Utility Analysis of Software Defined Heterogeneous Cellular Networks

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Abstract. With the development of the 5G communication systems, the coexistence of a variety of wireless networks has become an inevitable trend. Different wireless networks have different features and applications. However, they are independent of each other and have no cooperative relationship in the most of cases. This paper investigates the application of the Software Defined Network (SDN) and wireless network function vitalization on the access control criterion of the heterogeneous cellular networks. The SDN controller manages all wireless access points based on the inaccurate feedback network state information. Wireless network virtualization technology can simplify the complexity of the system running and improve the efficiency of the communication system based on the utility theory which takes a number of respects into consideration, such as the maximum achievable data rate, signal-to-interference-and-noise ratio (SINR) and the traffic load state. Moreover, a discrete stochastic optimization algorithm is presented to solve the problem of inaccurate feedback information in a fast convergence rate, which is caused by the delay and noise over wireless channels. Extensive simulations show that our proposed model and algorithm can achieve utility optimization considering practical parameters configurations in wireless networks.

Keywords: Software Defined Network · Wireless network function vitalization · Utility function · Access control · Discrete stochastic optimization algorithm

1 Introduction

The emergence of various wireless network services and handheld mobile devices brings convenience to people's lives. At the same time, it causes the crazy growth of mobile traffic [1]. It is predicted that the volume of mobile data in 2019 will be 10 times of that in 2014 [2]. This unprecedented escalation has imposed significant challenges on the design of existing wireless network. In the face of

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the above problems and challenges, the researchers put forward the framework of the fifth generation (5G) mobile communications and corresponding solutions in the framework, for example, the paper [3] provides a guideline for optimizing vechicular communications in 5G cooperative MIMO small cell networks and energy efficiency is improved by more intelligent strategy in [4,5]. One of the most important aspects of 5G communication systems is Heterogeneous Cellular Networks (HCNs) architecture. The technology of HCNs can provide indoor hotpots coverage, extended coverage, seamless coverage at a low cost and high service rate to effectively satisfy the explosively growing demands of mobile data, service quantity and types in existing cellular network [3].

As the emergence of the new network applications, wireless users are not only dependent on network for data transmission, but also for various services based on an open and flexible network. Under this circumstance, Software Defined Network (SDN) and Wireless Network Function Vitalization (WNVF) are introduced [6]. WNFV provides a good basis for the development of SDN, because WNFV provides the abstract resource for the top running of the SDN control plane [6]. The core idea of the WNFV is realizing the centralized and dynamic management of network resources by the way of software definition.

The application of the SDN and WNFV on the wireless communication network is still in its infancy. In [7], the author put forward a new wireless network architecture on the basis of SDN, named Software Defined Mobile Network (SDMN), through which the wireless networks can become more open, flexible and programmable. The paper [8] proposed a method to resolve the management of mobility in HCNs and interference among different tiers based on the SDN network architecture. Thus the pressure of the controller can be distributed, and the useless information can be filtered at the same time. At present, most SDN related studies focus on wired networks not wireless ones. In [8], the author discusses the challenges and opportunities of the application of the SDN on the wireless network, and has addressed the challenges of deploying WNFV in a network.

In this paper we propose the intelligent schemes of software defined HCN to control the wireless access of users in the dynamic environment of 5G mobile communications. In contrast to previous researches, we address the system utility optimization for multi-tier HCNs, where load-balancing, the achievable data rate and cost of clients are jointly considered towards optimizing system performance. In addition, the concept of Homogeneous Poisson Point Process (HPPP) and signal-to-interference-and-noise ratio (SINR) are involved to calculate data rates of clients. Furthermore, each considering element is set as an independent variable of sigmoid function in order to select one optimal wireless network. Based on the SDN framework and inaccurate feedback network state information, which is because of the time delay and noise of wireless channel, we have proposed a tractable discrete stochastic approximation algorithm to solve the problems caused by the characteristics of wireless communication.

The remainder of this paper is organized as follows. In the Sect. 2, we introduce the model of heterogeneous wireless cellular network involved SDN, and the WNFV technology in the SDN controller. The Sect. 3 discusses the policy of user association according to the utility theory. In the Sect. 4 one discrete stochastic optimization algorithm is presented and its properties of convergence are summarized based on the inaccurate load state information. Section 5 presents the numerical results. Finally, Sect. 6 concludes this study.

2 System Model

In this section, we consider the system model that integrates intelligent SDN and WNFV into the infrastructure of 5G communication systems. The architecture consists of three planes, as shown in Fig. 1.

