

Admission Control of Wireless Virtual Networks in HetHetNets

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Abstract—In this paper, we propose an efficient analytical method for admission control of wireless virtual networks (VNs), with heterogeneous traffic profiles, and various quality-of-experience (QoE) requirements, in the future software-defined radio access networks. We present a novel methodology for the admission control process that includes feedback information to the VN customers to improve their traffic profile accuracy, and consequently, their QoE. We formulate the virtual network admission control problem as a convex optimization problem which allows general multiple association between user equipment and base stations. Consequently, we propose an algorithm for solving this problem. The proposed method is applicable on heterogeneous networks with heterogeneous traffic distributions. We also propose a number of extensions to the problem including mechanisms that consider minimization of the network and service cost, and optimization according to the backhaul limitations. The simulation results show that our proposed methods are accurate and result in significant improvement in network resource utilization and customer satisfaction.

Index Terms—Admission control, wireless virtual networks, heterogeneous traffic, convex optimization.

I. INTRODUCTION

IN FUTURE software-defined networks (SDNs), wireless access service is envisioned to be requested not only for individual users but also for groups of users. The user groups are assigned with virtual slices of the network called virtual networks (VNs). VN customers request service from infrastructure providers who operate substrate networks (SNs). Examples of SNs include future 5G/5G+ cellular networks and future Wi-Fi networks, and examples of VN customers include taxi operators, Police, bus operators, post companies, second-level service providers, and many other private and public organizations. Fig. 1 shows an example of network structure in a SDN.

Upon arrival of VN service requests, which might have heterogeneous traffic profiles and different quality-of-experience

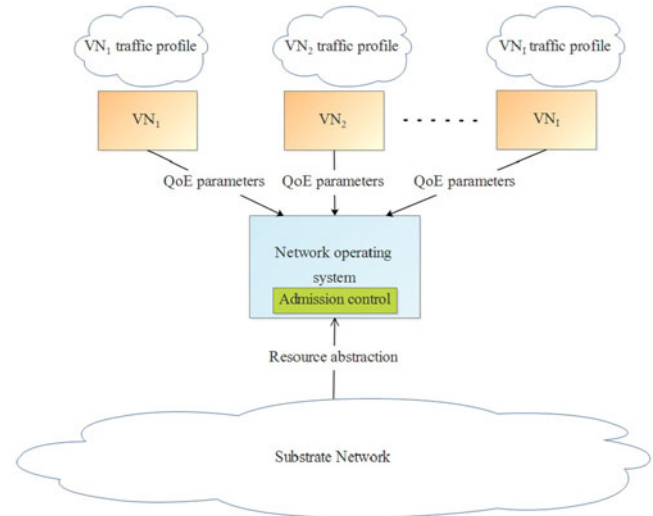


Fig. 1. Network structure: admission control, as a function in NOS, decides on admission or rejection of VN requests based on the customer traffic profiles, required QoE, and resource availability in SNs.

(QoE) requirements, a central network admission control entity, which can be considered as a network function in the network operating system (NOS), must decide to whether admit or reject the customer service request. Admission control is performed based on a large number of parameters including the customer traffic profile (user equipment (UE) locations), available bandwidth at base stations (BSs),¹ and customer QoE requirements.

The virtual network admission control in a wireless network is different from (and more complicated than) the regular single-session admission control. In the single-session admission control, decision is made based on a (deterministic) snapshot of already existing UE locations and the new UE location; while in the VN admission control, the UE locations and traffic demand distribution information are provided statistically by the VN customers. For instance, VN customers might indicate the expected distribution of traffic in various areas of the network. Therefore, the VN requests must be admitted if their QoE can be satisfied statistically. After (long-term) admission of a VN, (short-term) single-sessions of the VN are admitted only if they follow the restrictions and limitations of the VN admission

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¹Since the network discussed in this paper is general and there is no assumption on network technology, the general term BS is used to refer to any serving point. Therefore, BS might refer to access points (APs) in Wi-Fi, evolved Node Bs (eNodeBs) in LTE, or serving nodes in other technologies.

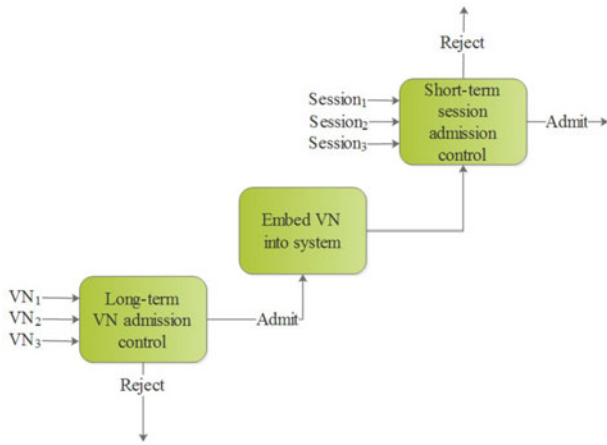


Fig. 2. Admission control is performed in two levels: in the long-term level, VNs are admitted and embedded into the system statistically based on resource availabilities, and in the short-term level, single-sessions are admitted based on VN customer contracts.

contract. Fig. 2 illustrates the VN admission control concept and its relation to the regular single-session admission control.

Admission control for VN is for a network of users/applications; therefore, the time dynamics is less of a concern due to the aggregation, similar to the situation in the backhaul link of a BS which is for a large number of users. Therefore, it is worth stressing the different time scales: VN admission control is a much slower process in comparison to user/application admission control; in turn, user/application admission control is much slower in comparison to resource scheduling.

In future 5G/5G+ networks, an envisioned characteristic of the networks is heterogeneity. It is expected that the network infrastructure will be heterogeneous in 5G/5G+ networks including different types of access points and base stations such as macro-BSs, pico-BSs, and femto-BSs. On the other hand, due to the emergence of various applications with different rate requirements, the traffic distribution is becoming highly heterogeneous (non-uniform)² both in the time domain and the space domain. Therefore, a desirable admission control mechanism must be able to work in heterogeneous wireless networks with heterogeneous traffic distributions (HetHetNets) [1]–[4].

A. Contributions of This Paper

In this paper, a novel mechanism for admission control of VN requests is proposed which is also applicable to HetHetNets. The VN admission control construct is formulated as a convex problem which is tractable and efficient to solve.

The main contributions of this paper are summarized as follows:

- We propose a wireless VN admission control mechanism which incorporates feedback information to the customer to update its traffic profile according to the real traffic measurements conducted by the VN service provider. This results in more accurate traffic specification and better

²In this paper, we use the terms “heterogeneous” and “non-uniform” interchangeably. Similarly, we use the terms “homogeneous” and “uniform” interchangeably.

QoE. The proposed methodology is applicable to any traffic profile including heterogeneous scenarios and HetHetNets.

- We formulate VN admission control as a convex optimization problem which is computationally tractable and efficient. We also present a number of extensions which incorporate network cost minimization and network backhaul limitations in the problem.
- Our proposed VN admission control method allows general multiple association between UEs and BSs. The simulation results verify that a higher number of VN requests can be admitted to the network using the proposed technique compared to the existing methods.

B. Related Works

Admission control is a very well investigated concept and there is a great volume of literature focusing on various aspects of admission control [5]–[8]. However, since the idea of network virtualization is relatively new [9]–[11], admission control for VNs, also referred to as VN embedding, has been a hot research topic recently [12]–[15]. Indeed, admission control problem is studied very well for an individual user or an individual session but the admission control of groups of users and VN requests is relatively recent.

