University of New York, New Paltz, New York12561, USA
[4]School of Computing & Mathematical Sciences, Liverpool John Moores University, Liverpool, UK
[5]Department of Computer Science, Missouri University of Science and Technology, Rolla, USA
[6]School of Computer Science and Engineering, Northeastern University, Shenyang, China

***Abstract**:* The rapid development and integration of heterogeneous wireless networks provide ubiquitous communications for mobile users. The intelligent and multimodal mobile terminals should select the best access network at any time anywhere. However, the "best" is a complex and fuzzy concept, which has different meanings to different users and even to the same user under different conditions. There are various factors to consider when deciding which one is the best for a mobile terminal. In this paper, we design a generalized and flexible framework for the access network selection in heterogeneous wireless networks. The framework is generalized because it considers various factors in a comprehensive way to get the solutions. These factors can be classified as network-related or user-related, economic or non-economic, objective or subjective, accurate or fuzzy. Meanwhile, the framework is also flexible because these factors can be customized and adapted to specific solutions. Under the framework, given N mobile terminals and M access networks, we have developed a novel access network selection scheme based on a Quantum-inspired Immune Clonal Algorithm (QICA). Experimental results demonstrate that our proposed scheme provides better utilities for both the users and the access networks, and also better services for users as compared with four other schemes.

***Keywords**:* Access network selection; heterogeneous wireless network; generalized and flexible framework; user utility; network utility

1 Introduction

Due to the rapid development of wireless networks and mobile communication technologies, the fourth generation (4G) networks have become the infrastructure hotspots nowadays. The first commercial Long Term Evolution (LTE) network was built in 2009. There had been 428 commercial 4G networks in 155 countries or

*Corresponding author. Tel. +86 24 83691732
Email address: dapengqu@lnu.edu.cn

regions until the end of 2015. For example, in China, three major network operators, namely China Mobile (CM), China Telecom (CT), and China Unicom (CU) started to provide their commercial Time Division Long Term Evolution (TD-LTE) networks in the first quarter of 2014. There have already been 391.418 million users, 79.52 million users, and 63.679 million 4G users in China Mobile, China Telecom, China Union respectively until April 2016 [2]. At the same time, the third generation (3G) mobile networks are still at their further development stage. "Measuring the Information Society Report" released by International Telecommunication Union (ITU) showed that the number of users with 3G networks in urban population reached 3.56 billion and accounted for about 89% of global urban population, while the number of users with 3G networks in rural population was less than 1 billion and accounted for about 29% of global rural population at the end of 2015 [3]. The Internet Society of China also reported that 3G networks had covered every town in China by the end of 2013. Meanwhile, the second generation (2G) mobile networks still hold a great number of users on the earth, although the number began to decrease in 2013 for the first time. Furthermore, the fifth generation (5G) wireless networks appear on the horizon. As the first country to open op wide swaths of high-band spectrum, America had paved the way for 5G broadband. The U.K., Germany, Japan, Korea, China and so on, also launched experiments for 5G technology research and development. Moreover, Verizon in USA pronounced that there will be full commercial 5G networks in some American cities in 2017. Korea and Japan pronounced that there will be commercial 5G networks in 2018 Winter Olympic Games and 2020 Summer Olympic Games respectively. China clearly declared that the commercial 5G will be launched in 2020. Therefore, 2G, 3G, and 4G networks and future 5G networks will coexist for a very long time.

To improve the wireless coverage and the interior quality of service (QoS), small cells, such as microcell and femtocell, often have been deployed among macro cells. For example, American Sprint has deployed more than 1 million ordinary consumer femtocells and 10 thousand enterprise femtocells. Wireless communications are also in a shift from traditional voice- and text-based services to multimedia-based services. Wireless Personal Area Networks (WPAN), Wireless Local Area Networks (WLAN), and Wireless Wide Area Networks (WWAN) have been widely deployed. Bluetooth, Wi-Fi, and satellite networks are their major access technologies. All these networks coexist with overlapping coverage, thus forming a heterogeneous wireless network environment.

The mobile terminals, such as smart phones, tablets, and laptops, have become increasingly smart, powerful, and affordable. They have been used as the primary devices to access the heterogeneous wireless networks. The global mobile Internet report from comScore showed that the mobile device has become the preferred choice to access Internet. Moreover, the percentages of the number of netizens only with mobile device to the total number of netizens are 49%, 48%, and 34% in USA, Canada and UK respectively. The 37th China Internet Development Report released by China Internet Network Information Center (CNNIC) also showed that in China the number of mobile netizens reached 620 million and it accounted for about 90.1% of all the netizens [4]. Moreover, the percentage of the number of mobile netizens using 3G and 4G to the number of mobile netizens reached 88.8%.

In such heterogeneous wireless networking environments, the mobile users inevitably want to be Always Best Connected (ABC) to the networks. ABC means that the users are not only always connected, but also connected to the best available network at all times. In order to keep ABC connections [5] for mobile applications, the mobile users should be able to select the best access network among the available ones. However, the “best” is a complex and fuzzy concept. Not only various factors, such as QoS requirements of the applications, user personal preference and so on, need to be considered, but also the types of factors considered by different users are different. For example, a business man pays more attention to the quality of the service, while an ordinary user is more concerned with the price of the service. Moreover, even the same user may consider different factors in different scenarios. For instance, a user would make different selections of the access network when the remaining battery power level of his mobile terminal varies. When the level is high, he would consider extra factors in addition to the battery power, on the contrary, the user would prefer to select a network with small coverage in order to save energy. Furthermore, with the diversity of access technologies and the development of perceptibility, the “best” concept can be extended and new factors should be taken into consideration. Personal preference is a good example.

As shown in Fig. 1, a user is covered by heterogeneous wireless networks consisting of Wi-Fi, satellite network, Time Division-Synchronous Code Division Multiple Access (TD-SCDMA), and femtocell. Considering QoS requirements of the current applications, the remaining battery power, and personal preference etc, how does he choose an access network that best suits his current demands?

To really achieve the “best”, on one hand, various factors should be considered in the access network selection procedure. On the other hand, they should be formulated into variables which can be conveniently adjusted under different conditions. To the former, we have considered the factors from the following aspects. First of all, the access network selection is not the user’s own wishful thinking, so both the access network side and the user side should be considered. Second, in commercial network environments, the economical factors, including minimum payment for users and maximum revenue for network providers [6], should be taken into account. Third, not only the objective factors, but also the subjective preferences should be considered. For example, the selection history is an objective factor and the user preference on network providers is a subjective factor. Both of them should be considered. Fourth, from the decision-making viewpoint, some factors can be accurately described, such as the remaining battery power and the moving speed of mobile terminals, but some other factors, for example, QoS requirements of applications, are intrinsically uncertain and dynamic in wireless networks [7].

To the latter, an effective mechanism should be designed to adjust the above aspects based on the actual requirements. Because there are multiple access networks and multiple users in heterogeneous wireless networks, only when the requirements of all the participators are satisfied, can the “win-to-win” situation be realized, and the “best” is achieved. Furthermore, the ABC supported access network selection should be stable, and it cannot change frequently in order to avoid the ping-pong effect [8]. It is worth noting that, when there are plenty of factors which need to be considered, some Multiple Attribute Decision Making (MADM) methods can be applied [9]. They make preference decision among alternatives that are characterized by multiple attributes (usually conflicting).

Through the above analysis, the access network selection scheme with ABC supported can be summarized as follows. Assume that there are N mobile terminals covered by M access networks simultaneously, the problem is to find the best access network from M for each of the N mobile terminals. The objective is to make both the user utilities and the network provider utilities achieve or approach Nash equilibrium under certain constraints. The constraints come from the access networks and the users. They can be classified as objective or subjective, economic or non-economic, accurate or fuzzy, etc. Moreover, these constraints are dynamic and they vary under different conditions. Obviously, it is a fuzzy multi-objective optimization problem. Furthermore, the problem complexity increases sharply with the increase of M and N since there are M^N candidate solutions. Therefore, intelligent or heuristic algorithms should be employed to get the optimal solution.

In this paper, we propose a flexible and generalized framework for the access network selection in heterogeneous wireless networks. The framework considers various comprehensive factors. Specifically, for the network-related ones, we consider QoS parameters, network load, price, and cost; whilst for the user-related ones, we consider moving speed, battery power, selection history, personal preference and budget. The price, cost, and budget are the economic factors which assure that both the network provider revenue (the difference between price and cost) and the user revenue (the difference between budget and price) are considered, the other factors are non-economic. The QoS parameters, network load, moving speed, battery power, selection history, price and cost belong to the objective factors, and the personal preference and budget belong to the subjective factors. The QoS parameters provided by the networks and the QoS requirements of the applications are hard to be accurately described, thus, their descriptions are based on the related fuzzy mathematics methods.

The feature of considering such comprehensive factors makes this framework generalized and the access network selection with the “ABC” supported can be achieved. These factors can be adapted and tailored to the user requirements, which makes this framework flexible. Finally, we implement an access network selection scheme based on Quantum-inspired Immune Clonal Algorithm (QICA) [10]. Simulation results demonstrate that the proposed scheme achieves higher user utility and network utility than four other popular schemes, i.e., VIKOR [11], UGT [12], MANS [18] and MCAS [21]. The proposed scheme also gets higher preference satisfaction for a network provider and higher fitness on high-speed movement and low available battery.

The major contributions of our work are summarized as follows:

- For the first time, we build a flexible and generalized framework for the access network selection in heterogeneous wireless networks. We consider comprehensive factors from four dimensions, namely, network-related or user related, economic or non-economic, objective or subjective, and accurate or fuzzy. These four dimensions cover nearly all the previous work. In terms of flexibility, our framework is built on modules which can be added or removed or replaced. Thus, any previous work can be mapped as a subset under our framework easily. In terms of generalization, this framework is capable of producing the generalized solutions, which can be adapted and tailored to the actual requirements. Under the flexible and generalized framework, new models and solutions can also be easily developed and explored.
- For the first time, we model the access network selection problem under ABC environments. We believe that ABC will be the first priority for both the access networks and the mobile terminals. Therefore, both of them have been modeled with appropriate parameters respectively to reflect the

ABC requirements.

- Instead of simply optimizing one objective, we propose gaming strategy and devise the user utility and the network utility, as motivated by the economics theory. Thus, our models aim at achieving the win-win situation for both the users and the network providers under the Nash equilibrium. In this way, our models and problem are rooted in the real-world scenarios.
- Under our framework, we have developed a specific method to solve the access network selection problem. Due to its high computation complexity, the method applies an artificial intelligence algorithm, QICA, to find the best solutions. The method shows remarkable performance as QICA achieves natural balance between exploration and exploitation. The method will serve as an example for developing other novel methods under our framework and also give benchmark solutions for comparison purposes.

The rest of this paper is organized as follows. The related works are reviewed and compared with our work in Section 2. The models and the framework are described in Section 3.The proposed access network selection scheme is presented in Section 4. Simulation experiments are described in Section 5. Finally, Section 6 concludes the paper.