Infrastructure plane: the infrastructure plane consists of the bottom layer, that is HCNs. The macro-cell BSs are outfitted with an OpenFlow switch which can be used to feedback the load state information of cells regularly at all times. The rest of the small-cell BSs are deployed without OpenFlow switches, therefore, they need to send information to SDN controller through wireless channel. What's more, the most important technology is network virtualization technology whose core idea is abstracting out the required network resources from the substrate network, in which the performance parameters of each network are mapped to the tag of each virtual network, as shown in Fig. 1.

Control plane: the most important part in this architecture is the SDN controller, which uniformly manages the access interface in the HCNs [9]. The SDN controller can calculate the appropriate access point for the terminal through the appropriate algorithm according to the collected information about the network state and demand information sent by users. Different from the traditional network architecture, the architecture of the HCNs in this paper has the features of configuring the network services quickly and centralized control management. Through the centralized control, the controller can master the overall situation better, use more suitable algorithms, configure network services faster, and easily download the new algorithm, such as load balancing algorithm, not belong to the network architecture to meet the needs of network on load balancing.

Application plane: it is mainly for achieving functions of various Application (APP), where application requests will be duly sent to the control layer to handle. Besides, some innovative technologies and concepts, such as computation offloading by more energy-efficient and intelligent strategy in 5G communication system [9], cloud computing integrating SDN and NFV and the novel framework named EMC in the context of 5G [10] and so on, can be designed and implemented using the corresponding source code in the application plane.

3 Access Control Based on the Utility Theory

In this paper, we study a three-layer HCNs in 5G environment, among which a large number of micro-cell BSs and femto-cell BSs with high density and low transmit power are deployed in each macro-cell BS. In this process, even if the received power from small-cell BSs is less than the macro-cell power, some users

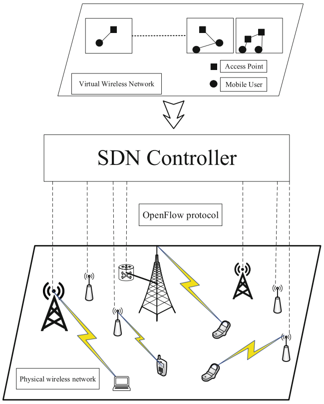

Fig. 1. The software defined heterogeneous cellular network with wireless virtual network.

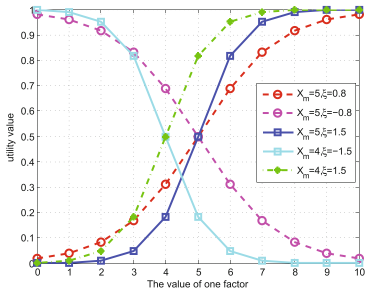

Fig. 2. Sigmoid curve.

may be offloaded to a small-cell BS using some user association, in which load balancing and better Quality-of-Service (QoS) of users can be obtained. Thus in this paper, we propose to force some users to access the small-cell BS through the utility theory instead of the Max-SINR based criterion.

In this model, we assume that the k-tier BSs can satisfy the HPPP Φ_k with intensity λ_k, where the distribution of users also meets the HPPP Φ_u with intensity λ_u that is independent of the distribution of BSs. Each tier presents a different type of BSs, for example, tier 1 means traditional macro-cell BSs, and tier 2 and tier 3 mean pico-cell and femto-cell BSs respectively. There are different path loss exponents $\{\alpha_k\}_{k=1,\cdots,K} > 2$ of different tiers' signals. The transmit power $\{P_k\}_{k=1,\cdots,K}$ of each BS is used to calculate the coverage probability and achievable rate of the user.

Assume that the access point in the wireless virtualization network is $K = \{1, 2, \cdots, k, \cdots, K\}$, and the cost value is respectively $C = \{c_1, c_2, \cdots, c_k, \cdots, c_K\}$, which means that when a user is connected to one virtual wireless network k, the cost value is c_k, in which the expenditure, terminal consumptions and so on are included. Maximum achievable data rate for one wireless network and corresponding SINR can be determined with the Shannon capacity formula based on the stochastic geometry, especially, the theory of Poisson point process. The maximum achievable data rate R_k from one BS for a connected user can be represented as: $R_k = W_k \log_2(1 + \gamma_k)$, where W_k is denoted as the channel bandwidth provided by the network k to some user.

