Network Selection for Heterogeneous Wireless Networks Based on Multiple Attribute Decision Making and Evolutionary Game Theory

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ABSTRACT

Network selection is a key technology to realize fair resource allocation and load balancing for converged multi-radio heterogeneous networks. In this paper, we propose a Multiple attribute decision making and Evolutionary Game Theory (MEGT) integrated network selection scheme. In MEGT, utility functions are designed appropriately to compute user QoS satisfaction of the candidate network. User preferences are considered in this paper and are computed by analytic hierarchy process (AHP). Then the dynamics of the population's behavior are explicitly described by EGT. And a centralized population algorithm is adopted to implement the proposed scheme in practical wireless systems. At last, the validity of the proposed scheme is verified by numerical and simulation results.

Keywords: *Evolutionary game theory, Heterogeneous networks, Integrated network selection scheme, Multiple attribute decision making (MADM), Utility functions*

1. INTRODUCTION

Nowadays, the rapid development of smart multimode terminals and mobile Internet applications have raised a great challenge to service provisioning paradigm. While the converged multi radio access technologies (RATs) such as long term evolution (LTE) networks, universal mobile telecommunications systems (UMTS), wireless metropolitan area network (WMAN), and Wireless Local Area Networks (WLAN), would alleviate this problem [1]. Network selection is a key technology to enable the multi-RAT convergence, by which users could obtain high quality of services (QoS) and ubiquitous network access opportunities.

Multiple attribute decision making (MADM) algorithms including simple additive weighting (SAW), multiplicative exponential weighting (MEW) and technique for order preference by similarity to an ideal solution (TOPSIS) , use utility to measure the satisfaction that a network could provide to the mobile user [2]. Different form traditional games, evolutionary game theory (EGT) focuses on population's behavior evolution and is applicable to large scale systems [3]. EGT have been used to deal with the network selection problem in [4] and the dynamic spectrum share problem in [5]. However, utility functions used in these two works considered only the bandwidth. The key is how to design appropriate utility functions, such as linear form in [6], logarithm form in [7] and exponential form in [8][9], for both user centric and network centric attributes.

User preferences, which have a great influence on quality of experience (QoE), are considered in this paper. AHP could decompose network selection into a hierarchy of several simpler sub-problems and compute the preference weights according to their relative dominances [10][11].

In this paper, we integrate MADM and EGT (MEGT) to address the network selection issue. Both user centric requirements like bandwidth and network centric concerns like load balancing are taken into account. The utility functions are carefully designed to precisely quantify the relationship between the QoE and these attributes, and the preference weights are calculated by AHP. A centralized population evolution algorithm is presented, and its convergence and adaptation properties are demonstrated by numerical and simulation results.

The rest of this paper is organized as follows. The system model is described in Section 2. The details of our proposed MEGT network selection scheme are presented in Section 3. Section 4 are the discussions of the numerical and simulation results. The conclusion is stated in Section 5.

2. SYSTEM MODEL

A typical heterogeneous wireless network scenario is shown in Fig. 1, which consists of a UMTS network, a WMAN network and a WLAN network. We denote UMTS, WMAN and WLAN by $i \in \{1,2,3\}$ respectively. We use $a \in \{1,2,3\}$ to mark the different service area in this figure. The user number in area a is N^a .

In this paper, we take the streaming application like video as a typical application. Four carefully selected attributes are used to characterize the candidate network. They are upward attribute available bandwidth (AB) which means the higher the better, downward attribute delay and BER which means the lower the better, and dynamic attribute network load, which are denoted by $j \in \{1,2,3,4\}$ respectively. In addition, we assume the users connecting with the same network will obtain the same allocated resources (i.e., utility).

In general, UMTS network has a wide coverage and would provide the mobile users with guaranteed QoS in a high price. As an enhancement, WMAN performs better in terms of coverage, data rate and security. While in the hotspot like the shopping center, users would prefer WLAN due to its lower price and higher data rate. User's QoE would decline with the increase in network load. Therefore, a user equipped with multi-interface device would select the best access network according to its own QoS requirements, its preferences and network conditions.