Although there is a rich literature on VN admission control [16] in wired networks, there are only few works on wireless VN admission control [17]–[22]. In [17] and [18], fixed snapshots of UEs are considered, but the statistical specifications of traffic demand are not incorporated. In [19]–[22], the authors consider statistical arrival of VN requests with statistical demands. However, the demand and the resources are not specified in rate or delay, but rather in number of channels. To be more accurate, these papers assume that customers require a specific number of wireless channels, and the network allocates a number of channels to each UE upon availability, i.e., the spectral efficiency is not included in the allocation scheme and rate satisfaction is not the ultimate objective in these works.

The novelty and advantage of the proposed framework in this paper is that we consider the customer satisfaction in terms of rate, packet delay, and outage probability at the same time which are the important performance indicators and relevant QoE parameters for customers. We also assume that VN customers have statistical demand profiles and the traffic density is specified for each VN and for various areas of the network.

In [6], a comprehensive classification of admission control methods is provided. The first categorization is on central versus distributed methods. Even though the central methods, due to the availability of more network-wide information, achieve higher efficiency, they are not appropriate for single-session admission control since they are more complicated and result in long delays in decision making while users might have strict thresholds. However, in VN admission control, delay tolerance is higher and the utilization of centralized schemes is extremely beneficial. In this paper, we propose a centralized admission control scheme which takes place in NOS.

The next classification in [6] is single-class admission control versus multiple-class admission control. In traditional wireless

networks, since the main network service was voice call, single-class admission control schemes were beneficial. However, in 3G, 4G, and 5G/5G+ networks, multimedia services with different QoE requirements are required. So, multiple-class admission control schemes are needed. The VN admission control method proposed in this paper is multiple-class and highly flexible in QoE specification.

Finally, the last classification is channel-quality-based versus rate-based methods. In the admission control methods which are based on channel quality, the new customer is admitted if the channel quality is higher than their requirements. On the other hand, in rate-based admission control methods, the new customers are admitted if their required rate can be provided. Although channel-quality-based methods are mathematically easier to deal with, they are less relevant in future networks where BS load is a pivotal criteria and UE rates are totally dependent on BS load as well as channel quality. Our proposed method in this paper is rate-based.

C. Organization of the Paper

The remaining of this paper is organized as follows. In Section II-A, we introduce the system model and define the problem. In Section III, we present our novel wireless VN admission control methods and mechanism. Section IV presents the simulation parameters and experimental results. The paper is concluded in Section V with some remarks and future work directions.

II. SYSTEM MODEL AND PROBLEM DEFINITION

In this section, we describe the system model and parameters (Section II-A), and define the wireless VN admission control problem in specific terms (Section II-B).

A. System Model

We consider a software-defined radio access network (SD-RAN) with limited backhaul capacities and general access parts. Target systems could be, but are not limited to, WiMAX2, Wi-Fi, 4G LTE, 5G/5G+ HetNets or a combination of them. We focus on downlink in this paper but our method is also applicable to uplink. In particular, in this paper we focus on admission or rejection of VNs according to the downlink requirements. However, the uplink requirements, or a combination of downlink and uplink requirements, can also be considered.

We should point out that there can be two dimensions of heterogeneity in traffic:

- The first dimension is heterogeneity in time domain, meaning that traffic might vary over time for one user.
- The second dimension is heterogeneity in the space domain, meaning that density of network users might vary over space in the network.

In this paper, we mainly focus on the heterogeneity and complexity of traffic in the space domain with adding non-uniform traffic distribution for various VNs. We hope that this paper triggers interest in the research community to add time domain heterogeneity to the problem.

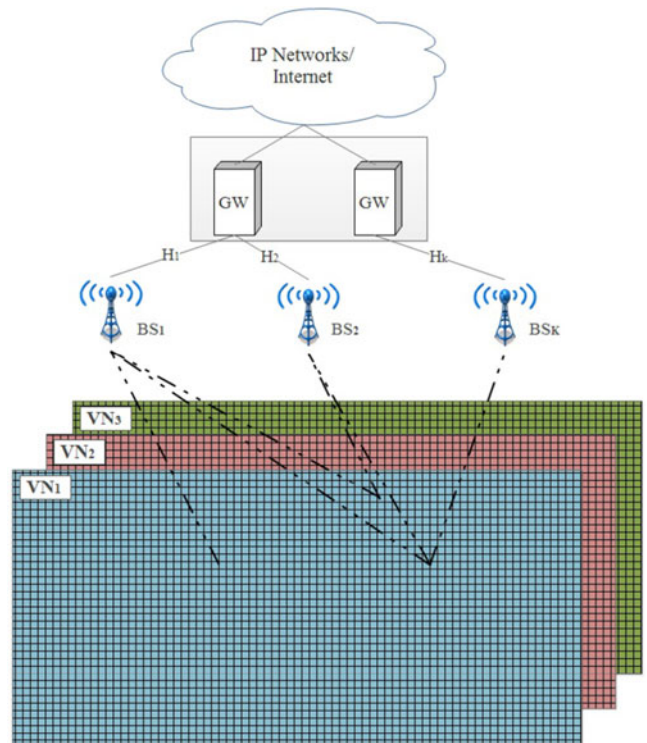


Fig. 3. System model: VNs with heterogeneous traffic profiles to be served by a general SN with backhaul capacity limits. Every bin can be associated to one, two, or multiple BSs.

We consider a geographical region $L \subset \mathbb{R}^2$ (i.e., two dimensional plane) as the network layout that is served by a set of BSs B . Each BS is characterized by its transmit power, backhaul capacity H_k , $k \in K = \{1, \dots, |B|\}$, and its available bandwidth W_k , as shown in Fig. 3. In this paper, we always use k as the index for BSs.

Let $l \in L$ denote a location on the network layout. We assume that demand arrivals for the i th VN, $v_i \in V$, at location l and at time t , d_{il}^t , are random variables that follow arbitrary distributions with mean λ_{il}^t , where V is the set of VNs. This provides flexibility for inhomogeneous, i.e., heterogeneous or non-uniform, traffic characterization. We always use i for indexing VNs. Detailed investigation of heterogeneous traffic modeling is performed in [1]–[3]. To avoid notation complexity, we drop the time index t in this paper. It can be shown that our results can be easily extended to span time-varying traffic statistics by profiling traffic for specific times of day, week, or year. Moreover, to avoid unnecessary technical difficulties, in this paper, we assume that the region L is divided into a set of small (e.g., 5 m \times 5 m) bins (areas) $a \in A$, and the demand for each bin is defined as

$$d_{ij} = \int_{l \in a_j} d_{il}, j \in J, i \in I, \quad (1)$$

where j is used for indexing bins, $J = \{1, \dots, |A|\}$ is the set of bin indices, and $I = \{1, \dots, |V|\}$ is the set of VN indices.

In this paper, we assume that the BSs transmit with constant (not necessarily equal) power; we leave power control extension as a future work. The signal-to-interference-plus-noise ratio (SINR) for the center of bin $a_j \in A$ if it is connected to BS

TABLE I
LIST OF SYMBOLS

Symbol	Definition
L	Network region
B	Set of BSs
b	A typical BS
l	A typical location
d	Traffic demand matrix
λ	Traffic demand mean matrix
t	Time index
A	Set of bins
a	A typical bin
k	BS index
K	BS index set
j	Bin index
J	Bin index set
i	VN index
I	VN index set
V	Set of VNs
P	Received power matrix
P_N	Noise power
γ	SINR matrix
η	SE matrix
U	BS maximum utilization array
O	Outage requirement array
C	Coverage requirement array
D	Delay requirement array
H	BS backhaul capacity array
W	BS available bandwidth array
x	Rate association matrix
M	BS loads array
r	Total received rate matrix
Δ	Average of experienced delay matrix
Θ	Experienced delay matrix
ξ	Experienced coverage matrix
χ	Network cost

$b_k \in B$ is defined as

$$\gamma_{jk} = \frac{P_{jk}}{P_N + \sum_{j' \in J \setminus j} P_{j'k}}, \quad (2)$$

where P_{jk} is the effective received power from BS b_k , $k \in K$ at bin a_j , and P_N is the noise power.