2 Related Works

In mobile communication, handover or handoff refers to the process of transferring a mobile terminal from one access network to another access network smoothly [13]. Before the physical handover takes place, the mobile terminal should decide which access network to be the target. The access network selection is a key step in the handover (or handoff) process since it decides the quality of the service the user will experience in the future communication

Extensive work has been conducted on the access network selection. They define the meaning of the "best" from different viewpoints and considered various factors, such as Received Signal Strength (RSS), Signal to Interference plus Noise Ratio (SINR), monetary service cost, throughput, delay etc [14]. Due to the easy detection and calculation supported by the hardware, RSS has been widely used in a large number of studies [15]. However, RSS can not reflect the network conditions adequately and it is unable to compare RSS of different wireless networks directly in heterogeneous wireless network environments. Therefore, it will be insufficient to make the access network selection only based on RSS [16]. Since there are various factors to be considered, the access network selection in heterogeneous wireless networks turns to be a Multi-Criteria Decision Making (MCDM) problem [17].

Sehgal et al. [18] proposed an access network selection scheme which can satisfy the user need by computing weighted distance function. Meng et al. [19] proposed an adaptive scheme which considers both user mobility and network load. They got Mobility Threshold (MT) by considering the distribution of the whole users' movement characteristics and arrival rate, then used MT to differentiate mobile users to access different networks. Chang et al. [12] investigated the access network selection based on utility function and game theory. Its utility function combines bandwidth, delay and error rate. Its cooperative game aims to find the set of strategies that can maximize the payoff function for each candidate network. The work also places more preference on the network with more available resource to accommodate user mobility. Shen et al. [20] proposed a cost-function based network selection (CFNS) scheme from a system's perspective and the scheme also considered the user's needs. Nguyen-Vuong et al. [21] developed an analytical model to capture the end user preferences which indicate how importance a criterion should be considered in the selection process compared to other ones. Based on this model, they proposed an access network selection scheme considering all aspects of tradeoff between the quality of the connections, user preference and cost. Niyato et al. [22] formulated the bandwidth competition among groups of users in different service areas as a dynamic evolutionary game. They presented population evolution and reinforcement-learning algorithms to achieve evolutionary equilibrium. Chen et al. [23] proposed an access network selection scheme for maximizing user performance/cost ratio. Tabrizi et al. [24] used the Markov Decision Process (MDP) to formulate the network selection with the goal of maximizing QoS and applied Reinforcement Learning (RL) to select the best network based on the current network load and predicted future network state.

Among the MADM based schemes, Gallardo-Medina et al. [11] developed the Visekriterijumska optimizacija I KOmpromisno Resenje (VIKOR) method which uses an aggregating function to represent the closeness to the ideal solution. They consider bandwidth, delay, delay jitter, error rate and price. Zhang [25] applied Simple Additive Weighting (SAW) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to search the best solution. SAW chooses the alternative network with the maximum score by adding the product of every candidate network normalized contribution of each metric and corresponding weight. TOPSIS chooses the alternative network which has the shortest geometric distance to the positive ideal solution and the longest geometric distance to the negative ideal solution. They consider bandwidth, Signal-to-Noise Ratio (SNR), price, battery and node mobility. Stevens-Navarro et al. [26] compared the performance of SAW, Multiplicative Exponent Weighting (MEW), TOPSIS and Grey Relational Analysis (GRA). Similar to SAW, MEW computes the overall score of every network as the weighted product of its all attribute values. GRA prefers the network with higher Grey Relational Coefficient (GRC) which describes the similarity between every candidate network and the best reference network.

The above research has considered various factors affecting the access network selection. For easy comparison, in Table 1, we summarize the features of some representative access network selection schemes we have reviewed and our proposed scheme. Although some research work provided the selection schemes with ABC supported, for example, Ref [19] considers the network environment where cellular and wireless local area networks (WLAN) are integrated, they are only suitable for special scenarios, and when the scenarios or requirements change, they cannot provide the best scheme any more.

We propose a flexible and generalized framework for the access network selection. As shown in Fig. 2, under this framework, the access networks collect QoS parameters, network load, price and cost, and mobile terminals collect moving speed, battery power, selection history, personal preference and budget. Then they respectively compute decision values and get network utility and user utility respectively. Finally, the target access network is selected.

In experiment analysis, to do performance comparison, we choose the following as the benchmarks: Ref [12] which integrates utility function and game theory, Ref [18] of which factors cover the four dimensions of our framework, Ref [21] which is flexible and of which factors cover the four dimensions of our framework except the fuzziness of QoS. Moreover, for the various factors are considered in the access network selection problem, Ref [11] which proposes an effective MADM scheme is compared. To be fair, we do comparison from the two levels, namely basic comparison and extended comparison. In the former, we compare the five different schemes directly, and in the latter, we compare these schemes by adjusting our flexible framework to consider the same factors as in other four schemes and modifying these four schemes to consider the same factors as in our generalized framework.

3 Models and Problem Formulation

Following the recommendations of ITU-T Y.1541 [27], six different types of applications are supported in this paper, as shown in Table 2. For each application type, four QoS parameters, namely bandwidth *bw*, delay *dl*, delay jitter *jt*, and error rate *er* are considered. The notations and terminologies used in this paper are defined in Table 3. For convenience, we use δ to represent *bw*, *dl*, *jt* and *er*, and θ to represent *dl*, *jt* and *er* respectively.

In this section, we first develop models for both access networks and mobile terminals, and then analyze network-related factors and user-related factors, followed by a flexible and generalized framework and its mathematical model.

3.1 Access Network Model

To fully exploit QoS, price of service and meet different user requirements, the service-level agreement (SLA) [28] is set between network providers and users. That is, each access network provides a specific service level for every type of supported application. Every service level has a corresponding price based on the network resource consumption and a QoS interval which is a subset of QoS requirement intervals of related applications.

When plenty of mobile terminals roam among heterogeneous wireless networks at the same time, the available bandwidth of access networks becomes so precious that different access control mechanisms should be executed. As shown in Table 3, there are three cases. If $AB_j > AB_j^h$, the available bandwidth of AN_j is sufficient so that new calls can be admitted freely. If $AB_j^l \le AB_j \le AB_j^h$, the available bandwidth starts to become rare and an access control mechanism based on load fitness should be executed. If $AB_j < AB_j^l$, the available bandwidth is not sufficient to accommodate new calls.

3.2 Mobile Terminal Model

An investigation report released by Apple Inc. showed that the top reason for buying an Android phone not an iPhone is that the customers wanted to stay with current wireless service providers which do not support iPhone [29]. Therefore, to represent the user's subjective preference, every mobile terminal records a preference sequence over network providers, which is from the most preferred to the least preferred. Moreover, considering the dynamics of the user preference, the specific application type is taken into account to reflect the user's current context.

Users usually prefer to selecting the networks which they have successfully accessed before. Therefore, every mobile terminal maintains a selection history table which records the historical information of MT_t

selecting each access network. Every item consists of AN_j, the number of successful accesses AN_j, the number of failed accesses AN_j, and the latest time of accessing AN_j.

Furthermore, for AP_i $(1 \le i \le 6)$, every terminal records corresponding weights and requirement intervals associated with four QoS parameters. The weights are calculated with Analytic Hierarchy Process (AHP) based on triangular fuzzy number [30]. AHP combines both the qualitative and quantitative analysis, determines the relative importance of every factor in hierarchy structure by pair-wise comparison, and calculates the total relative importance of every factor by comprehensive comparison. Triangular fuzzy number is used to deal with the uncertainty in comparison.

Now, we illustrate the models of access networks and mobile terminals with an example. We consider two users with different mobile terminals covered by two different networks. The detailed conditions of these two mobile terminals and two networks are shown in Table 4 and Table 5, respectively. Referring to [27], the corresponding QoS requirement intervals of different applications are shown in Table 6. For the application running on every mobile terminal, four service levels are provided by access networks and the QoS parameter intervals at different levels are shown in Table 7.

3.3 Network-related Factors

The QoS satisfaction $SQ_j^{i_k}$ of the service policy $policy_j^{i_k}$ is represented as the product of evaluation coefficient $R_j^{i_k}$ and total QoS evaluation value $CQ_j^{i_k}$. $R_j^{i_k}$ represents the closeness between AN_j and the ideal solution (which is composed of the best evaluation value of the involved parameters) and is calculated by TOPSIS method [25] which ranks candidate networks based on their distances to the ideal solution and the negative ideal solution (which is composed of the worst evaluation value of the involved parameters).The calculation is as follows:

$$R_j^{i_k}=\mathrm{e}^{-\left(\sqrt{(Ebw_j^{i_k}-Ebw_{IS})^2+(Edl_j^{i_k}-Edl_{IS})^2+(Ejt_j^{i_k}-Ejt_{IS})^2+(Eer_j^{i_k}-Eer_{IS})^2}+\frac{1}{\sqrt{(Ebw_j^{i_k}-Ebw_{NIS})^2+(Edl_j^{i_k}-Edl_{NIS})^2+(Ejt_j^{i_k}-Ejt_{NIS})^2+(Eer_j^{i_k}-Eer_{NIS})^2}}\right)} \tag{1}$$

$$Ebw_j^{i_k} = w_{bw}{}^i \times (\frac{1}{2} \times e^{\frac{bw\_l_j^{i_k}-bw\_h_j^{i_k}}{bw^h-bw^l}} + \frac{1}{2} \times e^{\frac{\frac{bw\_l_j^{i_k}+bw\_h_j^{i_k}}{2}-bw^h}{bw_{IS}}}) \tag{2}$$

$$E\theta_j^{i_k} = w_\theta{}^i \times (\frac{e^{\frac{\theta\_l_j^{i_k}-\theta\_h_j^{i_k}}{\theta^h-\theta^l}}}{2} + \frac{e^{\frac{\theta^l-\frac{\theta\_l_j^{i_k}+\theta\_h_j^{i_k}}{2}}{\theta_{NIS}}}}{2}) \tag{3}$$

Obviously, the smaller the distance between AN_j and the ideal solution is, or the bigger the distance between it and the negative ideal solution is, the better is $R_j^{i_k}$.

The total QoS evaluation value of the service policy $policy_j^{i_k}$ is calculated as follows:

$$CQ_j^{i_k} = w_{bw}{}^i \times CB_j^{i_k} + w_{dl}{}^i \times CD_j^{i_k} + w_{jt}{}^i \times CJ_j^{i_k} + w_{er}{}^i \times CE_j^{i_k} \tag{4}$$

$$C\delta_j^{i_k} = \frac{1}{2} EI_\delta(\delta\_l_j^{i_k}, \delta\_h_j^{i_k}) + \frac{1}{2} Fit_\delta(\frac{\delta\_l_j^{i_k} + \delta\_h_j^{i_k}}{2}) \tag{5}$$

where $EI_{\delta}(\delta\_l_j^{i_k},\delta\_h_j^{i_k})$ is the evaluation of $[\delta\_l_j^{i_k},\delta\_h_j^{i_k}]$ and increases with the decrease of interval range, and $Fit_{\delta}(x)$ is the evaluation of the fitness of δ to the user requirements. When δ takes bandwidth, $Fit_{\delta}(x)$ increases with the decrease of distance between bandwidth and the upper bound of user requirement. When δ takes θ, $Fit_{\theta}(x)$ increase with the decrease of the distance between θ and the lower bound of requirements. As shown in Fig. 3, $EI_{\delta}(\delta\_l_j^{i_k},\delta\_h_j^{i_k})$, $Fit_{bw}(x)$, and $Fit_{\theta}(x)$ are defined in Eqs. (6), (7) and (8) respectively.

$$EI_{\delta}(\delta\_l_j^{i_k},\delta\_h_j^{i_k}) = 1-\left(\frac{\delta\_h_j^{i_k}-\delta\_l_j^{i_k}}{\delta_i^h-\delta_i^l}\right)^2 \tag{6}$$

$$Fit_{bw}(x)=\begin{cases}\dfrac{2(x-BW_i^l)^2}{(BW_i^h-BW_i^l)^2}, & BW_i^l \le x \le \dfrac{BW_i^l+BW_i^h}{2}\\ 1-\dfrac{2(BW_i^h-x)^2}{(BW_i^h-BW_i^l)^2}, & \dfrac{BW_i^l+BW_i^h}{2} < x \le BW_i^h\end{cases} \tag{7}$$

$$Fit_{\theta}(x)=\begin{cases}1-\dfrac{2(x-\theta_i^l)^2}{(\theta_i^h-\theta_i^l)^2}, & \theta_i^l \le x \le \dfrac{\theta_i^l+\theta_i^h}{2}\\ \dfrac{2(\theta_i^h-x)^2}{(\theta_i^h-\theta_i^l)^2}, & \dfrac{\theta_i^l+\theta_i^h}{2} < x \le \theta_i^h\end{cases} \tag{8}$$

It is worth noting that, if $ER_i^l = ER_i^h = 0$ and $er\_l_j^{i_k} = er\_h_j^{i_k} = 0$, $CE_j^{i_k}$ takes 1; if $ER_i^l = ER_i^h = 0$ and $er\_l_j^{i_k} \ne er\_h_j^{i_k} \ne 0$, $CE_j^{i_k}$ takes 0; otherwise, $CE_j^{i_k}$ takes Eq. (5).