It is assumed that a BS transmits to only one user via channel at one time, with maximum power to achieve the optimal physical rate, the SINR γ_k can be shown as: $\gamma_k = \frac{G_k P_k}{\sigma^2 + \sum_{i=1, i\neq k}^{K} G_i P_i}$, where G_k is denoted as the channel gain between the connected BS and a user, in addition, G_i represents the channel gain from other BSs whose effects are negative to servicing users and σ^2 is the thermal noise power.

The algorithm in this paper is based on the utility theory considering multiple criteria. In economics, the satisfaction of a particular thing or service to a human being is indirectly reflected in utility [11]. In the current wireless communication field, the same environment of wireless communication makes different efficiency for different users or applications. Therefore, it is necessary to introduce the utility function to access standards in the environment of 5G communication systems. Many function may satisfy the mentioned properties of wireless communications. However, for the issue including some aspect of QoS of user, data rate and so on, generally a sigmoid function is considered to express satisfaction of a given parameter, In this paper, we choose the Sigmoid function to imitate the relationship of attribute value and efficiency value. The form of the functions selected is: $U(x) = \frac{1}{1+\exp\{\xi(x_m - x)\}}$ $(x_m > 0, \xi > 0)$.

In order to intuitively perceive the Sigmoid function, this paper shows the value got by adjusting the parameters in the curve Fig. 2. The features of the curve obviously show that the demand for a factor is strong at the beginning, and when the value of a certain factor exceeds a certain amount, continuing to increase a certain factor will not have a significant increasement on the degree of utility. We can set the value of parameter x_m to control curve center, and set the value of ξ to adjust the steepness of the curve. The more bigger the value ξ is, the steeper the curve is. In addition, when ξ takes a negative value, the trend of sigmoid is opposite to the positive value of ξ. The trend of sigmoid curve is various when we choose different elements as shown in Fig. 2, and the effect of some parameters must be converted to be positive by some methods such as taking countdown.

In the HCNs, the utility function $U_u(c_k)$ based on the QoS of the user is defined as: $U_u(c_i) = \frac{1}{1+\exp\{\xi_u(x_u - c_k)\}}$, in which c_k refers to the cost of users who need to access the wireless network k, which contains energy consumption, service fee and so on. What's more, the sub-function based on the data rate is $U_a(R_k) = \frac{1}{1+\exp\{\xi_a(x_a - R_k)\}}$, in which R_k refers to the maximum achievable data rate of one user connected with the k-th tier. This part of utility value pays more attention to the QoS and Quality of Experience (QoE) of users. Furthermore, we consider the load state of the whole system, which makes the system traffic load reach to a balance to some extent. Thus the utility sub-function based on the load state information is defined as: $U_L(L_k) = \frac{1}{1+\exp\{\xi_L(x_L - L_k)\}}$, where L_k refers to the current load state of the virtual wireless network k and the value is the number of users access of the kth-tier wireless network, which is feedback from the BSs. What is more, because the trend of growth in terms of c_k and L_k is adverse to the users' satisfaction, we have to set the value of ξ_u and ξ_L as negative.

This status information is transmitted by the BS to the SDN controller through wireless channel. Therefore, we can get the general value of the utility value of wireless virtual network i: $U(c_i, R_i, L_i) = \varsigma U_u(c_i) + \tau U_a(R_i) + \upsilon U_L(L_i)$, where $\varsigma > 0, \tau > 0, \upsilon > 0, \varsigma + \tau + \upsilon = 1$, ς refers to the utility weight generated by the user costs, τ and υ denote the weights produced by the maximum achievable data rate, and load state of the system respectively. Besides, the values of ς, τ

and υ can be adjusted based on the type of service and overall system status, for example, the value of τ should be larger than other weights if the service of client is video streaming.

4 Wireless Network Selection with Inaccurate Load State Information

As we can conclude from the previous discussion, it is very important to determine the optimal selection of virtual wireless network, which can provide users with the best QoS and load balancing of the whole system to some extent in the control plane based on Load State Information (LSI) [12]. However, the LSI may be inaccurate because of the limitation of the measuring methods and the dynamic nature of the wireless communication system. What is more, it may be worse in virtual wireless network, because there is some time delay caused by rate-limited backhaul links transmitted to the central controller.

Firstly in this paper we define the set of all the possible virtual wireless networks as Ω, and the decision selection variable at the decision time t, is the $w^t \in \Omega$, which represents a particular virtual wireless network meeting the requirements of users. In order to simplify description of the algorithm, we defined $U(c_i, R_i, L_i^t)$ as the objective function $\phi\left[\hat{\mathbf{L}}^t, w^t\right]$, in which the parameter w^t and L^t are denoted as the wireless network selected in the SDN controller and the load state information of system in the time t, respectively.