The received power can be calculated based on path-loss exponent and channel models as well as the other environmental parameters. In practical cases, it also can be collected from field measurements. Spectral efficiency (SE) can be any arbitrary function of SINR in this method. In our simulations, we assume that it follows the Shannon's formula as follows:

$$\eta_{jk} = \log_2(1 + \gamma_{jk}). \quad (3)$$

For the sake of a better readability and an easier understanding, a list of parameters used in this paper with their associated symbols are summarized in Table I.

B. Problem Definition

In this paper, we assume that QoE expectations are specified by each customer and each VN, $v_i \in V$, by three main parameters:

- 1) the required traffic demand which is specified by the traffic demand matrix d , or more specifically, by the distribution parameters of traffic in each bin,

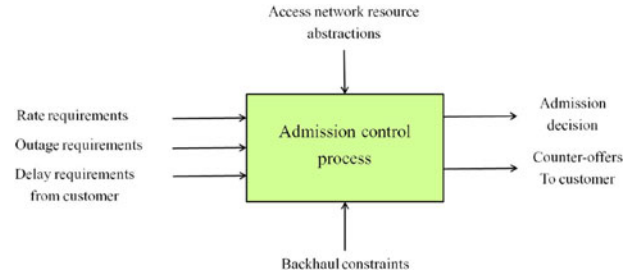


Fig. 4. Specific input parameters and outputs of the admission control process are illustrated.

- 2) the required maximum outage O_i (or equivalently, the required minimum coverage probability C_i),
- 3) and the required maximum delay D_i , or the delay thresholds with associated probabilities.

In the heterogeneous wireless network system described in Section II-A, VN requests arrive with specific traffic profiles and QoE requirements. Upon the arrival of each new VN request, the VN admission control problem must be executed and solved to decide whether or not the newly arrived VN request can be admitted and incorporated in the system, with all of its QoE requirements satisfied, and without affecting the already existing VNs' services.

One of the main QoE parameters considered in this paper is the coverage. We define network coverage in this paper as follows:

Coverage probability for one VN is the probability of the weighted average of the traffic demand for VN users being less than the total rate that can be delivered to the user by the network resources including all of the BSs in the network.

A mathematical description of coverage probability is given in Section III-B.

Fig. 4 shows the input parameters and the side information which is entered in the admission control module along with the possible outputs driven from solving the admission control problem.

III. ADMISSION CONTROL FOR VIRTUAL NETWORKS

In this section, the admission control process and method for virtual networks is described. Section III-A describes the broad view of the VN admission control process. The multiple association optimization method for VN admission control is explained in Section III-B, and proved to be convex in Section III-C. Two extensions are added to the optimization framework in Section III-D.

A. Admission Control Process

The broad view of the proposed VN admission control process is illustrated in Fig. 5. Fig. 5 depicts a comprehensive procedure for admission control of VNs which includes the interface to the customers and network operation feedback. The various steps of the process are explained from upper-left corner as follows:

- The VN customers provide their QoE expectations including the demand statistics, outage requirements, and delay requirements.

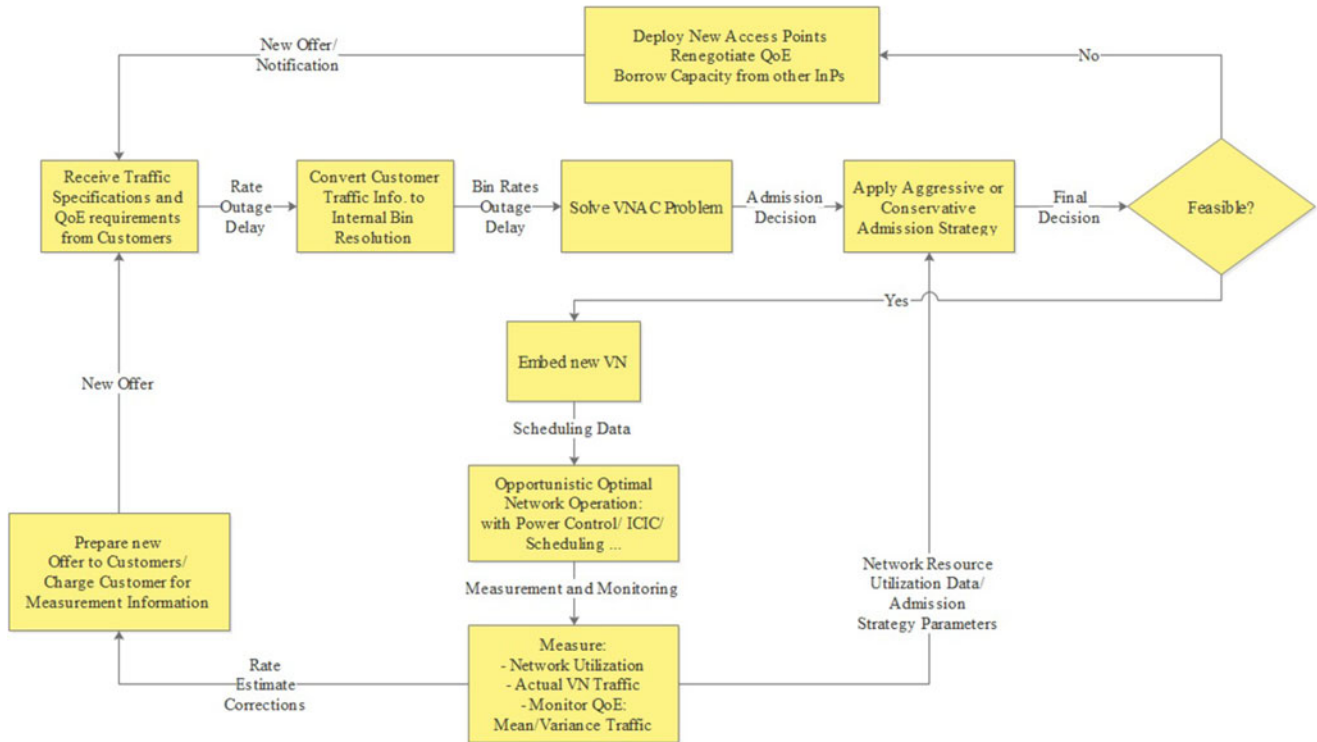


Fig. 5. VN admission control process: network-wide traffic measurement provides feedback information for the customers, traffic monitoring for QoE assurance, and possibility for an aggressive admission.

- The demand statistics might be provided by the customer in a resolution different than the network. Therefore, they must be converted to the network bin resolution. The customer may specify the overall mean rate only, he can specify some hotspots, or he can specify very detailed demand information.
- The VN admission control problem is executed and solved using convex optimization method explained later in Section III-B. This part is the main problem solving element of the VN admission procedure.
- If a VN is admitted to the system, after embedding the VN into system, the scheduling is done opportunistically, even though the admission was done statistically. This means that a better QoE can be achieved in comparison to what admission control is based on. On the other hand, the network operator might be aware of some inefficiency which cannot be quantified in the admission control problem. Therefore, the network operator may decide to do an aggressive or conservative admission.
- If the final decision is to reject the new VN request, there are some alternative actions including: deployment of new access points (e.g., femto or pico at hotspots), negotiating the QoE parameters with customer, borrowing some resources from the other infrastructure providers, and guiding customers to move to better locations if possible (e.g., user-in-the-loop [23]).
- If the final decision is to admit the new VN request, then the new VN is embedded into the system (resources are reserved and setup is done). In the operation phase,

scheduling can be performed with power control and inter-cell interference coordination (ICIC) [24].