When multiple mobile terminals are roaming among multiple access networks, the network load is an important factor to avoid the situation where too many terminals select the same access network. As shown in Fig. 4(a), the load evaluation function $SL_{t,j}$ of MT_t in AN_j is defined as follows:

$$SL_{t,j}=\begin{cases}1, & AB_j > AB_j^h\\ e^{\frac{\eta_j^l - x_j^u}{2}}, & AB_j^l \le AB_j \le AB_j^h\\ 0, & AB_j < AB_j^l\end{cases} \tag{9}$$

where $x_j^u = (TB_j - AB_j)/TB_j$ represents the current load of AN_j, $\eta_j^l = (TB_j - AB_j^h)/TB_j$ represents the load when $AB_j = AB_j^h$, $\eta_j^h = (TB_j - AB_j^l)/TB_j$ represents the load when $AB_j = AB_j^l$.

As mentioned earlier, the price is an important factor in network selection. As shown in Fig. 4(b), the price satisfaction function $SP_{t,j}^{i_k}$ of MT_t to $policy_j^{i_k}$ is defined as follows:

$$SP_{t,j}^{i_k}=\begin{cases}0, & pr_j^{i_k} > HP_t^i\\ 1-\dfrac{1}{2}\times\dfrac{pr_j^{i_k}}{HP_t^i}, & 0 \le pr_j^{i_k} \le HP_t^i\end{cases} \tag{10}$$

When the price is higher than the budget, $SP_{t,j}^{i_k}$ is set as 0. When it is lower than the budget, $SP_{t,j}^{i_k}$

increases with the decrease of price. If the service is free, $SP^{i_k}_{t,j}$ is set as 1.

Based on the example introduced in Section 3.2, we assume that MT_2 running AT_2 chooses AN_1 at service level 3, which means that w^2_{bw}=0.32, w^2_{dl}=0.32, w^2_{jt}=0.23, w^2_{er}=0.13, and $CB^{2_3}_1$=0.7525, $CD^{2_3}_1$ =0.82, $CJ^{2_3}_1$=0.8725, and $CE^{2_3}_1$=1.0. Then we get $R^{2_3}_1$=0.8798, $CQ^{2_3}_1$=0.8339, and $SQ^{2_3}_1$=0.7337. Meanwhile, $x^u_1=(TB_1-AB_1)/TB_1$=0.92 and $\eta^l_1=(TB_1-AB^h_1)/TB_1$=0.9, imply $AB^l_1 < AB_1 < AB^h_1$, and $SL_{2,1}$=0.9901; $pr^{2_3}_1$=0.24, HP^2_2=0.3, and $SP^{2_3}_1$=0.6.

3.4 User-related Factors

To cope with user preferences, we calculate preference satisfaction. As shown in Fig. 4(c), the preference satisfaction function $SR^i_{t,j}$ of MT_t running application type AT_i in PI_j is defined as follows:

$$SR^i_{t,j}=\begin{cases}(\frac{|PSR^i_t|+1-xr^i_{t,j}}{|PSR^i_t|})^2, & PI_j\in PSR^i_t\\ 0, & otherwise\end{cases} \tag{11}$$

If $xr^i_{t,j}$ is 1, that means PI_j is the most preferred to the user with MT_t and running application type AT_i, then $SR^i_{t,j}$ is 1. Note that $SR^i_{t,j}$ increases with the decrease of $xr^i_{t,j}$.

The access network selection depends on the specific situation which the user is in. For example, for users in high speed movement, access networks with larger coverage radius would yield longer residence time and smaller number of re-selections caused by handover. As shown in Fig. 4(d), the movement fitness function $SV_{t,j}$ of MT_t in AN_j is defined as follows:

$$SV_{t,j}=\begin{cases}1, & (CV_t<CV^{th}_t)\wedge(CV_t<MV_j)\\ \frac{|PSV_t|+1-xv_{t,j}}{|PSV_t|}, & CV^{th}_t\le CV_t\le MV_j\\ 0, & otherwise\end{cases} \tag{12}$$

A smaller $xv_{t,j}$ means a larger CR_j and a larger $SV_{t,j}$.

For users with low available battery power, on the other hand, access networks with smaller coverage radius would be more appropriate to achieve longer life time. As shown in Fig. 4(e), the battery power fitness function $SY_{t,j}$ of MT_t in AN_j is defined as follows:

$$SY_{t,j}=\begin{cases}\frac{|PSY_t|+1-xy_{t,j}}{|PSY_t|}, & RC_t\le RC^{th}_t\\ 1, & otherwise\end{cases} \tag{13}$$

A smaller $xy_{t,j}$ means a smaller CR_j and a larger $SY_{t,j}$.

Based on the example in Section3.2, we assume that MT_2 running AT_2 chooses AN_1 and the service level 3, it means that $xr^2_{2,1}$=1, $|PSR^2_2|$=2, and $SR^2_{2,1}$=1; $(CV_2<CV^{th}_2)\wedge(CV_2<MV_1)$, and $SV_{2,1}$=1; $x^y_{2,1}$=1,

$|PSY_2|=2$, and $SY_{2,1}=1$.

3.5 Gaming

We introduce gaming [31] into the access network selection problem, and the mobile terminal and the access network are two players in the gaming scenarios. The mobile terminal has two game strategies, that is, accessing the network (a_1) or not (a_2), whilst the access network also has two game strategies, that is, admitting the terminal (b_1) or not (b_2).Therefore, the gain matrices of MT_t and AN_j are defined as in Eqs. (14) and (15) respectively.

$$TG=\begin{bmatrix} HP_t^i-pr_j^{i_k} & 0 \\ -v\times(HP_t^i-pr_j^{i_k}) & 0 \end{bmatrix} \tag{14}$$

$$NG=\begin{bmatrix} pr_j^{i_k}-ct_j^{i_k} & -v\times(pr_j^{i_k}-ct_j^{i_k}) \\ 0 & 0 \end{bmatrix} \tag{15}$$

The row and column in the above matrices represent strategies of MT_t and AN_j respectively. If MT_t accesses $AN_j(a_1)$ and AN_j admits $MT_t(b_1)$, the gain of MT_t is $HP_t^i-pr_j^{i_k}$ which is the user revenue; the gain of AN_j is $pr_j^{i_k}-ct_j^{i_k}$ which is the network provider revenue. If MT_t does not access $AN_j(a_2)$, but AN_j admits $MT_t(b_1)$, the gain of MT_t is $-v\times(HP_t^i-pr_j^{i_k})$, where "-$v$" is a penalty factor denoting the negative effect on MT_t in future for rejecting access AN_j which admits it; the gain of AN_j is 0 which represents no gain for MT_t rejecting to access it. Similarly, if MT_t accesses $AN_j(a_1)$ but AN_j does not admit $MT_t(b_2)$, the gain of MT_t is 0 representing no gain for AN_j rejecting to admit it; the gain of AN_j is $-v\times(pr_j^{i_k}-ct_j^{i_k})$, where "-$v$" is similar to that in TG. If MT_t does not access $AN_j(a_2)$ and AN_j does not admit $MT_t(b_2)$; the gains are 0 for both of them for their non-cooperation.

If the strategy pairs (a_{c^*},b_{d^*}) (c, d=1, 2) satisfy Eqs. (16) - (17), it makes MT_t and AN_j achieve the Nash equilibrium. The corresponding service policy is thus win-win to both the user and the network provider.

$$TG_{c^*,d^*}\geq TG_{c,d^*} \tag{16}$$

$$NG_{c^*,d^*}\geq NG_{c^*,d} \tag{17}$$

3.6 Flexible and Generalized Framework

Based on the above analysis, to achieve "the best", we integrate these factors into a utility function. Therefore, to both MT_t and AN_j for AT_i at service level k, the user utility and network utility are defined as follows:

$$uu_{t,j}^{i_k} = \Omega_{t,j} \times \Phi_{t,j} \times (w_{SQ} \times SQ_j^{i_k} + w_{SL} \times SL_{t,j} + w_{SP} \times SP_{t,j}^{i_k} + w_{SR} \times SR_{t,j} + w_{SV} \times SV_{t,j} + w_{SY} \times SY_{t,j}) \times \frac{HP_t^i - pr_j^{i_k}}{HP_t^i} \quad (18)$$

$$nu_{t,j}^{i_k} = \Omega_{t,j} \times \Phi_{t,j} \times (w_{SQ} \times SQ_j^{i_k} + w_{SL} \times SL_{t,j} + w_{SP} \times SP_{t,j}^{i_k} + w_{SR} \times SR_{t,j} + w_{SV} \times SV_{t,j} + w_{SY} \times SY_{t,j}) \times \frac{pr_j^{i_k} - ct_j^{i_k}}{pr_j^{i_k}} \quad (19)$$

where w_{SQ}, w_{SL}, w_{SP}, w_{SR}, w_{SV}, and w_{SY} are the weights associated with QoS satisfaction, load evaluation, price satisfaction, preference satisfaction over network providers, movement fitness, and battery power fitness in the proposed framework respectively. They are calculated with AHP based on triangular fuzzy number as the weightings of QoS parameters in section 3.2. Moreover, w_{SQ}, w_{SL}, w_{SP}, w_{SR}, w_{SV}, $w_{SY} > 0$, $w_{SQ}+w_{SL}+w_{SP}+w_{SR}+w_{SV}+w_{SY}=1$. $\Omega_{t,j}$ is the gaming factor which is 1 only when this is a Nash equilibrium solution for MT_t and AN_j; otherwise it is a pure decimal. $\Phi_{t,j}$ is the selection history factor which is represented as the historical selection success ratio of MT_t in AN_j.

More importantly, the framework is flexible and generalized for the access network selection, since it contains the above comprehensive factors and works in common circumstance, and it can adapt to any special circumstance by setting the corresponding weights as zero to ignore other factors. Furthermore, the weights can be set properly to reflect the importance of different factors. For example, a user with very low available battery power would set priority on the battery power, and pay attention on some other factors, such as QoS parameter, price and load. The influence of preference satisfaction and movement fitness may be negligible. Thus we can correspondingly set w_{SR} and w_{SV} as 0, and set w_{SY}, w_{SQ}, w_{Sp}, w_{SL} non-zero values properly.