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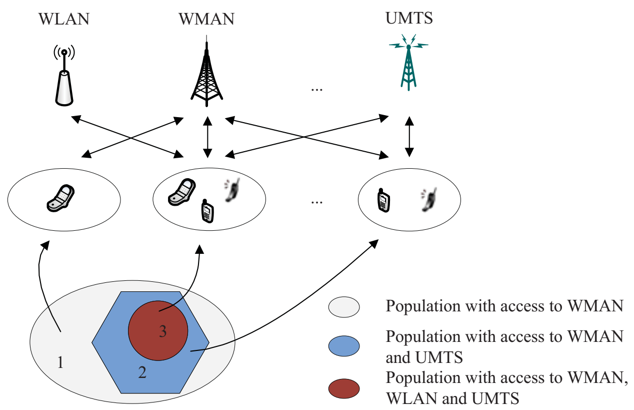

Fig. 1. The heterogeneous network scenario.

2. MEGT NETWORK SELECTION SCHEME

3.1 Utility functions design

The sigmoid utility function form is most suitable for both upward and downward attributes. It shows good monotonic, differentiable and convexity properties to adapt to diverse applications such as real time voice, video stream and web. It could also characterize the diminishing marginal utility of user satisfaction.

For upward attribute, user utility of network i in terms of attribute j is defined as:

$$u_{ij} = f_j(v_{ij}) = \begin{cases} 1 - e^{-\frac{\alpha_j (v_{ij}-\gamma_j)^2}{\beta_j + (v_{ij}-\gamma_j)}}, & v_{ij} \ge \gamma_j \\ 0, & v_{ij} < \gamma_j \end{cases} \tag{1}$$

where $u_{ij} \in [0,1]$ and v_{ij} is the value of attribute j in network i . γ_j is a threshold which means the service can't be accepted if $v_{ij} < \gamma_j$ and is determined according to user experience. The shape of the utility function is determined by α_j and β_j for specific applications. Accordingly, the utility function for downward attributes can be expressed as:

$$u_{ij} = f_j(v_{ij}) = \begin{cases} e^{-\frac{\alpha_j (v_{ij}-\gamma_j)^2}{\beta_j + (v_{ij}-\gamma_j)}}, & v_{ij} \ge \gamma_j \\ 1, & v_{ij} < \gamma_j \end{cases} \tag{2}$$

where γ_j is a threshold which means the service quality is perfect if $v_{ij} < \gamma_j$ and is determined according to user experience.

Then MEW method is used to compute the overall score U_i of network i , in which the importance of each single attribute are considered.

$$U_i = \prod_{j=1}^{4} u_{ij}^{w_j} \tag{3}$$

where $w_j \in [0,1]$ is the preference weight of attribute j and is subjected to $\sum_j w_j = 1$.

3.2 AHP for user preferences computing

The attribute weights are numerical metrics of user preferences which represent the sensitivities of the total utility to the variation in the attribute values. They can be predefined by the user when subscribing to a service. This method is simple but doesn't fit for the real complex heterogeneous wireless environment.

In this paper, we use AHP to compute the objective attribute weights. The network selection problem is decomposed into a hierarchy of easy to solve sub-problems. The network selection is on the top level, the multiple attributes are on the second level and the solution networks are at the bottom. We make pair-wise comparison of these attributes and construct a AHP matrix M based on their contributions to the final utility. $m_{ij} = w_i / w_j \in M$ is a scale from 1 to 9 which denote the dominance ratio of attribute i to attribute j and is obtained according to user experience.

At last, the weight vector $\mathbf{w}^T = [w_1, w_2, w_3, w_4]$ can be obtained as the eigenvector of the matrix corresponding to the largest eigenvalue. Note that we need to normalize the eigenvector $\mathbf{w}$ in order to satisfy the constraint $\sum_j w_j = 1$.

3.3 Evolutionary game theory

As an alternative to the classical Nash game approach, evolutionary game is a very promising tool for describing competitions in large scale systems or strategic interactions among large number of players [13]. Evolutionary game theory extends the basic components of traditional game with the concept of population. In the network selection model, population means a group of users in a certain service area who have the same access opportunities. The user's strategies in the population are the available access networks and his payoff is the utility obtained from the service provided by the network. The motivation of a user is to obtain higher utility than the average population utility. The user with bounded rationality can adapt his behavior gradually according to simple observation.