- A very important part of the VN admission control process is monitoring. Monitoring the network includes measurement of VN traffic and network utilization. Monitoring provides three main advantages:
 - 1) Network resource utilization can be measured. This information can be fed back to the admission control function. For instance, if the utilization is low, then an aggressive admission can be performed and if the utilization is very high, then admission must be conducted conservatively. Presume that always less than U_k % of the resources in BS b_k are used during the network operation. In this case, the effective bandwidth for this BS that can be used for future admission control can be W_k/U_k .
 - 2) Traffic demands for VNs must be measured. This assures that the customers are following the contracts. For instance, the mean and the standard deviation of the traffic for each VN at each bin can be calculated to make sure that it follows the promised statistics.
 - 3) The actual measured traffic statistics can be fed back to customers (for a particular fee) to correct their initial estimations. Many VN customers don't have the measurement facilities and can benefit from this information and correct their traffic profiles.

The explained process is a comprehensive reference procedure that might be implemented partially or fully by a network operator to consider different aspects of VN admission control.

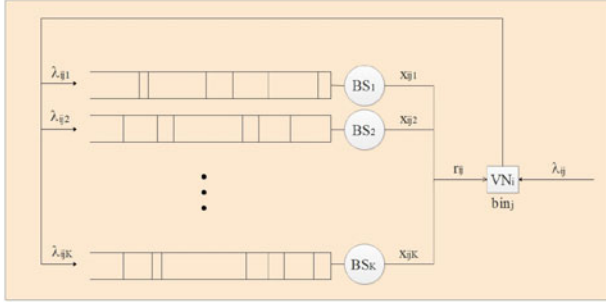


Fig. 6. The downlink queues in BSs: every bin is served by multiple BSs with downlink queues which have different arrival rates and service rates which can be modeled by separate parallel M/M/1 queues.

In this paper we focus on the main admission problem which is cast as a convex optimization problem in Section III-B.

B. Admission Control Method

While the simplest (and mostly used) UE-BS association is based on maximum received power and maximum SINR (max-SINR), technology advances in future wireless networks allow for general multiple association in which a UE (or a bin in this paper) can be associated to multiple BSs, or to a BS with low SINR but high available bandwidth.

It is shown in the recent literature [25]–[27] that general association can result in significant improvement in network key parameter indicators, specially in future HetNets where small cells have limited coverage areas hence lower load compared to macro cells. In this section, a VN admission control method with general association is proposed.

First, note that VN admission control problem is a feasibility problem in which we are not trying to improve an objective function as the ultimate goal is to determine if some admission control constraints can be satisfied or not. Let x_{ijk} denote the amount of rate received from BS $b_k \in B$ at bin $a_j \in A$ by VN $v_i \in V$. The objective of the optimization is to find a solution x^* that satisfies optimization constraints.

The first constraint is that the sum of the resources allocated by each BS to all bins cannot exceed its available resources:

$$C1: \quad M_k = \sum_{i \in I} \sum_{j \in J} \frac{x_{ijk}}{\eta_{jk}} \leq W_k, \forall k \in K, \quad (4)$$

where M_k is the amount of used resources from BS k , W_k is the available resources, and η_{jk} is the effective spectral efficiency experienced from BS k at bin j .

Assuming that session inter-arrival time in the time domain is exponentially distributed and is independent at all bins for all VNs, and the session sizes are distributed independently and exponentially, the downlink queues in BSs can be modeled by parallel M/M/1 queues as illustrated in Fig. 6.

We know that the total arrival rate for VN $v_i \in V$ at bin $a_j \in A$ is λ_{ij} . Now assume that the arrived session requests are sent to BS $b_k \in B$ with probability p_{ijk} . Then, the effective arrival rate for this BS is $\lambda_{ijk} = p_{ijk} \lambda_{ij}$ where

$$\sum_{k \in K} p_{ijk} = 1, \quad \forall i \in I, \forall j \in J. \quad (5)$$

Therefore, the second constraint is as follows:

$$C2: \quad \sum_{k \in K} \lambda_{ijk} = \lambda_{ij}, \quad \forall i \in I, \forall j \in J. \quad (6)$$

Based on Burke's theorem on parallel queues [28], the average service delay for each bin $a_j \in A$ for each VN $v_i \in V$ from BS $b_k \in B$ is defined as

$$\Delta_{ijk} = \frac{1}{x_{ijk} - \lambda_{ijk}}. \quad (7)$$

The third constraint is that each VN at each bin cannot experience a delay higher than its required maximum delay (note that delay requirement is defined only for time sensitive services). The maximum experienced delay by each VN at each bin is the maximum experienced delay in all parallel queues. Therefore,

$$\max_{k \in K} \Delta_{ijk} \leq D_i, \forall i \in I, \forall j \in J. \quad (8)$$

Delay requirement can also be defined by customers for every single bin. In that case, D_{ij} , the delay requirement matrix will replace D_i , the delay requirement array. However, this is not a common case and is not considered in this paper.

In (8), the maximum delay for all parallel queues must be less than or equal to the delay threshold. This means that all delays for all parallel queues must be less than or equal to the delay threshold (third constraint):

$$C3: \quad \Delta_{ijk} \leq D_i, \forall i \in I, \forall j \in J, \forall k \in K. \quad (9)$$

The total delay experienced by UEs is the sum of all delays from the moment that the service request is submitted to the wireless system until the moment when the UE receives the service. For instance, backhaul transmission might add considerable delay in service. Processing delay (in BS as well as in UE) and propagation delay also must be added to the total delay. In this paper, we only considered the queuing and wireless service delay for downlink part, assuming that other delays sum up to zero.

For all the queues in the BSs to be stable, it is also necessary that all arrival rates in all queues be less than service rates:

$$C4: \quad \lambda_{ijk} \leq x_{ijk}, \forall i \in I, \forall j \in J, \forall k \in K. \quad (10)$$

Also note that in (9) we are limiting the maximum of the average experienced delays Δ_{ijk} to be less than tolerance threshold D_i . However, this can be extended to any percentile of delays. To be more specific, assume that we want the experienced delays Θ_{ijk} to be less than a threshold D_i with a probability of q :

$$\Pr\{\Theta_{ijk} \leq D_i\} \geq q, \forall i \in I, \forall j \in J, \forall k \in K. \quad (11)$$

This means that we want the cumulative distribution function (CDF) of delays to be greater than q at D_i :

$$F_{\Theta_{ijk}}(D_i) \geq q, \forall i \in I, \forall j \in J, \forall k \in K. \quad (12)$$

From M/M/1 queue analysis, it is known that the delay has an exponential distribution with parameter $x_{ijk} - \lambda_{ijk}$ [29]. Therefore, (12) can be written as

$$1 - \exp(-D_i(x_{ijk} - \lambda_{ijk})) \geq q, \forall i \in I, \forall j \in J, \forall k \in K, \quad (13)$$

which can be in turn simplified to

$$x_{ijk} - \lambda_{ijk} \geq \frac{-\log(1-q)}{D_i}, \forall i \in I, \forall j \in J, \forall k \in K. \quad (14)$$