Recalling the example in Section3.2, we assume that $\Phi_{2,1}=1$. They achieve the Nash equilibrium when they accept the other. The weights for six factors are set as 0.1667 for simplicity. Thus, $uu_{2,1}^{2_3}=0.1775$, and $nu_{2,1}^{2_3}=0.2218$.

3.7 Mathematical Model for Access Network Selection

In this paper, we study N mobile terminals performing network selection among M access networks. The objective is to make the utilities of all members achieve or approach Nash equilibrium. Not only should the utilities of every terminal and every network be maximized, but also the utilities of all terminals and all networks should be maximized, formulated as follows:

$$\text{Maximize } \{uu_{t,j}^{i_k}\} \quad (20)$$

$$\text{Maximize } \{nu_{t,j}^{i_k}\} \quad (21)$$

$$\text{Maximize } \{\sum_{t=1}^{N}\sum_{j=1}^{M} uu_{t,j}^{i_k}\} \quad (22)$$

$$\text{Maximize } \{\sum_{t=1}^{N}\sum_{j=1}^{M} nu_{t,j}^{i_k}\} \quad (23)$$

$$\text{Maximize } \{\sum_{t=1}^{N}\sum_{j=1}^{M} (uu_{t,j}^{i_k} + nu_{t,j}^{i_k})\} \quad (24)$$

$$\text{s.t. } TAS_t \subseteq NAS_j \quad (25)$$

$$MCS_t \cap CS_j \neq \Phi \tag{26}$$

$$pr_j^{i_k} \leq HP_t^i \tag{27}$$

$$WF_t \in FR_j \tag{28}$$

$$CV_t \leq MV_j \tag{29}$$

$$RS_t \leq TP_j \tag{30}$$

$$AB_j - bw\_h_j^{i_k} \geq AB_j^l \tag{31}$$

Constraints (25) - (31) guarantee that the feasibility of MT_t accessing AN_j for AT_i at service level k. Specifically they mean that the set of network application types of MT_t need be supported by AN_j, the coding scheme set of MT_t need be compatible with the coding scheme set supported by AN_j, the price of $policy_j^{i_k}$ need be accepted by MT_t, the working frequency of MT_t need belong to the range of AN_j, the moving speed of MT_t need be supported by AN_j, the signal of AN_j need be received by MT_t, and AN_j need admit new calls after allocating the highest required bandwidth for MT_t respectively.

Obviously, it is a fuzzy multi-objective optimization problem for ($1 \leq t \leq N$, $1 \leq j \leq M$, $1 \leq i \leq 6$, $1 \leq k \leq |SL|$). Recalling the example in Section3.2, we need plenty of calculation even if there are only two users and two networks. Therefore, we should apply a heuristic or intelligent algorithm.

4 Algorithm Description

In this section, we first introduce Quantum-inspired Immune Clonal Algorithm (QICA). Then we present the solution representation, objective function and the ways to calculate the feasible solution, and we finally design an access network selection scheme based on QICA.

4.1 Introduction to QICA

QICA combines quantum coding scheme and immune clone algorithm which achieves optimization by antibody clone and mutation. QICA constructs antibodies with additivity of quantum coding to make operation on antibodies concurrent, controls mutation with the information from the best current antibody to evolve population to accelerate convergence, and executes crossover operation to improve the search efficiency. QICA achieves natural balance between exploration and exploitation, thus resulting in excellent and stable performance. It enables QICA to be the basis of the proposed access network selection scheme and solve the fuzzy multi-objective optimization problem in Section 3.7.

The main operators in QICA include clone, immune gene, and clone selection operation. The clone operation is used to expand the population size. The immune gene operation contains quantum mutation operation and quantum recombination operation, the former contains quantum rotation gate which applies the dynamic adjusting angle to accelerate convergence and quantum NOT gate which could avoid premature convergence, and the latter realizes the information communication between subpopulation to improve the search efficiency. The clone selection operation reserves the high quality antibody in population. The basic procedure of QICA is shown in Fig 5.

4.2 Solution Representation and Initiation

In the QICA based network selection scheme, every antibody is a candidate solution. QICA contains integer coding and qubit coding. For ease of understanding, we comparatively give the notations in the two coding patterns as described in Table 8. In integer coding, $x^q_{g,t} =< AN^q_{g,t}, sl^q_{g,t} >$ (1≤t≤N) represents MT_t accessing $AN^q_{g,t}$ for service level $sl^q_{g,t}$, where $AN^q_{g,t}$ is an integer between 0 and M-1, and $sl^q_{g,t}$ is an integer between 0 and |SL|-1. In qubit coding, each antibody consists of N groups and each group consists of two qubits, that is, $y^q_{g,t} = \begin{bmatrix} \alpha^{AN}_{g,q,t} & \alpha^{sl}_{g,q,t} \\ \beta^{AN}_{g,q,t} & \beta^{sl}_{g,q,t} \end{bmatrix}$, corresponding to $AN^q_{g,t}$ and $sl^q_{g,t}$ respectively. For $\begin{bmatrix} \alpha^{AN}_{g,q,t} \\ \beta^{AN}_{g,q,t} \end{bmatrix}$, $|0\rangle$ represents 1 and $|1\rangle$ represents M. For $\begin{bmatrix} \alpha^{sl}_{g,q,t} \\ \beta^{sl}_{g,q,t} \end{bmatrix}$, $|0\rangle$ represents 1 and $|1\rangle$ represents $|SL|$.

We can derive an integer coding antibody by mapping the corresponding qubit coding antibody as follows:

$$AN^q_{g,t} = \lfloor |\alpha^{AN}_{g,q,t}|^2 \cdot 1 + |\beta^{AN}_{g,q,t}|^2 \cdot M \rfloor - 1 \tag{32}$$

$$sl^q_{g,t} = \lfloor |\alpha^{sl}_{g,q,t}|^2 \cdot 1 + |\beta^{sl}_{g,q,t}|^2 \cdot |SL| \rfloor - 1 \tag{33}$$

To each dimension (that is, the network selection of each terminal) of each antibody in qubit coding population Y_1, we initialize with the generated random values, then generate corresponding dimension of each antibody in integer coding population X_1 by the mapping operation.

4.3 Feasible Solution and Objective Function

A selection scheme denoted by $x^q_{g,t} =< AN^q_{g,t}, sl^q_{g,t} >$ is feasible only when the Constraints (25) - (31) satisfied. The solution denoted by antibody x^q_g is feasible only when all $x^q_{g,t}$ (1≤t≤N) are feasible.

The objective function of the solution denoted by antibody x^q_g is defined as follows:

$$Minimize \quad f(x^q_g) = \begin{cases} \sum_{t=1}^{N} \left(\frac{1}{uu^{i_{sl^q_{g,t}}}_{t, AN^q_{g,t}}} + \frac{1}{nu^{i_{sl^q_{g,t}}}_{t, AN^q_{g,t}}} \right), & \textit{feasible solution} \\ +\infty, & \textit{otherwise} \end{cases} \tag{34}$$

The affinity of antibody $D(x)$ is equal to the negative value of the objective function. Obviously, the bigger the network utility and user utility, the better the solution, at the same time the smaller the objective function value, the bigger the affinity value.

4.4 Main Operators

4.4.1 Clone Operation

The clone operation of population Y_g can be represented as follows:

$$\Theta(Y_g) = [\Theta(y_g^1), \Theta(y_g^2), ..., \Theta(y_g^S)]^T \tag{35}$$

where $\Theta(y_g^q) = I_q y_g^q$ ($1 \leqslant q \leqslant S$), and is given by

$$C_q = \left\lceil N_c * \frac{D(y_g^q)}{\sum_{q=1}^{S} D(y_g^q)} \right\rceil \tag{36}$$

The new population after the clone operation is given by $Y_g' = \{Y_g, y'^1_g, ..., y'^S_g\}$, where $y'^q_g = \{y^q_{g,2}, y^q_{g,2}, ..., y^q_{g,C_q}\}$, $y^q_{g,z} = y^q_g$ ($2 \leqslant z \leqslant C_q$). The clone operation generates C_q mirror images for antibody y_g^q.

4.4.2 Immune Gene Operation

The immune gene operation contains quantum mutation operation and quantum recombination operation, whilst quantum mutation operation contains quantum rotation gate and quantum NOT gate. The quantum rotation gate $U(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}$, where θ is defined as

$$\theta = 10 \cdot \exp(-C_q / N_c) \cdot f(\alpha', \beta') \tag{37}$$

where $f(\alpha', \beta')$ is calculated as in Table 9.

In Table 9, $d_1 = \alpha_1 * \beta_1$, $\omega_1 = \arctan(\beta_1 / \alpha_1)$, $d_2 = \alpha_2 * \beta_2$, $\omega_2 = \arctan(\beta_2 / \alpha_2)$, $f(\alpha', \beta')$ determines the search direction. The quantum rotation gate operation is executed as follows:

$$\begin{bmatrix} \alpha'' \\ \beta'' \end{bmatrix} = U(\theta) \cdot \begin{bmatrix} \alpha' \\ \beta' \end{bmatrix}. \tag{38}$$

Quantum NOT gate is used to realize quantum mutation and avoid premature convergences. It changes the probability of the 1 (or 0) state to that of the 0 (or 1) state with probability p_m.

To store the parent generation information, the quantum mutation operation is taken on y'^q_g ($1 \leqslant q \leqslant S$), and the new population after that is Y''_g.

In quantum recombination, we execute all interference crossover operation, i.e., randomly generating an integer v ($1 \leqslant v \leqslant N$) as the crossover point. Then, the vth qubit of every antibody remains unchanged, and other qubits of every antibody are given as follows:

$$y^q_{g+1,t} = by_{g,t}^{[(q+t-v)\%S]} (1 \le q \le S, 1 \le t \le N) \tag{39}$$

where by^q_g is the qth antibody in population BY_g, and $by^q_g = \{by^q_{g,1}, by^q_{g,2}, ..., by^q_{g,N}\}$.

4.4.3 Clone Selection Operation

We map population Y''_g with qubit coding to population X''_g with integer coding based on Eqs. (33) and (34). For X''_g, we choose antibody $b^q_g (1 \le q \le S)$ which satisfies $\max\{D(x''^q_g)\}$ and compare it with the corresponding x_g^q in its parent population X_g. If $D(b_g^q) > D(x_g^q)$, then b_g^q is taken as the qth antibody in population BX_g and the corresponding quantum coding antibody is recorded as the qth antibody in population BY_g. Otherwise, x_g^q is chosen as the qth antibody in population BX_g and the corresponding quantum coding antibody is recorded as the qth antibody in population BY_g.

4.5 Algorithm Procedure

The pseudo code of QICA based access network selection scheme is shown in Algorithm 1. Its inputs are S, N_c, p_m and G; its output is x_b.