As shown in Fig. 1, there are three populations in the considered heterogeneous scenario, and the users in population 1 can only access to WMAN. N_i^a is the number of users who select network i in population a . The state of these populations can be represented by a vector $\mathbf{x} = \{x_2^2, x_1^3, x_2^3\}$, where $x_i^a = N_i^a / N^a$ is the proportion of users choosing network i in population a . The evolution process of the population can be ruled by a set of ordinary differential equations, called replicator dynamic equations:

$$\dot{x}_i^a(t) = \sigma x_i^a(t)(U_i^a(\mathbf{x}) - \bar{U}^a(\mathbf{x})) \tag{4}$$

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where σ is a positive parameter used to control the rate of evolution, $U_i^a(\mathbf{x})$ is user utility obtained from network i in area a at a given population state $\mathbf{x}$ and $U_i^a(\mathbf{x}) = U_i(\mathbf{x}), \forall i, a$. $\bar{U}^a(\mathbf{x}) = \sum_i x_i^a U_i^a(\mathbf{x})$ is the average population utility.

The replicator equations reveal such a fact that successful strategy which provides the users with higher utility will spread in the population. The information of the game at a given time point can be obtained from the replicator dynamics if the initial conditions are known. The EGT makes the predictions of the player's dynamic behavior in the game be possible.

3.4 Existence of evolutionary equilibrium

The population states may converge to a set of fixed points which are considered as the solutions to this game, called evolutionary equilibria. According to the definition of the equilibrium, all the mobile users will get the same utility at these stable states and no one wants to change his current strategy. So All the population states $\mathbf{x}$ which can make the replicator dynamic equation given in (5) stable will be the equilibria. Considering the physical meaning of evolutionary equilibrium, it can be calculated by equations as follows [12][13]:

$$\dot{x}_i^a(t) = 0, \quad \forall i, a$$
$$subject\ to \begin{cases} 0 \le x_i^a(t) \le 1, \forall i, a \\ \sum_i x_i^a(t) = 1 \end{cases} \tag{5}$$

3.5 Centralized population evolution algorithm

In order to make our proposed MEGT scheme feasible in real wireless systems, a centralized population evolution algorithm is adopted in this paper. The media independent information services (MIIS) defined in IEEE 802.21 standard enable the mobile node to report to a central information collector and to obtain information of other users in the same service area [14]. So the centralized population evolution algorithm can be implemented in physical networks. The users in the heterogeneous network make network selection decision based on the current payoff information and select a network to improve their utility randomly . The main part of this algorithm is described in Table I.

4. NUMERICAL AND SIMULATION RESULTS

4.1 Simulation setting

We design WMAN as a dominant alternative of WLAN for streaming traffic due to its large bandwidth capacity. We let $\sigma = 1$, and the parameters of the networks and user QoS requirements are listed in Table II [10][15]. In the simulation process, the user's available bandwidth allocated by network i is $b_i = \min(1, C_i / N_i)$ and the load of network i is $L_i = N_i b_i / C_i$, where N_i is the total user number in network i and C_i is the total bandwidth of network i . We assume that the streaming user is more sensitive to the available bandwidth. Network load is another important factor used for load balancing. The AHP matrix and the associated weights are showed in Table III.

TABLE I. MEGT ALGORITHM

1. For all users in the populaiton
2. **Loop**:
3. user m computes his payoff U_i^a , and compare it with $\bar{U}^a$
4. **if** $U_i^a < \bar{U}^a$ **then**
5. **if** $rand() < \left(U_i^a - \bar{U}^a\right)$ **then**
6. choose network j randomly, where $j \ne i$ and $U_j^a > \bar{U}^a$
7. **end if**
8. **end if**
9. **end loop**.

TABLE II. QOS PARAMETERS

QoS Parameters	UMTS	WMAN	WLAN	User Requirements
Bandwidth (Mbps)	5	35	20	1
Delay(ms)	50	75	100	100
BER	10^{-3}	10^{-4}	10^{-5}	10^{-5}

TABLE III. AHP MATRIX AND WEIGHTS

Streaming	AB	Delay	BER	Load	w_j
AB	1	6	4	2	0.4702
Delay	1/6	1	1/4	1/5	0.0552
BER	1/4	4	1	1/5	0.1253
Load	5	5	5	1	0.3493

4.2 Convergence properties and evolutionary equilibrium

We assume that the number of users in each area is $N^1 = 3, N^2 = 6, N^3 = 9$ and the initial population state is $\{x_2^2, x_1^3, x_2^3\} = \{2/3, 1/9, 1/3\}$, e.g., the user number in area 3 is $N^3 = 9$ and the proportion of users who access to WMAN in area 3 is $x_2^3 = 1/3$. Substitute these parameters into (4), then we can obtain the numerical results of population dynamics. As shown in Fig. 2, the populations evolve with time to a stable state, i.e., evolutionary equilibrium, where all the users' utilities are the same. Fig. 2 also shows the simulation results of MEGT algorithm under the same conditions. The simulation results match with the numerical analysis well and converge to the evolutionary equilibrium very fast. So the feasibility of our proposed MEGT network selection scheme in real wireless system is approved. Substitute the parameters mentioned above into (5), then we can determine all the possible evolutionary equilibria as shown in Fig. 3. The trajectories started from different initial population states will converge to different equilibira. So the EGT is very suit for describing the population dynamic behavior.