In this paper we assume the availability of LSI is the same as [12], in which we can obtain specific and detailed instructions, and the inaccuracy in LSI is modeled as additive noise. Therefore, the available and inaccurate LSI $\hat{\mathbf{L}}$ can be shown as $\hat{\mathbf{L}} = \mathbf{L} + \mathbf{N}$, where $\mathbf{N}$ is an independent Gaussian variable. And at each decision time, because $\mathbf{L}^t = \hat{\mathbf{L}}^t - \mathbf{N}$ is a random variable, the utility function of each-tier BS $U(c_i, R_i, L_i^t)$ is a random variable as well.

In this paper, we introduce an iterative algorithm that is similar to discrete stochastic approximation algorithm, which has obtained a lot of attention. One most important feature of this algorithm is the self-learning ability in terms of the direction and speed of selecting the optimal wireless network. Another advantage is that it can find the best wireless access network under time-varying scene due to the fast convergence.

In the stage of initialization, the controller of SDN identifies all virtual wireless networks by means of WNFV. At the same time, the SDN controller receives feedback information from users and wireless access points, which is used to select the optimal wireless virtual network.

In the process of sampling and evaluation, the Algorithm 1 can randomly choose a virtual network, and calculate the corresponding value $\phi\left[\hat{\mathbf{L}}^t, \tilde{w}^t\right]$, which is compared with the existing $\phi\left[\hat{\mathbf{L}}^t, w^t\right]$. In the process of acceptance, if the value of $\phi\left[\hat{\mathbf{L}}^t, \tilde{w}^t\right]$ is larger, the corresponding network is accepted as the next better virtual network, that is $w^{t+1} = \widetilde{w}^t$. After the process of acceptance, we have to replace the state occupation probability: $p[t, w^t] = \frac{\text{Number-of-chosen}(w)}{t}$, which can record the frequency of accession into one virtual wireless. In addition, the step size in each iteration is $\frac{1}{t}$, which indicates that the Algorithm 1 is getting more conservative to find the optimal wireless network, and the optimal selection is the most frequently chosen wireless network. Moreover, we can easily find that changing optimal virtual wireless network in the whole process is a Markov chain, where the set of decision $\{w^t\}$ would nearly transfer into the global optimal value w^* after a few iterations, that is because transition probability of w^* is becoming larger and larger with the process of iterations.

In terms of the conditions and environments, the global convergence of Algorithm 1 is similar to the paper [13]. Therefore, the proof of convergence has been given in [13].

Algorithm 1. Aggressive Discrete Stochastic Approximation Algorithm

{ Initialization }

SDN controller receives the user's access request, and determines all the possible virtual wireless networks subset Ω and the value of weight ς, τ and υ in terms of the category of service, such as voice and video.

Each BS measures the LSI of the network and feedbacks the LSI to the SDN controller.

SDN controller selects a virtual wireless network $w^0 \in \Omega$, and set $p^0\left[w^0\right] \leftarrow 1$

set $p^0\left[w^0\right] \leftarrow 0$, for all $w \neq w^0$

Initialize measure of the optimal selected virtual wireless as w^0

for k = 1,2,..., do

{ Sampling and evaluation }

Given the Load state information $\hat{\mathbf{L}}^t$, obtain $\phi\left[\hat{\mathbf{L}}^t, w^t\right]$

choose $\tilde{w}^t \in \Omega / w^t$ uniformly, obtain an independent observation $\phi\left[\hat{\mathbf{L}}^t, \tilde{w}^t\right]$

{ **Acceptance }**

if $\phi\left[\hat{\mathbf{L}}^t, w^t\right] < \phi\left[\hat{\mathbf{L}}^t, \tilde{w}^t\right]$ **then**

set $w^{t+1} = \tilde{w}^t$

else

$w^{t+1} = w^t$

end if

{ Adaptive filter for updating state occupation probabilities }

$p[t+1] = (1 - \mu[t+1])\, p[n] + \mu[t+1] D(t+1)$ with the decreasing step size $\mu[t] = 1/t$