Algorithm 1. QICA based access network selection algorithm

Input: S, N_c, p_m, G

Output: x_b

Initiate Y_1 with the generated random value and get the corresponding X_1 by the mapping operation, g=1;

  for each antibody $x_1^q \in X_1$ **do**

    if x_1^q is feasible **then**

      MT_t and $AN_{1,t}^q$ play gaming and update Ω;

    end if

  end for

  for each feasible antibody in X_1 **do**

    Calculate the affinity value $D(x)$;

  end for

Store the antibody with the maximum $D(x)$ ($x \in X_1$) in x_b;

Do mapping operation on x_b to get the corresponding quantum coding antibody and store it in y_b;

while $g \le G$ **do**

  Do clone operation on Y_g to generate new population Y_g';

  Do quantum rotation gate and quantum NOT gate on Y_g' to generate new population Y_g'' based on p_m;

  Do mapping operation on every antibody in Y_g and Y_g'' to generate the corresponding antibody in X_g and X_g'';

  Do clone selection operation on X_g and X_g'' to generate integer coding population BX_g and the corresponding quantum coding population BY_g;

  if the maximum $D(bx_g^q) \ge D(x_b)$ ($bx_g^q \in BX_g$) **then**

    Update x_b with bx_g^q;

    Do mapping operation on bx_g^q to get the corresponding quantum coding antibody by_g^q;

    Update y_b with by_g^q;

  end if

  Do quantum recombination operation on BY_g to get Y_{g+1};

end while

return x_b

Line 1 is to generate the initial solution. Lines 2-6 are to determine the feasibility of every antibody in the initial solution. Lines 7-11 are to choose the best antibody based on affinity value. Lines 12-23 are to optimize based on QICA. Line 24 is to output the best solution.

Recall the example in Section 3.2, for the initial solution X_1, the antibody $x_1^q=\{x_{1,1}^q, x_{1,2}^q\}$ represents a selection scheme of two mobile terminals among two access networks, and $x_{1,t}^q = < AN_{1,t}^q, sl_{1,t}^q >$ $(1 \leqslant t \leqslant 2)$ represents MT_t accessing $AN_{1,t}^q$ for the service level $sl_{1,t}^q$. After determining the feasibility, we calculate the affinity value of every antibody and choose the antibody with maximum affinity to store in x_b. Then we carry out iterative optimization through clone operation, quantum mutation operation (quantum rotation gate and quantum NOT gate), clone selection and quantum recombination operation. The time complexity of is $O(S^*(N+G))$. When M and N are big, appropriate G and S makes it much better than $O(M^N)$.

5 Performance Evaluations

To demonstrate the feasibility and effectiveness of our proposed scheme, we have implemented it using NS2 simulator [32] and compared it with the other four popular methods, namely VIKOR [11], UGT [12], MANS [18], and MCAS [21].

5.1 Experiment Settings

The network topology used in the experiments are fully covered hexagon cellular topologies with different number of nodes as shown in Fig. 6. If an area is covered by different networks, the mobile users can choose an access network freely. These access networks belong to different network service providers and each one can only belong to one provider.

To simulate user behavior in real-world networks, we set 30% users in low available battery power status, i.e., the available battery power is lower than 25%, whilst the other users are in normal battery power status implying the available battery power is higher than 25%. Based on the measurement provided by various traffic tools and referring to the report provided by Chinese transport department, the distribution of moving speed is shown in Table 10. Moreover, based on the statistics of telecom providers in China, the percentage of users in three network providers are as shown in Table 11. To show the performance, we investigate utility metrics of users and networks, QoS satisfaction, price satisfaction, preference satisfaction over network providers, movement fitness, battery power fitness and running time.

5.2 Experimental Results and Analysis

In order to provide the fairness of performance comparison, we firstly run experiments different times with the same random function seed. The result of 1000 times experiments is shown in Fig. 7. The results show a convergence trend as the times of experiments increase, although there are some results which have larger standard deviation. We find that the difference between the average values of 500 and 1000 times experiments is very small and its impact on the comparison among different algorithms is negligible. Moreover, the time consumed by 500 times experiments is much less than that consumed by 1000 times. Therefore, we run experiments 500 times for different numbers of users, and get the average value.

5.2.1 Basic Comparison

Fig. 8 shows the utility with increasing number of users. As the number of users increases, the network resource becomes scarcer and scarcer, the user requirements cannot be fully satisfied, hence the utility decreases. QICA and MANS achieve better average utility than VIKOR, UGT, and MCAS. The reason is that the former two schemes consider more factors than the latter three schemes. MCAS gets the lowest average utility for considering energy consumption, data rate, and load and so on. As a matter of fact, they all involve bandwidth and MCAS considers less factors than other schemes.

Fig. 9 shows QoS, price and preference satisfaction as functions of the number of users respectively. In Fig. 9(a), the UGT scheme exhibits the highest QoS satisfaction, the MCAS scheme exhibits the second satisfaction, the MANS method gets the least, and the QICA and VIKOR method get the middle one. While in Fig. 9(b), the contrary is the case. The reason is that the UGT scheme considers QoS not price, MCAS scheme considers bandwidth from several different factors, and thus UGT and MCAS prefer to choose those good service schemes with high prices, MANS only considers bandwidth in QoS factors, while VIKOR and QICA method consider both QoS and price, and they balance QoS satisfaction and price satisfaction in network selection respectively, for example QICA balances them in pursuing the maximum total utilities. As the number of users increases, they will compete for limited resources. Therefore, the QoS satisfaction of these schemes decreases. Fig. 9(c) shows the preference satisfaction as a function of the number of users. VIKOR, UGT, MANS and MCAS schemes do not take user preference over the network providers into consideration, so their preference satisfactions are less than the QICA scheme which considers directly. As the number of users increases, the resource becomes scarcer and scarcer, the preference satisfaction also decreases.

Fig. 10(a) shows the movement fitness with increasing number of users. It reflects the fitness degree of access networks to the mobile terminals under different moving speed. Clearly, QICA scheme shows the best results for considering directly. MCAS scheme gets the least performance for considering multiple factors involving bandwidth, the other three schemes get the middle results. As the number of users increases, the fitness decreases gradually. Fig. 10(b) depicts battery power fitness which reflects the fitness degree of access networks to the mobile terminals under different battery power capacity. Again QICA and MCAS show the best and the least results respectively.

Fig. 11 demonstrates that QICA based scheme has the longest running time. In this scheme, every antibody clones before it mutates, hence more solutions are searched in the same number of iterations, leading to a better solution. Results from the above experiments also prove that the performance of QICA is better than the other four schemes. However, with increased population size, more space and computation time are required in each of the iterations.

5.2.2 Extended Comparison

As a generalized framework, we consider more factors than other schemes do. However, for fair comparison, we adjust this flexible framework to consider the same factors as in UGT. Fig. 12 shows the QoS satisfaction and price satisfaction with varying number of users. Due to not all factors being considered, especially the price, N-QICA (New QICA) can select a good service and get a better QoS satisfaction than QICA does. The reason of the performance of N-QICA is slightly lower than UGT is that UGT gives more weights on QoS evaluation functions. Similarly, N-QICA gets a lower price satisfaction than QICA, and a higher one than

UGT.

We further modify VIKOR, UGT, MANS, and MCAS to consider the same factors as in QICA. For those factors not considered by these four schemes, we use the same calculation methods as in QICA. Fig. 13(a) shows the QoS satisfaction of users with varying number of users. The adding of factors reduces the performance of N-VIKOR (New VIKOR) and N-UGT (New UGT), and they are slightly lower than VIKOR and UGT which pay main attention on QoS respectively. While the performance of N-MANS (New MANS) and N-MCAS (New MCAS) are slightly higher than MANS and MCAS respectively, and the reason is that N-MANS and N-MCAS consider delay, delay jitter and error rate on the basis of MANS and MCAS which consider bandwidth. Similarly, Fig. 13(b) shows the price satisfaction of users with varying number of users. The performance of N-UGT is much better than UGT for considering price, and that of N-VIKOR is slightly lower than VIKOR for considering more factors. The performance of N-MCAS and MCAS are similar for they both consider price factor. As a comprehensive framework, QICA gets a better result and balances the relationship between QoS and price. We could get better performance on some factors by increasing their corresponding weights, at the expense of decreasing the performances on other factors.

6 Conclusions

In this work, we propose a flexible and generalized framework for the access network selection problem in heterogeneous wireless networks. This framework covers comprehensive factors coming from different viewpoints and dimensions, i.e., network-related or user-related, economic or non-economic, objective or subjective, and accurate or fuzzy. Therefore, this framework is generalized and can select the best access network in common circumstance. Meanwhile, these factors can be adapted based on specific requirements, which makes this framework flexible in providing special solutions. Moreover, appropriate models for access networks and mobile terminals are designed under this framework. Based on the game theory and Nash equilibrium, user utility and network utility are devised to reach win-win situations. We also design an intelligent selection scheme based on QICA to find optimal solutions. Simulation results demonstrate that, at the cost of higher running time, our proposed scheme provides better utilities for both users and access networks, better QoS and price satisfaction, and better preference satisfaction over network providers. For users in high speed motion and with low available battery power, the scheme also gives high fitness.

With the development of perceptibility and access technology, some new environments, such as 5G and Internet of Things (IoT), have emerged. As a matter of fact, any network selection scheme cannot cover all factors and be applied in all environments directly. However, based on the above analysis from the four different dimensions, on one hand, some new factors or old factors with new characteristics, for example, users and QoS levels which are not clearly defined in IoT, are still in the category of these four dimensions. In our proposed framework, we have analyzed the accurately described factors and the intrinsically uncertain and dynamic factors from the decision-making viewpoint, and those factors newly generated in the new environments can be easily integrated into our framework by computing appropriate decision values. On the other hand, since ABC is the first priority for both the access networks and the mobile terminals in network selection problem, some novel access schemes, for example, the licensed (unlicensed) spectrum by a primary (legal) or secondary (opportunistic) users in 5G are easily integrated into our proposed framework by modeling both the access networks and the mobile terminals with appropriate parameters respectively. Therefore, our proposed scheme can be flexibly applicable to newly emerged environments by modeling appropriately, collecting data, calculating decision value, calculating network utility and user utility, and making network selection decision as shown in Fig. 2.

We plan to carry out our future work from the following three directions. One is to model access networks and mobile terminals properly, and adapt factors to our generalized and flexible framework to produce special solutions for actual environments. The second is to use some other intelligence algorithms, for example ant colony optimization, to solve this problem. Exploration and exploitation are two important characteristics in intelligence algorithms. Some algorithms are good at finding a feasible solution with shorter time, and the others are skilled in local search ability. They have different significances in access network selection problem. To maturate our framework, we will conduct extensive analysis and experiments to compare these network selection schemes based on different intelligence algorithms to see if further performance improvements can be achieved. The third is to implement our proposed scheme in a prototype system. We plan to deploy it in the campus heterogeneous wireless networking environments with WiFi, 2G, 3G, 4G and even China Mobile 5G experimental test bed integrated in Northeastern University of China to provide services to faculties and students in order to make it practical and enhance its performance.

Acknowledgements

This work is supported by the National Science Foundation for Distinguished Young Scholars of China under Grant No. 61225012 and No. 71325002; the National Natural Science Foundation of China under Grant No. 61572123.