Finally, the last constraint is that coverage probability for all customers must be higher than the minimum required coverage. The coverage probability for a VN $v_i \in V$ for one bin $a_j \in A$ is equal to the probability that the demand for this VN in this bin is less than its received rate from all BSs:

$$\xi_{ij} = \Pr\{d_{ij} \leq r_{ij}\}, \quad (15)$$

where r_{ij} is the total rate received by VN $v_i \in V$ at bin $a_j \in A$:

$$\text{C5: } r_{ij} = \sum_{k \in K} x_{ijk}, \forall i \in I, \forall j \in J. \quad (16)$$

To calculate the coverage probability for a VN over the entire network, one way is to take the normal average. However, since different bins have different traffic demands, a better measure is a weighted average:

$$\xi_i = \frac{1}{\lambda_i} \left(\sum_{j \in J} \lambda_{ij} \cdot \xi_{ij} \right), \quad (17)$$

where $\lambda_i = \sum_{j \in J} \lambda_{ij}$ is the total demand for VN $v_i \in V$. Therefore, the last constraint is

$$\text{C6: } \xi_i \geq C_i, \forall i \in I. \quad (18)$$

In summary, the VN admission control problem can be cast as the following problem:

$$\text{find}_{x,r,\lambda} x \quad \text{subject to: C1–C6.} \quad (19)$$

C. Convexity of the Problem

A mathematical optimization problem can be solved efficiently and methodically if it can be cast as a convex problem [30]. A problem is convex if the objective function and the constraints are convex functions. In this section, we show that the problem (19) is convex and can be solved efficiently with well-known convex optimization tools and optimization methods such as interior point methods. Interior point methods are a certain class of algorithms that solve linear and nonlinear convex optimization problems [30].

In (19), the constraints C1–C5 are convex w.r.t. x , λ , and r . So, the problem is convex if the last constraint (C6) is convex. First, note that C6 is convex if ξ_i is a concave function of r . Also note that ξ_i is a summation of ξ_{ij} . So, it is concave if ξ_{ij} is a concave function w.r.t. r . From (15) it is clear that ξ_{ij} is the CDF of d_{ij} at r_{ij} . Therefore, (19) is a convex optimization problem if d has a concave CDF. It can be easily shown that the exponential distribution and uniform distribution have concave CDFs. The CDF of the exponential distribution is defined as

$$F_X(x) = 1 - \exp(-\Lambda x), \quad (20)$$

for parameter Λ , which has the following second derivative:

$$\frac{d^2 F}{dx^2} = -\Lambda^2 \exp(-\Lambda x), \quad (21)$$

which is always negative.

The CDF of uniform distribution is defined as

$$F_X(x) = \frac{x-a}{b-a}, \quad (22)$$

for parameters a and b , which is a linear function.

It can also be shown that Gaussian distribution has a concave CDF for $r \geq \lambda$. The CDF of the Gaussian distribution is defined as

$$F_X(x) = \frac{1}{2} \left[1 + \text{erf} \left(\frac{x-\mu}{\sqrt{2}\sigma} \right) \right], \quad (23)$$

for parameters μ and σ , where $\text{erf}(\cdot)$ is the error function defined as

$$\text{erf}(x) = E(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2) dt, \quad (24)$$

which has the following second derivative:

$$\frac{d^2 E}{dx^2} = \frac{-4x}{\sqrt{\pi}} \exp(-x^2), \quad (25)$$

which is negative for positive x . Poisson distribution can be approximated by Gaussian distribution with very high accuracy for $\lambda > 1000$ [31].

D. Extensions

Solving (19) returns a x value that satisfies the constraints C1–C6. However, there is no guarantee that the result is the best result. For instance, there might be other x values which satisfy the constraints and also result in lower energy consumption or network cost.

The first proposed extension to problem (19) is to minimize the network cost while trying to find a solution which satisfies all constraints:

$$\text{minimize}_{x,r,\lambda} \chi \quad \text{subject to: C1–C6,} \quad (26)$$

where the network cost χ can be any convex function of the variables x . One common way of defining the network cost is an exponential function of BS load:

$$\chi = \sum_{k \in K} e^{M_k}. \quad (27)$$

This definition results in a degree of load balancing among BSs. Another definition that results in min-max load balancing is the following:

$$\chi = \max_{k \in K} M_k. \quad (28)$$

In the formulation of VN admission control problem in (19), the backhaul capacities are not considered. In other words, there might be situations where the access part of a BS has enough capacity to serve high number of UEs while the backhaul capacity is limited. In particular, in the future 5G/5G+ HetNets, whereby femto BSs will be deployed by customers and operators will face deployment restrictions (or cost considerations) to lay fiber in many areas, it is not realistic to presume that backhaul links have unlimited capacities.

In a wireless network with ideal backhaul connections, the lack of capacity is mainly due to the access connection limitation, that is, the wireless access problem and low channel quality between UEs and BSs. However, in the envisioned 5G/5G+ networks with small cells deployed in residential and office buildings, the assumption of ideal backhaul is more optimistic than realistic, especially considering the fact that a main portion of the small cells (i.e., femto-cells) will be deployed by customers rather than service providers. Recently, there has been increasing interest in the literature in the study of limited backhaul capacities in future HetHetNets [4], [32].

The next proposed extension for problem (19) is to take backhaul constraints,

$$C7: \sum_{i \in I} \sum_{j \in J} x_{ijk} \leq H_k, \forall k \in K, \quad (29)$$

into account and reformulate (19) as

$$\text{minimize}_{x,r,\lambda} \chi \quad \text{subject to: C1–C7.} \quad (30)$$

IV. EXPERIMENTAL RESULTS

Considering the system explained in Section II-A, in this section, the experimental results are presented that show the efficiency of the VN admission control methodology proposed in Section III. The simulation parameters and setup are described in Section IV-A, and the simulation results are presented in Section IV-B.

A. Simulation Setup and Parameters

We use a MATLAB based simulation to verify our analytical results drawn in Section III. The network is comprised of 19 macro-cells on the X-Y plane with 3-sector antennas (57 sectors in total) and 57 pico-cells randomly and uniformly deployed in the plane with omni-directional antennas. The inter-site distance among macro-BSs is 150 meters. The antenna height is considered 32 meters for macro-BSs and 10 meters for pico-BSs.

In this paper, we used proportional fair scheduling method for the simulations [33]. As discussed in the system model, Section II-A, users are assumed to be distributed according to the user density of VNs admitted to the network with heterogeneous traffic profiles and each user generates M/M/1 traffic in the time domain.

The entire network is divided into $5 \text{ m} \times 5 \text{ m}$ bins and the spectral efficiency for the bin centers represents each bin. The path-loss exponent and the channel model is based on 3GPP Technical Report on further advancements for E-UTRA physical layer aspects (3GPP TR 36.814) [34]. The shadowing model is also from [34]. BS transmit power is 46 dBm for macro-BSs and 30 dBm for pico-BSs and fading is not considered (assumed to be averaged over time). The noise power is $P_N = -174$ [dBm/Hz] and each BS has 10 MHz bandwidth for downlink. Table II summarizes the simulation parameters used in this paper.