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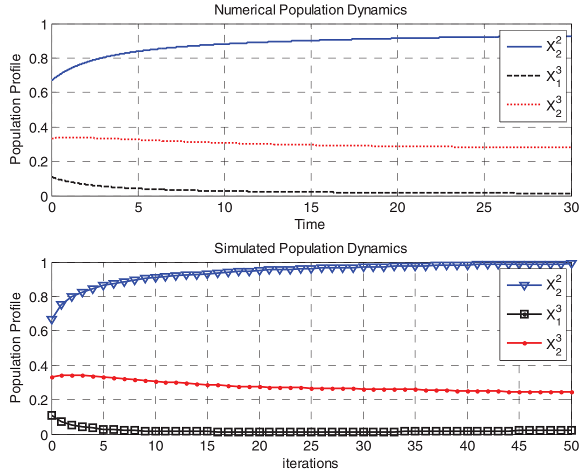

Fig. 2. Numerical and simulation results of population dynamics.

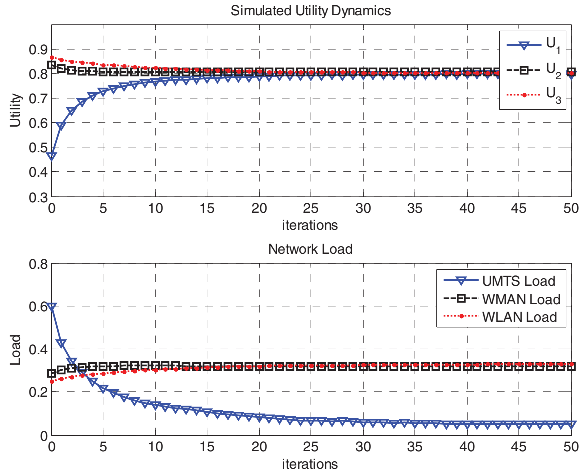

Fig. 4. Utility and network load simulation results, $N^1=3, N^2=6, N^3=9$

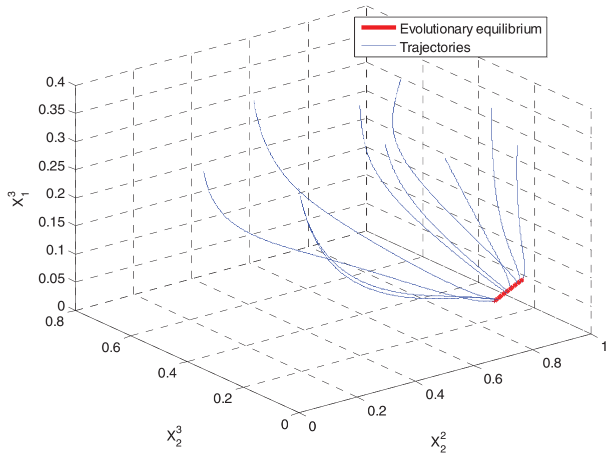

Fig. 3. Evolutionary equilibria.

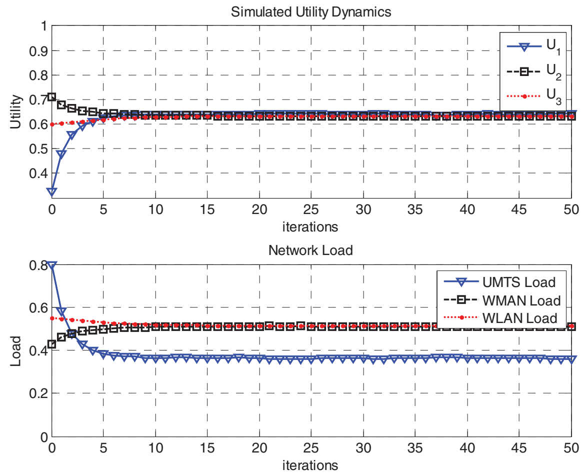

Fig. 5. Utility and network load simulation results, $N^1=5, N^2=10, N^3=15$

4.3 Load balancing

The original MADM method doesn't involve load balancing. In reality, however, load balancing is of vital importance to wireless resource management. In general, the capacity of an access network is limited. When the accommodated traffics exceed a certain threshold, the network performance will decline dramatically. Moreover, in network operator's opinion, load balancing is an effective approach to improve resource utilization and avoid network congestion.