References

[1] http://www.gsacom.com/gsm_3g/info_papers.php 2016-7-17
[2] http://www.askci.com/news/chanye/20160521/16250718858.shtml 2016-7-17
[3] Measuring the information society report 2015
http://www.itu.int/en/ITU-D/Statistics/Documents/publications/misr2015/MISR2015-w5.pdf, 2016-07-17
[4] http://www.cnnic.org.cn/hlwfzyj/hlwxzbg/201601/P020160122469130059846.pdf, 2016-7-17
[5] E. Gustafsson, and A. Jonsson, "Always best connected," *IEEE Wireless Communications*, vol. 10, no. 1, pp. 49-55, Feb. 2003.
[6] M. Zekri, M. Hadji, B. Jouaber, and D. Zeghlache, "A nash stackelberg approach for network pricing, revenue maximization and vertical handover decision making," *Proc. IEEE 36th Conf. on Local Computer Networks* (*LCN*), pp. 622-629, Oct. 2011.
[7] E. H. Ong, and J. Y. Khan, "Dynamic access network selection with QoS parameters estimation: a step closer to ABC," *Proc. IEEE Vehicular Technology Conf.* (*VTC*), pp. 2671-2676, May 2008.
[8] W. Kim, B. J. Lee, J. S. Song, Y. S. Shin, and Y. J. Kim, "Ping-pong avoidance algorithm for vertical handover in wireless overlay networks," *Proc IEEE Vehicular Technology Conf.* (*VTC*), pp. 1509-1512, Oct. 2007.
[9] L. Wang, and G.S. Kuo, "Mathematical modeling for network selection in heterogeneous wireless networks – a tutorial," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 1, pp. 271-292, Jan. 2013.
[10] L. Jiao, Y. Li, M. Gong, and X. Zhang, "Quantum-inspired immune clonal algorithm for global optimization," *IEEE Trans. on System, Man, and Cybernetics, Part B,* vol. 38, no. 5, pp. 1234-1253, Oct 2008.
[11] J.R. Gallardo-Medina, U. Pineda-Rico, and E. Stevens-Navarro, "VIKOR method for vertical handoff decision in beyond 3Gwireless networks," *Proc. Sixth Int'l Conf. on Electrical Engineering, Computing Science and Automatic Control*(*CCE*), pp. 1-5, Jan. 2009.
[12] C. Chang, T. Tsai, and Y. Chen, "Utility and game-theory based network selection scheme in heterogeneous wireless networks," *Proc. IEEE Wireless Communications and Networking Conf.* (*WCNC*), pp. 1-5, Apr. 2009.
[13] X. Yan, Y. A. Sekercioglu, and S. Narayanan, "A survey of vertical handover decision algorithms in fourth generation heterogeneous wireless networks," *Computer Networks*, vol. 54, no. 11, pp. 1848-1863, Aug. 2010.
[14] M. Corici, J. Fiedler, T. Magedanz, and D. Vingarzan, "Access network discovery and selection in the future

wireless communication," *Mobile Networks and Applications*, vol. 16, no. 3, pp. 337-349, Jun. 2011.
[15] J. McNair, and Z. Fang, "Vertical handoffs in fourth-generation multi-network environments," IEEE Wireless Communications, vol. 11, no. 3, pp. 8-15, Jun. 2004.
[16] W. Chen, and Y. Shu, "Active application oriented vertical handoff in next-generation wireless networks," *Proc. IEEE Wireless Communications and Networking Conf.* (*WCNC*), pp. 1383-1388, Mar. 2005.
[17] A. Ahmed, L. M. Boulahia, and D. Gaiti, "Enabling vertical handover decisions in heterogeneous wireless networks: a state-of-the-art and a classification," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 2, pp. 776-811, May 2013.
[18] A. Sehgal, and R. Agrawal, "QoS based network selection scheme for 4G systems," *IEEE Transactions on Consumer Electronics*, vol. 56, no. 2, pp. 560-565, May 2010.
[19] Y. Meng, J. Li, H. Li, and P. Zhang, "An adaptive network selection scheme based on the combination of user mobility and traffic load," *Proc. 32rd International Symposium on Personal, Indoor and Mobile Radio Communications* (*PIMRC*), pp. 1491-1496, Sept. 2012.
[20] W. Shen, and Q. Zeng, "Cost-function based network selection strategy in integrated wireless and mobile networks," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 6, pp. 3778-3788, Nov. 2008.
[21] Q. Nguyen-Vuong,N. Agoulmine,E. H. Cherkaoui, and L. Toni, "Multicriteria optimization of access selection to improve the quality of experience in heterogeneous wireless access networks," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 4, pp. 1785-1800, May. 2013.
[22] D. Niyato, and E. Hossain, "Dynamics of network selection in heterogeneous wireless networks: an evolutionary game approach," *IEEE Transactions on Vehicular Technology*, Vol. 58, No.4, pp. 2008-2017, May. 2009.
[23] Q.B. Chen, W.G. Zhou, R. Chai, and L. Tang, "Game-theoretic approach for pricing strategy and network selection in heterogeneous wireless networks," *IET Communications*, Vol. 5, no. 5, pp. 676-682, Mar. 2011.
[24] H. Tabrizi, G. Farhadi, and J. Cioffi, "A learning-based network selection method in heterogeneous wireless systems," *Proc. IEEE Global Telecommunications Conf.* (*GLOBECOM*), pp. 1-5, Dec. 2011.
[25] W. Zhang, "Handover decision using fuzzy MADM in heterogeneous networks," *Proc IEEE Wireless Communication and Networking Conf.* (*WCNC*), pp. 653-658, Mar. 2004.
[26] E. Stevens-Navarro, and V.W.S. Wong, "Comparison between vertical handoff decision algorithms for heterogeneous wireless networks," *Proc IEEE Vehicular Technology Conf.* (*VTC*), pp. 947-951, May. 2006.
[27] Network performance objectives for IP-based services, ITU-T Y. 1541, 2011.
http://www.itu.int/rec/T-REC-Y.1541/en
[28] E. Bouillet, D. Mitra, and K.G. Ramakrishnan, "The structure and management of service level agreements in networks," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 4, pp. 691-699, May, 2002.
[29] http://www.reddit.com/r/apple/comments/y7g58/ 2016-7-17
[30] P. Witold, E. Petr, and P. Roberta, "Fuzzy multi-criteria decision-making models, methods and applications," Wiley Press, 2011.
[31] K. Sungwook. Game theory applications in network design, Information Science Reference, 2014.
[32] http://www.isi.edu/nsnam/ns/ 2016-7-17.

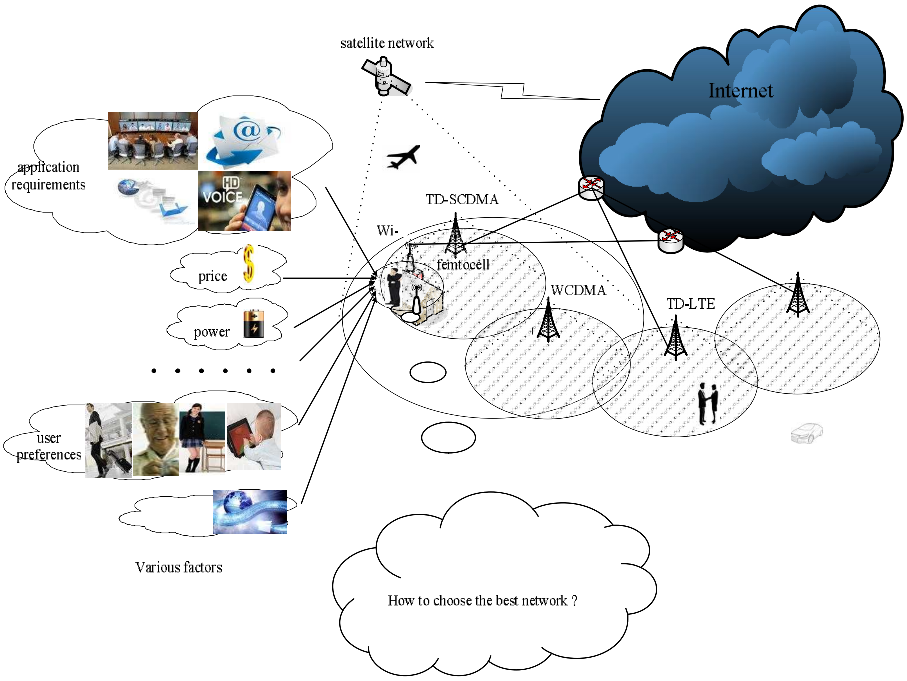


Fig. 1. A mobile user ina heterogeneous wireless network environment.

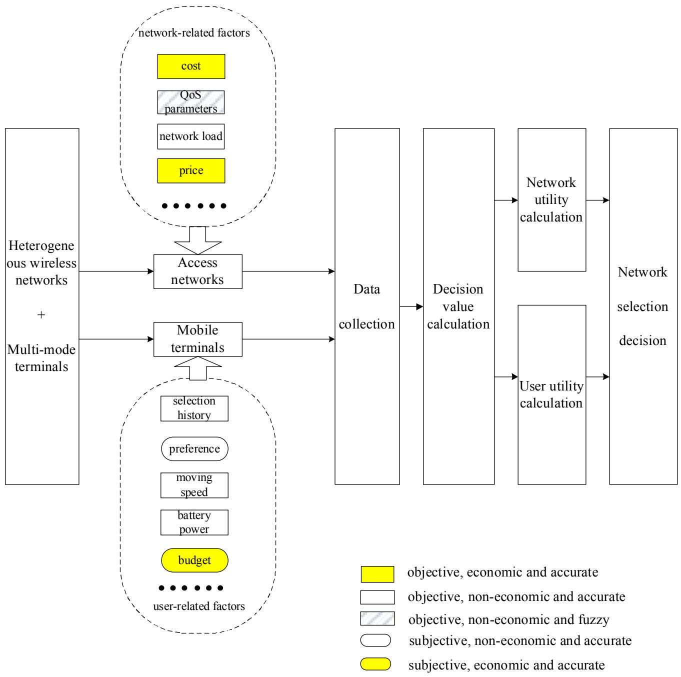
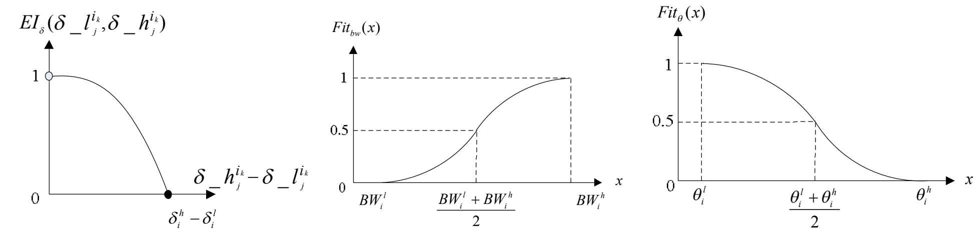
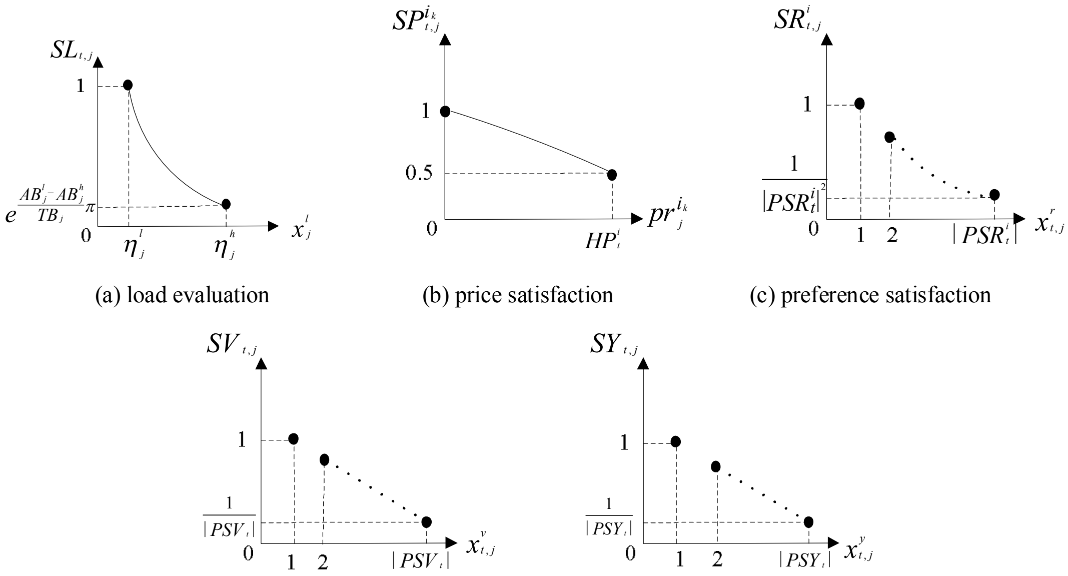


Fig. 2. A flexible and generalized framework for the access network selection.