It is important here to mention that there are two aspects of traffic modeling in a wireless cellular network: traffic distribution in the time domain, and traffic distribution in the space

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Number of macro-BSs	19
Number of pico-BSs	57
Number of sectors for each macro-BS	3
Inter-site distance for macro-BSs	150 m
Pico-cell deployment	uniform PPP
Macro-BS antenna height	32 m
Pico-BS antenna height	10 m
Bin size	$5 \text{ m} \times 5 \text{ m}$
Noise power	-174 dBm/Hz
Bandwidth for each BS	10 MHz
Macro-BS transmit power	46 dBm
Pico-BS transmit power	30 dBm
Shadowing	specified in [34]
Macro-BS antenna gain	14 dB
Pico-BS antenna gain	5 dB
UE antenna gain	0 dB
Scheduling	Proportional Fair
Traffic distribution in time	M/M/1

domain. In a wired network, since the noise, interference, and in general, signal strength are not the main concern, only traffic modeling in the time domain has been investigated in the literature. However, in wireless networks, the user locations, BS locations, and in general, space domain modeling is a main concern and is studied and investigated deeply in the literature.

In this paper, the main focus and novelty is in the space domain. The M/M/1 modeling in the time domain is only considered for the purpose of simulation. Otherwise, we are not claiming any investigation or novelty in traffic modeling in the time domain.

B. Simulation Results

In the first experiment, we generate VNs with spatially uniform traffic, i.e., homogeneous Poisson point process (PPP). Each VN has mean traffic demand density of 0.2 Mbps at every bin. We increase the number of VNs and measure the maximum coverage probability (we assume that coverage requirement for all VNs is equal). Fig. 7 illustrates the achievable coverages (customer satisfactions) versus the number of VNs. Obviously, with an increasing number of VNs, the coverage decreases.

We compare our analytical method (optimization) with simulation results obtained via simulation of 1000 drops of traffic demands. Here we assume that the rate given to a VN at a bin by each BS is fixed during network operation because the admission decision is made at the time of VN arrival. As presented in Fig. 7, the simulation results verify the analytic method results.

In our VN admission control method, we use general association for bins, meaning that every bin can be served by multiple BSs. In Fig. 8, we compare a VN admission control method with multiple association to a VN admission control method without multiple association. The most popular alternative is max-SINR association in which each UE connects to the BS with most strong SINR.

The next alternative association is to run general multiple association optimization and find the rate values x^* ; Then associate each VN at each bin to the BS with maximum

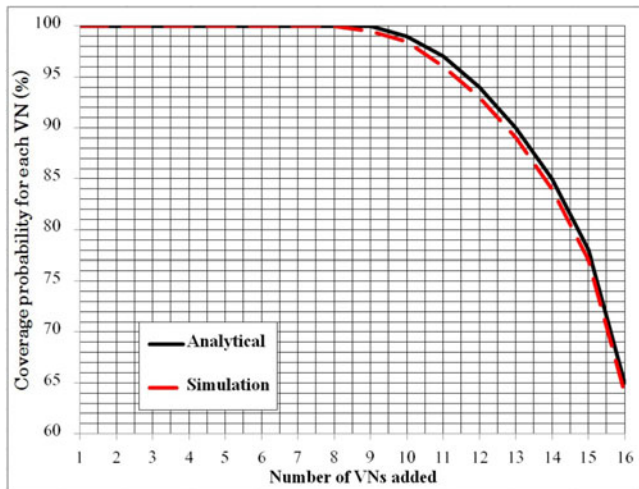


Fig. 7. Analytical results versus simulation results: the small difference between the simulation and analytical results is in part due to the limited number of drops and shows the accuracy of the optimization results.

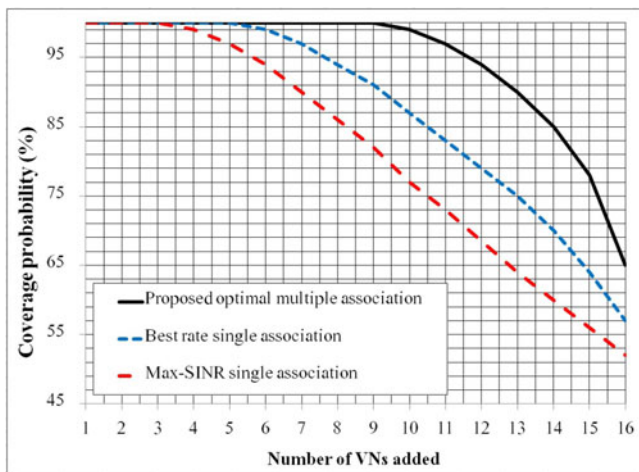


Fig. 8. A VN admission control method with multiple association is compared to single association and max-SINR association methods. Multiple association leads to significant increase in network performance hence VN admission control results.

rate, i.e.,

$$m_{ij} = \arg \max_k x_{ijk}. \quad (31)$$

This method is called best-rate association in which instead of SINR, achieved rate is evaluated as the decision making criteria for associating users to BSs.

Fig. 8 shows that multiple association results in significant increase in network performance and subsequently number of admitted VNs with high QoE requirements.

Table III compares the number of VNs admitted with different QoE requirements for multiple association versus max-SINR association.

One of the advantages of our proposed VN admission control method is that the customer traffic specification is not limited and can be any distribution with concave CDF. As a main result, the customer traffic profiles can be heterogeneous. In this section,

TABLE III
MULTIPLE ASSOCIATION VERSUS MAX-SINR ASSOCIATION

QoE requirement	max-SINR	multiple association
100%	3 VNs	9 VNs
98%	4 VNs	11 VNs
88%	6 VNs	14 VNs

TABLE IV
THE IMPACT OF TRAFFIC SPATIAL HETEROGENEITY

Traffic	100%	98%	88%
PPP	9 VNs	11 VNs	14 VNs
Matern	4 to 12 VNs	5 to 14 VNs	6 to 16 VNs

we investigate the impact of traffic heterogeneity on the VN admission control results.

We generate two different traffic profiles. The first profile is a homogeneous PPP with constant density all over the network while the second profile is a clustered distribution with the same total density. In the clustered distribution, a Matern-like [35] distribution is applied. First, we select a number of cluster center locations which are uniformly distributed in the network. Then, the bins around the cluster centers (with certain radius) have higher density while the other bins have low or zero density.

Table IV summarizes the number of VNs with certain satisfaction requirements for homogeneous PPP versus Matern heterogeneous PPP with 10 cluster centers. As expected, the number of admitted VNs in a network with heterogeneous traffic depends on the cluster locations and varies in a range. If the clusters shape near BSs, then the network performance increases and if the clusters shape far from BSs (at cell edges), then the network performance decreases.

Two main parameters can be changed to illustrate the impact of traffic heterogeneity on the admission control process:

- The first parameter is the level of heterogeneity of traffic. This can be captured by many metrics including coefficient of variation (CoV) introduced and explained in [2] and [1]. CoV (explained below) value of 0 indicates complete homogeneity and CoV value of 1 indicates complete randomness. The higher CoV value shows more heterogeneity as shown in Fig. 9.
- The second parameter is the correlation between UE traffic and BSs (ρ) which ranges from -1 (where all UEs are at the cell edges) to $+1$ (where all UEs are at the cell centers) [1].

A very important problem in heterogeneous traffic modeling is the measurement of the level of the heterogeneity. It is crucial to have a benchmark metric which determines the heterogeneity of the distribution with one (or few) parameter(s), so it is easy for everybody to gain an understanding of the level of clustering of traffic by having this metric value. In [2], we proposed simple metrics for the measurement and understanding of the heterogeneity of spatial point patterns. Specifically, we proposed the statistical characteristics of the random tessellations of point distributions as accurate and very appropriate metrics of spatial heterogeneity. We showed that the coefficient of

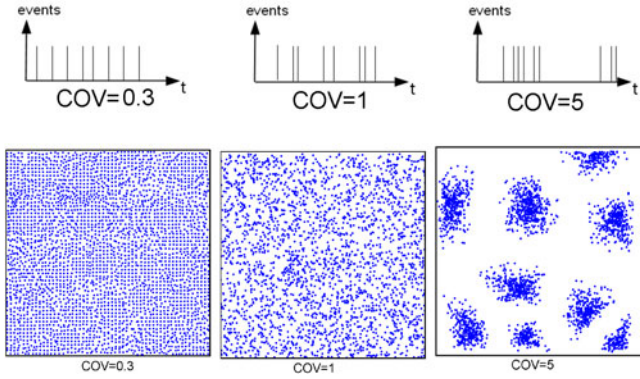


Fig. 9. CoV value of 0 indicates complete homogeneity and CoV value of 1 indicates complete randomness. The higher CoV value shows more heterogeneity.