{ Computing the maximum }

if $p[t+1, w^{t+1}] < p[t+1, \tilde{w}^t]$ **then**

$\tilde{w}^{t+1} = w^{t+1}$

else

set $\tilde{w}^{t+1} = \tilde{w}^t$

end if

end for

5 Numerical Evaluation and Discussions

For performance evaluation, some numerical results for the Monte Carlo simulations are presented to make sure the advantages of our model and analyze the effectiveness of our proposed algorithm that is based on utility function theory. Three-tier HCNs are assumed in the simulation mode, namely macro-cell, pico-cell and femto-cell. In this simulation, the main system parameters are based on SCME channel model [14,15], in which we consider the three-tier HCNs with transmit power $\{P_1, P_2, P_3\} = \{46, 35, 20\}$ dBm and path loss $\{\alpha_1, \alpha_2, \alpha_3\} = \{3.8, 3.5, 4\}$. In addition, we assume that in our model different tiers are independent, with deployed density $\{\lambda_1, \lambda_2, \lambda_3\} = \left\{\frac{1}{\pi 500^2}, 5\lambda_1, 20\lambda_1\right\}$ and the cost of users $\{c_1, c_2, c_3\} = \{30, 60, 40\}$, available bandwidth for users $\{W_1, W_2, W_3\} = \{5, 20, 40\}$ MHz, $\{\xi_u, \xi_a, \xi_L\} = \{-0.8, 1.5, -2\}$, as well as the weight $\{\varsigma, \tau, \upsilon\} = \{0.3, 0.2, 0.5\}$.

First and foremost, take the two-tier network (only consists of macrocell and picocell) as example, we can observe in Fig. 3 that the probability of pico-cell user keeps the trend of increase when the SDN controller uses our proposed Algorithm 1 and is more than that based on the traditional max-SINR criterion, which means that the Algorithm 1 can shift some users from over-loaded macro-BSs to the light-loaded small-cell BSs, which allows each BS to better serve its remaining users. Therefore, we design our software defined HCNs, in which SDN controller selects and decides one perfect wireless network based on the imperfect LSI from the physical plane.

We can only illustrate the complexity of Algorithm refalgo1 using the numbers of iteration by simulations. In the following simulation, the LSI noise is modeled as a zero-mean Gaussian random variable $\sigma^2 = -104$ dBm. We consider the performance of Algorithm 1 which selects the optimal wireless virtual network maximizing the utility value using as an estimate of the objective function. The virtual wireless network is randomly generated and fixed between two decision epochs. As we can see from Fig. 4 that the Algorithm 1 converges to the optimal wireless access point although it takes some time. Moreover, it is

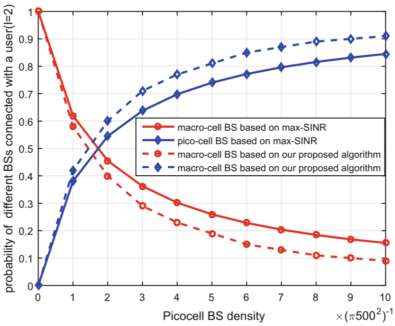

Fig. 3. Impact of pico-cell BS density in a HCNs of connecting macrocell and picocell.

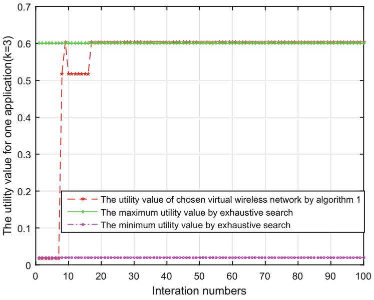

Fig. 4. Single run of Algorithm 1.

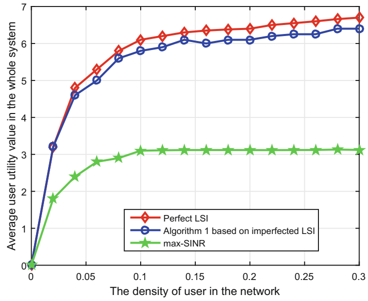

Fig. 5. Average user utility performance versus traffic arrival intensity.

observed that the speed of convergence is very fast, which is suitable for the framework of SDN.

Note that the maximum SINR cannot always give optimal QoS and QoE to the clients especially when the costs of the different tiers are different. Figure 5 shows that the discrete stochastic approximation algorithm can have close performance as the perfect LSI. However, the utility value caused by the Max-SINR scheme is far less than the one caused by our proposed access criteria.

6 Conclusion

In this paper, we have tried to jointly integrate SDN and HCNs in the environment of 5G mobile communications and considered some issues that arise. We proposed a novel standard of wireless access control that can achieve load balancing of the whole system and some better aspects of users' QoS in HCNs through solving a network-wide utility maximization problem. During this process, to address the challenge introduced by inaccurate LSI in this framework, we proposed network selection algorithm based on the concept of discrete stochastic approximation. Finally, we have provided extensive simulation results to demonstrate the performance of the model and new selection algorithm.

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