(a) $EI_{\delta}(\delta\_l_j^{i_k}, \delta\_h_j^{i_k})$ (b) $Fit_{bw}(x)$ (c) $Fit_{\theta}(x)$

Fig. 3. Three QoS parameter evaluation functions.



(a) load evaluation (b) price satisfaction (c) preference satisfaction

(d) movement fitness (e) battery power fitness

Fig. 4. Decision value functions of five different factors.

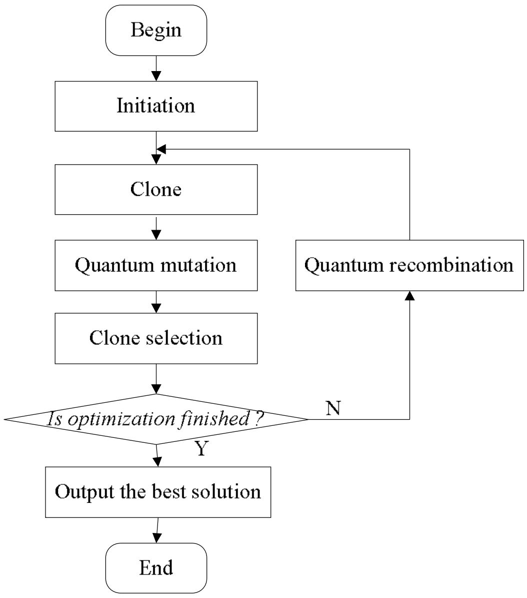


Fig. 5. The algorithm procedure of QICA.

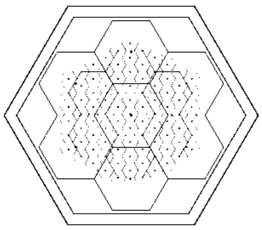


Fig. 6. Network topology.

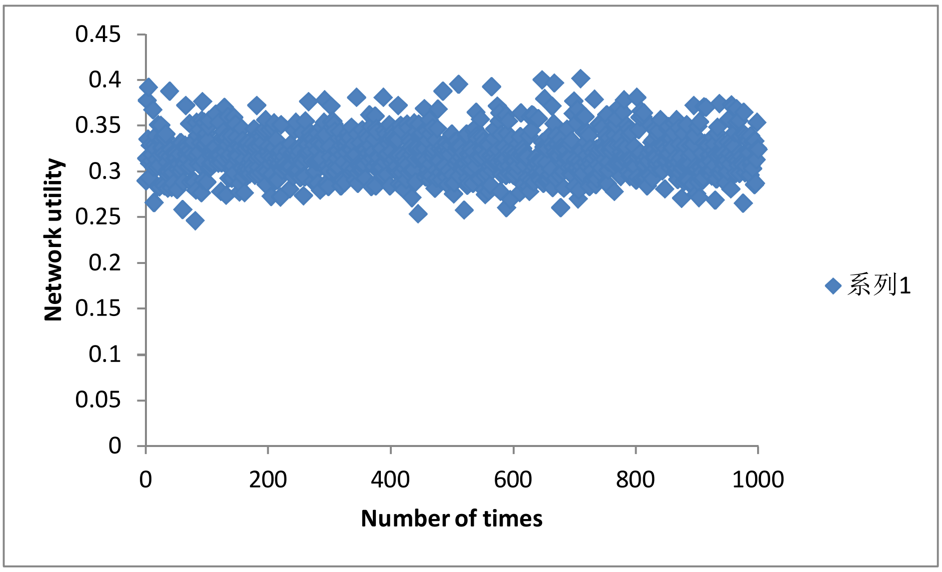
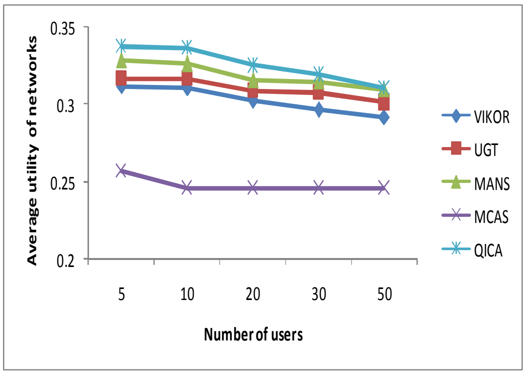
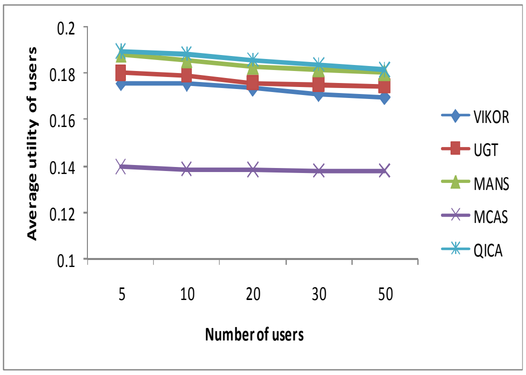


Fig. 7. The scatter diagram of results of 1000 times experiments

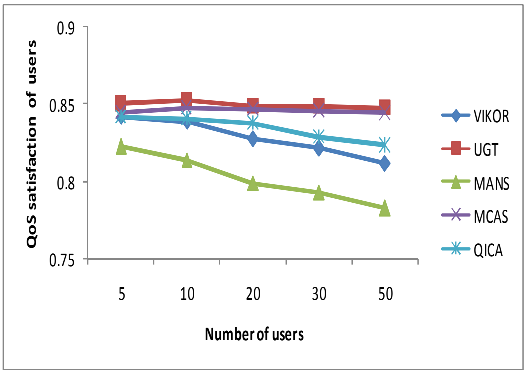


(a) Access network utility

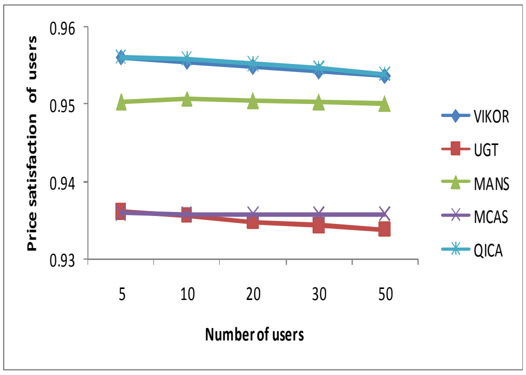


(b) User utility

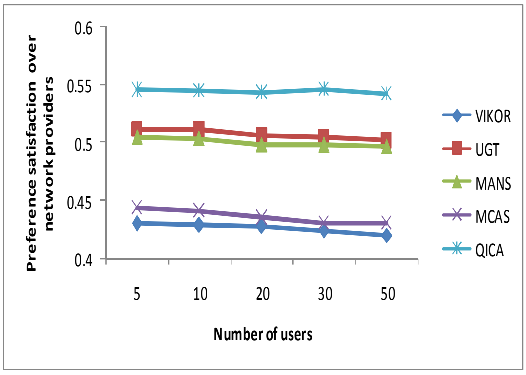
Fig. 8. Utility with varying number of users.



(a) QoS satisfaction of users

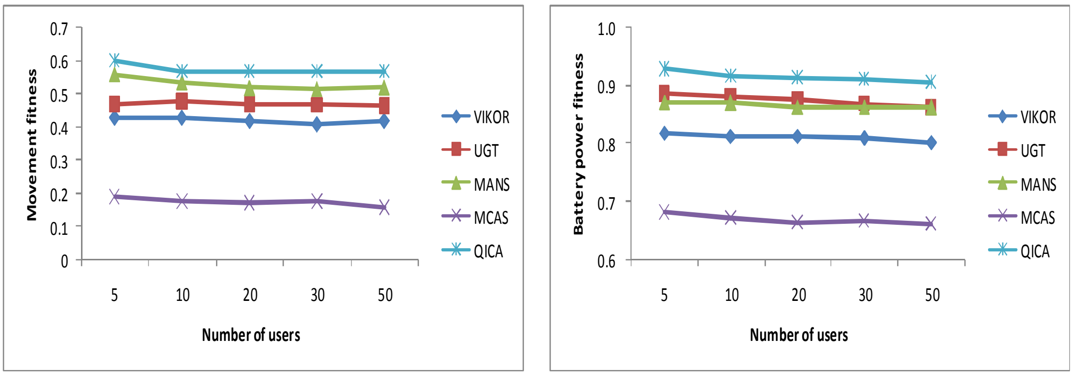


(b) Price satisfaction of users



(c) Preference satisfaction over network providers

Fig. 9. QoS, price and preference satisfaction with varying number of users.



(a) Movement fitness (b) Battery power fitness

Fig. 10. Fitness with varying number of users.

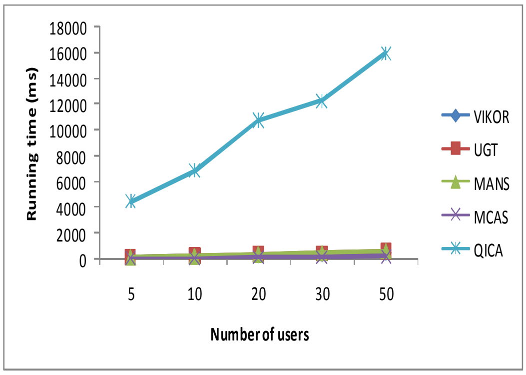
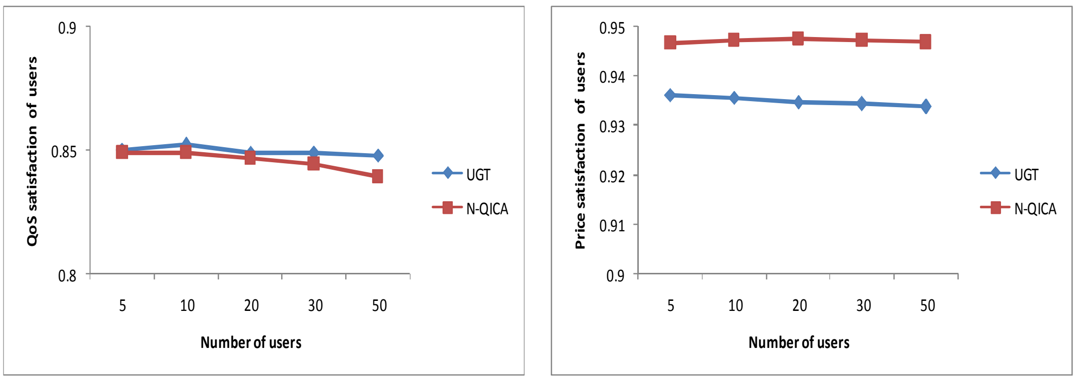
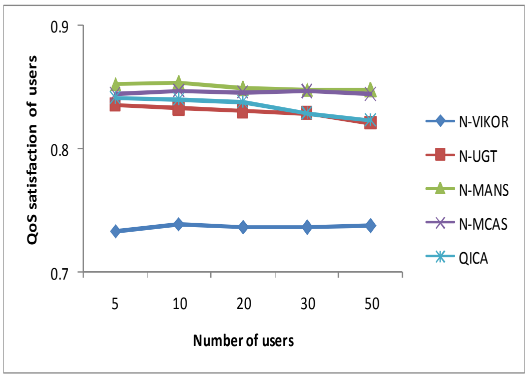


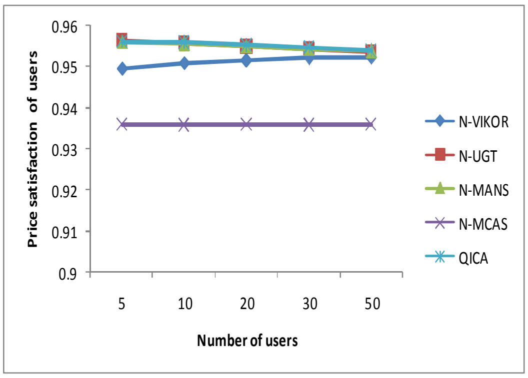
Fig. 11. The running time with varying number of users.