TABLE V
THE IMPACT OF TRAFFIC CORRELATION WITH BSS (CoV = 2)

ρ	100%	98%	88%
-0.5	7 VNs	9 VNs	11 VNs
0	9 VNs	11 VNs	14 VNs
+0.5	10 VNs	13 VNs	15 VNs

TABLE VI
THE IMPACT OF TRAFFIC CORRELATION WITH BSS (CoV = 3)

ρ	100%	98%	88%
-0.5	5 VNs	8 VNs	10 VNs
0	9 VNs	11 VNs	14 VNs
+0.5	11 VNs	14 VNs	16 VNs

variation (CoV), defined as the standard deviation σ divided by mean μ , $(\frac{\sigma}{\mu})$, is a revealing statistical parameter which captures a majority of the statistical characteristics of a metric. We also showed that the geometrical inferences of conventional tessellations such as Voronoi tessellations and Delaunay tessellations are very promising candidates. Such metrics as Voronoi-cell-areas and Delaunay-cell-edge-lengths are shown to be accurate enough and can be considered as analogues of popular inter-arrival-times metric in the temporal traffic modeling.

A CoV value of 0 means that the users are organized in a very structured manner and the Voronoi cells and Delaunay cells are all equal. A CoV value of 1 is associated with a completely random distribution where users are PPP distributed. CoV values between 0 and 1 refer to sub-Poissonian distributions in which the distribution is more homogeneous than Poisson. Finally, a CoV value of more than 1 means that the points are distributed heterogeneously (or non-uniformly) compared to PPP (super-Poissonian).

In the next experiment, the UE clusters are changed to show the effect of traffic correlation to BSSs. Tables V–VII show the maximum number of admitted VNs with various coverage requirements and correlation between traffic and BSSs for different CoV values.

One of the enhancements which was suggested on the admission control algorithm was to consider network resource cost

TABLE VII
THE IMPACT OF TRAFFIC CORRELATION WITH BSS (CoV = 4)

ρ	100%	98%	88%
-0.5	4 VNs	7 VNs	8 VNs
0	9 VNs	11 VNs	14 VNs
+0.5	12 VNs	15 VNs	17 VNs

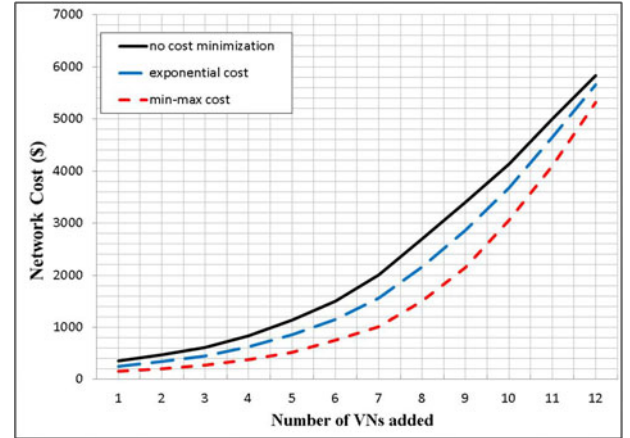


Fig. 10. The network cost can be minimized while admission control optimization algorithm determines if the VNs can be admitted to the network. Network cost increase is illustrated for exponential cost calculation and min-max cost calculation.

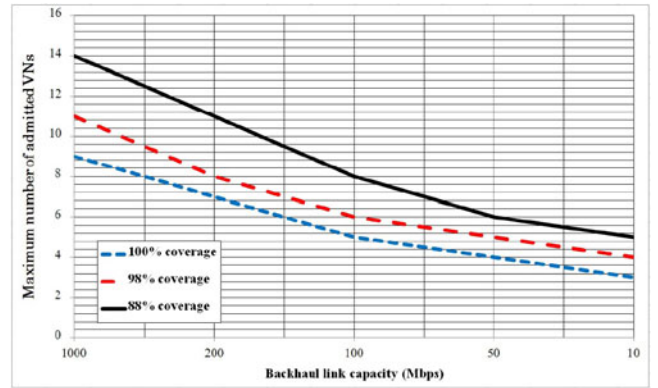


Fig. 11. The figure shows the number of admitted VNs in backhaul limited scenarios. As expected, the number of admitted VNs goes down with decreasing the backhaul limits.

as an objective function to minimize. To illustrate the impact of network cost minimization, in the next step, we compare the network cost when we use two different problems proposed in (19) and (26). For the calculation of network cost we can use either of the two formulas presented in (27) and (28). The cost of the resources is assumed to be one dollar per MHz. Fig. 10 shows the network cost for the service provider using different admission control methods versus the number of admitted VNs.

Finally, the last experiment is to capture the effect of backhaul limits on the performance and the number of VNs which can be admitted with certain coverage requirements. For this purpose, we decrease the backhaul limits of the pico-BSSs and leave the backhaul limits of macro-BSSs to be unlimited. As expected,

the number of admitted VNs goes down with decreasing the backhaul limits. Fig. 11 illustrates the maximum number of admitted VNs versus the capacity of the backhaul links of the pico-BSs.

V. CONCLUDING REMARKS

We proposed an analytical solution for virtual network admission control problem in future software-defined wireless networks. In particular, we presented an admission control procedure which includes a feedback mechanism to correct customer traffic information. We also proposed an optimization framework for virtual network admission control which allows various options and flexibility for specification of customer traffic and considers all important QoE parameters including rate, delay, and outage. We also proposed two extensions to consider network cost and backhaul limitations in the problem.

The simulation results reveal a number of interesting observations:

- First, the simulation results and the expected analytical results are closely matched. This shows that the optimization method provides accurate solutions and can be used to insure customer QoE as well as high network utilization.
- Secondly, the multiple association method out-performs the best rate single association method and the max-SINR association method.
- Finally, the heterogeneity in VN demand profiles results in a wide range of admission scenarios. In the cases where the UE clusters are close to the BSs, a higher number of VNs can be admitted; while in the cases where the UE clusters emerge in cell edges, less VNs with the same requirements can be admitted into the system.

This work can be extended in many directions. First, the power control is not considered in our method and we assumed that transmit power is constant. However, power control can increase the network performance, hence the number of admitted VNs. Secondly, we assumed that all BSs transmit on all channels and there is no interference control. Adding inter-cell interference coordination (ICIC) improves the network performance and can be considered as an extension of this work. Finally, the temporal aspects of traffic modeling can be investigated and more complicated models other than M/M/1 modeling can be considered in the time domain.