As shown in Table III, we set the utility function sensitive to both the allocated bandwidth and network load. With the same conditions used in Fig. 2, the simulated utility and traffic load results are depicted in Fig. 4. The total average traffic load is 30%, which is low under this condition. At first, the traffic load of WMAN and WLAN are relative low and their utilities are high. And therefore, WMAN and WLAN networks are more appealing to streaming users due to their large capacity. So the streaming users in UMTS network will switch to WLAN and WMAN network to improve their utilities. As the network load increase, the utility of WMAN and WLAN network decline. In contrast, the utility of UMTS increase. At last the populations converge to the equilibrium where the utility in different kinds of networks is the same and the traffic load of UMTS network is very low.

However, when $N^1=5, N^2=10, N^3=15$, the total average load in the entire service area reaches up to 50%. The simulated utility and load results under the initial condition $[x_2^2, x_1^3, x_2^3]=[0.7, 0.2, 1/15]$ are depicted in Fig. 5. At first, the utility of WMAN network is higher than that of WLAN and UMTS. So the users in WLAN and UMTS network deviate from their original networks and transit to WMAN. When the populations converge to the equilibrium, the average utility is lower than that in Fig. 4 and the UMTS load is higher than that in Fig. 4. That is because when total traffic is heavy, the network performance decline. And the UMTS network now has attraction for some streaming users. So MEGT scheme could realize load balance while do its best effort to meet user's QoS requirements in the heavy traffic scenario.

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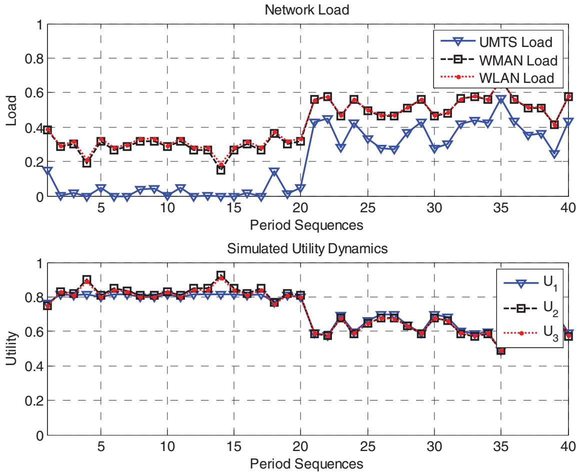

Fig. 6. Adaptability of the proposed MEGT network selection scheme.

4.4 Adaptation of MEGT scheme

As shown in Fig. 6, we assume that all the service requests shall be dealt with in T_0 time, i.e., T_0 is the service duration period. At first, the user number in the entire service area follows Poisson distribution with an average value of 15, $N^1 : N^2 : N^3 \approx 1:2:3$ and the overall traffic load is approximately 30%. Only a few of users wish to access to UMTS network under this scenario.

Usually the traffic in hotspot are heaviest and dynamic. We assume that there are plenty of users entering into area 3 after 20 periods, and the number follows Poisson distribution with an average value of 15. Then the overall traffic load suddenly increases to approximately 50%. Then there is degradation in the user satisfaction to WMAN and WLAN as shown in Fig. 6. The UMTS network shows attraction to the streaming users now and its load increases in this situation. Fig. 6 shows that our proposed MEGT network selection scheme can adapt to the changes of heterogeneous wireless networks well.

5. CONLUSION

The MEGT network selection scheme has been proposed in this paper to address the network selection problem for heterogeneous wireless networks. User preferences and network load are considered in the utility functions design. The convergence property and load balance ability of the proposed MEGT algorithm are approved by numerical and simulation results. Moreover, our proposed MEGT network selection scheme is scalable and adaptive to network traffic dynamics. It can be also applied to other service classes easily just with simple modification of the related parameters. From the simulation results we can conclude that mobile streaming users prefer WLAN and WMAN than UMTS. So the operators would benefit a lot if they deploy their own WLAN access point in the hotspots.

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