(a) QoS satisfaction of users (b) Price satisfaction of users

Fig. 12. Comparison of N-QICA and UGT with varying number of users.





(a) QoS satisfaction of users (b) Price satisfaction of users

Fig. 13. QoS and price satisfaction with varying number of users.

Table. 1 Comparison of the access network selection schemes in the literature.

Scheme	Feature								
	Generalized (factors considered)								Flexible
	Network -related	User -related	Non economic	Economic	Objective	Subjective	Accurate	Fuzzy	
Ref [11]	√		√	√	√		√		
Ref [12]	√	√	√		√	√	√		
Ref [18]	√	√	√	√	√	√	√	√	
Ref [19]	√	√	√		√		√		
Ref [20]	√		√	√	√		√		√
Ref [21]	√	√	√	√	√	√	√		√
Ref [22]	√	√	√	√	√		√	√	
Ref [23]	√	√	√	√	√		√		
Ref [24]	√	√	√		√		√	√	
Our Scheme	√	√	√	√	√	√	√	√	√

Table. 2 Six types of applications.

Type	Applications
1	Real-time, jitter sensitive, high interaction (HD VoIP)
2	Real-time, jitter sensitive, interactive (VoIP)
3	Transaction data, highly interactive (Signalling)
4	Transaction data, interactive
5	Low loss only (short transactions, bulk data, video streaming)
6	Traditional applications of default IP networks

Table. 3 Parameters of our network selection problem.

Name	Description
APS	Set of network application types
AP_i	ID of application type i
SL	Set of service level in each application type
M	The number of access networks
AN_j	ID of access network j
PI_j	ID of provider of access network j
CS_j	Coding scheme supported by access network j
NAS_j	Application types set supported by access network j
CR_j	Coverage radius of access network j
MV_j	Maximum moving speed supported by access network j
FR_j	Frequency range of access network j
TP_j	Lowest signal strength of access network j
TB_j	Total bandwidth of access network j
AB_j	Available bandwidth of access network j
AB_j^h	Upper bound of available bandwidth sensitive interval of access network j
AB_j^l	Lower bound of available bandwidth sensitive interval of access network j
$policy_j^{i_k}$	Service policy for application type AT_i and service level k of access network j (k is the sequence number in the service level set SL)
$pr_j^{i_k}$	Price of service policy of access network j for unit bandwidth in unit time
$ct_j^{i_k}$	Cost of service policy of access network j for unit bandwidth in unit time
$\left[\delta\_l_j^{i_k}, \delta\_h_j^{i_k}\right]$	Interval of access network j provided for application type AT_i and service level k on δ
PIS	Set of network providers
N	The number of mobile terminals
MT_t	ID of mobile terminal t
TAS_t	Set of network application types of mobile terminal t
MCS_t	Coding scheme supported by mobile terminal t
CV_t	Moving speed of mobile terminal t
CV_t^{th}	High moving speed threshold of mobile terminal t
RC_t	Available battery power of mobile terminal t
RC_t^{th}	Low available battery power threshold of mobile terminal t
RS_t	Lower bound of signal strength received by mobile terminal t
WF_t	Working frequency of
HP_t^i	Budget of mobile terminal t for application type AT_i for unit bandwidth in unit time
PSR_t^i	The preference sequence over network providers recorded by mobile terminal t with application type AT_i

w_{δ}^{i}	The weight of AP_i on δ
$[\delta_i^l, \delta_i^h]$	Requirement intervals of AP_i on δ
$E\delta_j^{i_k}$	The evaluation of access network *j* for application type AT_i and service level *k* on δ
$E\delta_{IS}$	The best evaluation value on δ
$E\delta_{NIS}$	The worst evaluation value on δ
$[bw^l, bw^h]$	The standard interval with maximum upper bound in intervals provided by all access networks
$[\theta^l, \theta^h]$	The standard interval with minimum lower bound in intervals provided by all access networks
$C\delta_j^{i_k}$	QoS evaluation of $policy_j^{i_k}$ for the user requirements on δ
$SQ_j^{i_k}$	The QoS satisfaction of service policy $policy_j^{i_k}$
$SL_{t,j}$	The load evaluation of MT_t in AN_j
$SP_{t,j}^{i_k}$	The price satisfaction of MT_t to $policy_j^{i_k}$
$SR_{t,j}^{i}$	The preference satisfaction of MT_t running application type AT_i in PI_j
$SV_{t,j}$	The movement fitness of MT_t in AN_j
$SY_{t,j}$	The battery power fitness of MT_t in AN_j
PSV_t	The access network which can support the moving speed sequence recorded by mobile terminal *t* according to the coverage radius from large to small
PSY_t	The access networks sequence recorded by mobile terminal *t* according to the coverage radius from small to large
$xr_{t,j}^{i}$	The sequence number of PI_j in PSR_t^i
$xv_{t,j}$	The sequence number of AN_j in PSV_t
$xy_{t,j}$	The sequence number of AN_j in PSY_t

Table. 4 Conditions of two example mobile terminals.

Name	MT_1	MT_2
TAS_t	{ E-mail }	{ VideoOnDemand }
MCS_t	{TD-LTE, W-CDMA, GSM}	{ TD-LTE, W-CDMA, TD-SCDMA, GSM}
CV_t	10km/h	20km/h
CV_t^{th}	150km/h	150km/h
RC_t	10%	75%
RC_t^{th}	25%	25%
RS_t	-90dBm	-95dBm

WF_t	2600MHz	2600MHz
HP_t^i	0.28	0.3
PSR_t	(CU, CM)	(CM, CU)

Table. 5 Conditions of two example access networks.

Name		AN_1	AN_2
PI_j		CM	CU
CS_j		{TD-LTE}	{W-CDMA}
NAS_j		*ATS*	*ATS*
CR_j		400m	500m
MV_j		240km/h	200km/h
FR_j		(1880-1900MHz, 2320-2340MHz, 2575-2620MHz)	(1920-1980MHz, 2110-2170MHz)
TP_j		-90dBm	-90dBm
TB_j		100Mbps	10Mbps
AB_j		8Mbps	7Mbps
AB_j^h		10Mbps	1Mbps
AB_j^l		1Mbps	0.5Mbps
$pr_j^{i_k}$	(i=2; k=1,2,3,4)	(0.22, 0.23, 0.24, 0.25)	(0.22, 0.23, 0.25, 0.26)
	(i=4; k=1,2,3,4)	(0.15, 0.16, 0.17, 0.18)	(0.15, 0.16, 0.18, 0.19)
$ct_j^{i_k}$	(i=2; k=1,2,3,4)	(0.16, 0.17, 0.18, 0.19)	(0.15, 0.16, 0.17, 0.18)
	(i=4; k=1,2,3,4)	(0.10, 0.11, 0.12, 0.13)	(0.10, 0.11, 0.13, 0.14)

Table. 6 QoS requirement intervals of different example applications.

Application (AP_i)	Bandwidth interval(kbps)	Delay interval(ms)	Delay jitter interval (ms)	Error rate interval
VideoOnDemand (2)	[1000, 6000]	[0, 10]	[0, 10]	[0, 0.01]
E-mail (4)	[20, 64]	[150, 1000]	[0, 10]	[0, 0]

Table. 7 QoS parameter intervals of different service level provided by access networks.

Application (service level)	Bandwidth interval (kbps)	Delay interval (ms)	Delay jitter interval (ms)	Error rate interval
VideoOnDemand (1)	[1000, 2000]	[7, 10]	[7, 10]	[0.005, 0.01]
VideoOnDemand (2)	[2000, 3000]	[5, 7]	[5, 7]	[0, 0.005]
VideoOnDemand (3)	[3000, 4500]	[3, 5]	[3, 5]	[0, 0]
VideoOnDemand (4)	[4500, 6000]	[0, 3]	[0, 3]	[0, 0]
E-mail (1)	[20, 30]	[750, 1000]	[7.5, 10]	[0, 0]
E-mail (2)	[30, 40]	[650, 750]	[5, 7.5]	[0, 0]
E-mail (3)	[40, 50]	[400, 650]	[2.5, 5]	[0, 0]
E-mail (4)	[50, 64]	[150, 400]	[0, 2.5]	[0, 0]

Table. 8 Notations of our QICA algorithm.

Name		Description
Integer coding	Qubit coding	
	S	The population size
	G	The upper bound of the iterations
x_b	y_b	The best solution
$X_g = \{x_g^1, ..., x_g^S\}$	$Y_g = \{y_g^1, ..., y_g^S\}$	The gth generation coding population
$x_g^q = \{x_{g,1}^q, ..., x_{g,N}^q\}$	$y_g^q = \{y_{g,1}^q, ..., y_{g,N}^q\}$	The qth antibody in gth generation population, a selection scheme of N mobile terminals among M access networks
---	C_q	The clone size of antibody y_g^q
---	I_q	The identity matrices of dimensionality C_q
---	N_c	Relating to the clone scale
---	θ	The rotate angle controlling the convergence speed
---	α_1, β_1	The probability amplitude of the best antibody in current population
---	α_2, β_2	The probability amplitude of the current antibody after clone

Table. 9 Rotation direction of quantum table.

$d_1 > 0$	$d_2 > 0$	$f(\alpha', \beta')$	
		$\|\omega_1\| > \|\omega_2\|$	$\|\omega_1\| < \|\omega_2\|$
true	true	+1	-1
true	false	-1	+1
false	true	-1	+1
false	false	+1	-1

Table. 10 Distribution of mobile users in moving speed.

Moving speed interval (km/h)	Percentage	Meaning
[0, 5]	20%	walking
(5, 80]	72%	urban public transport
(80, 200]	7%	railway
(200, 800]	1%	airplane

Table. 11 Distribution of mobile users in the network providers.

Network provider	Percentage
China Mobile	73%
China Unicom	12%
China Telecom	15%