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REFERENCES

- [1] M. Mirahsan, R. Schoenen, and H. Yanikomeroglu, "HetHetNets: Heterogeneous traffic distribution in heterogeneous wireless cellular networks," *IEEE J. Sel. Areas Commun. (JSAC) Spec. Issue Heterogeneous Netw.*, vol. 33, no. 10, pp. 2252–2265, Oct. 2015.
- [2] M. Mirahsan, Z. Wang, R. Schoenen, H. Yanikomeroglu, and M. St-Hilaire, "Unified and non-parameterized statistical modeling of temporal and spatial traffic heterogeneity in wireless cellular networks," in *Proc. IEEE Int. Conf. Commun. Workshops*, Sydney, NSW, Australia, Jun. 2014, pp. 55–60.
- [3] M. Mirahsan, R. Schoenen, and H. Yanikomeroglu, "Statistical modeling of spatial traffic distribution with adjustable heterogeneity and correlation in wireless cellular networks," in *Proc. IEEE Glob. Commun. Conf.*, Austin, TX, USA, Dec. 2014, pp. 3647–3652.
- [4] M. Mirahsan, R. Schoenen, H. Yanikomeroglu, G. Senarath, and N. Dung-Dao, "User-in-the-loop for HetHetNets with backhaul capacity constraints," *IEEE Wireless Commun.*, vol. 22, no. 5, pp. 50–57, Oct. 2015.
- [5] E. W. Knightly and N. B. Shroff, "Admission control for statistical qos: theory and practice," *IEEE Netw.*, vol. 13, no. 2, pp. 20–29, Mar./Apr. 1999.
- [6] M. H. Ahmed, "Call admission control in wireless networks: A comprehensive survey," *IEEE Commun. Surv. Tuts.*, vol. 7, no. 1–4, pp. 50–69, Feb. 2005.
- [7] M. Ghaderi and R. Boutaba, "Call admission control in mobile cellular networks: A comprehensive survey," *Wireless Commun. Mobile Comput.*, vol. 6, no. 1, pp. 69–93, Apr. 2006.
- [8] Y. Fang and Y. Zhang, "Call admission control schemes and performance analysis in wireless mobile networks," *IEEE Trans. Veh. Technol.*, vol. 51, no. 2, pp. 371–382, Aug. 2002.
- [9] N. M. K. Chowdhury and R. Boutaba, "Network virtualization: State of the art and research challenges," *IEEE Commun. Mag.*, vol. 47, no. 7, pp. 20–26, Jul. 2009.
- [10] N. M. K. Chowdhury and R. Boutaba, "A survey of network virtualization," *Comput. Netw.*, vol. 54, no. 5, pp. 862–876, Apr. 2010.
- [11] R. Jain and S. Paul, "Network virtualization and software defined networking for cloud computing: A survey," *IEEE Commun. Mag.*, vol. 51, no. 11, pp. 24–31, Nov. 2013.
- [12] N. M. K. Chowdhury, M. R. Rahman, and R. Boutaba, "Virtual network embedding with coordinated node and link mapping," in *Proc. IEEE Conf. Comput. Commun.*, 2009, pp. 783–791.
- [13] M. Chowdhury, M. R. Rahman, and R. Boutaba, "Vineyard: Virtual network embedding algorithms with coordinated node and link mapping," *IEEE/ACM Trans. Netw.*, vol. 20, no. 1, pp. 206–219, Feb. 2012.
- [14] M. Yu, Y. Yi, J. Rexford, and M. Chiang, "Rethinking virtual network embedding: substrate support for path splitting and migration," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 38, no. 2, pp. 17–29, Apr. 2008.
- [15] X. Cheng, S. Su, Z. Zhang, H. Wang, F. Yang, Y. Luo, and J. Wang, "Virtual network embedding through topology-aware node ranking," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 41, no. 2, pp. 38–47, Apr. 2011.
- [16] C. Liang and F. R. Yu, "Wireless network virtualization: A survey, some research issues and challenges," *IEEE Commun. Surv. Tuts.*, vol. 17, no. 1, pp. 358–380, Aug. 2015.
- [17] K.-M. Park and C.-K. Kim, "A framework for virtual network embedding in wireless networks," in *Proc. 4th Int. Conf. ACM Future Internet Technol.*, Jun. 2009, pp. 5–7.
- [18] D. Yun and Y. Yi, "Virtual network embedding in wireless multihop networks," in *Proc. 6th Int. Conf. ACM Future Internet Technol.*, Jun. 2011, pp. 30–33.
- [19] M. Yang, Y. Li, L. Zeng, D. Jin, and L. Su, "Karnaugh-map like online embedding algorithm of wireless virtualization," in *Proc. IEEE 15th Int. Symp. Wireless Pers. Multimedia Commun.*, May 2012, pp. 594–598.
- [20] M. Yang, Y. Li, D. Jin, J. Yuan, L. Su, and L. Zeng, "Opportunistic spectrum sharing based resource allocation for wireless virtualization," in *Proc. IEEE Seventh Int. Conf. Innovative Mobile Internet Serv. Ubiquitous Comput.*, Feb. 2013, pp. 51–58.
- [21] M. Yang, Y. Li, J. Liu, D. Jin, J. Yuan, and L. Zeng, "Opportunistic spectrum sharing for wireless virtualization," in *Proc. IEEE Wireless Commun. Netw. Conf.*, 2014, pp. 1803–1808.
- [22] J. van de Belt, H. Ahmadi, and L. E. Doyle, "A dynamic embedding algorithm for wireless network virtualization," in *Proc. IEEE 80th Veh. Technol. Conf.*, 2014, pp. 1–6.
- [23] R. Schoenen and H. Yanikomeroglu, "User-in-the-loop: Spatial and temporal demand shaping for sustainable wireless networks," *IEEE Commun. Mag.*, vol. 52, pp. 196–203, Feb. 2014.
- [24] M. Rahman and H. Yanikomeroglu, "Enhancing cell-edge performance: A downlink dynamic interference avoidance scheme with inter-cell coordination," *IEEE Trans. Wireless Commun.*, vol. 9, no. 4, pp. 1414–1425, Apr. 2010.
- [25] H. Kim, G. De Veciana, X. Yang, and M. Venkatchalam, "Distributed-optimal user association and cell load balancing in wireless networks," *IEEE/ACM Trans. Netw.*, vol. 20, no. 1, pp. 177–190, Feb. 2012.
- [26] Q. Ye, B. Rong, Y. Chen, M. Al-Shalash, C. Caramanis, and J. G. Andrews, "User association for load balancing in heterogeneous cellular networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 6, pp. 2706–2716, Jun. 2013.

- [27] J. G. Andrews, S. Singh, Q. Ye, X. Lin, and H. S. Dhillon, "An overview of load balancing in HetNets: Old myths and open problems," *IEEE Wireless Commun.*, vol. 21, no. 2, pp. 18–25, Apr. 2014.
- [28] P. J. Burke, "The output of a queuing system," *Oper. Res.*, vol. 4, no. 6, pp. 699–704, 1956.
- [29] D. Gross and C. Harris, *Fundamentals of Queueing Theory*. New York, NY, USA: Wiley, 1998.
- [30] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.
- [31] F. Baccelli and B. Błaszczyszyn, *Stochastic Geometry and Wireless Networks: Volume I Theory*. Delft, The Netherlands: Now Publ. Inc., 2010.
- [32] X. Ge, H. Cheng, M. Guizani, and T. Han, "5G wireless backhaul networks: Challenges and research advances," *IEEE Netw.*, vol. 28, no. 6, pp. 6–11, Nov./Dec. 2014.
- [33] R. Schoenen, A. Otyakmaz, and Z. Xu, "Resource allocation and scheduling in FDD multihop cellular systems," in *Proc. IEEE Int. Workshop Multiple Access Commun.*, Dresden, Germany, Jun. 2009.
- [34] 3rd Generation Partnership Project; Technical Specification Group Radio Access Network, "Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects (Release 9)," 3GPP TR 36.814, 2010.
- [35] B. Błaszczyszyn and D. Yogeshwaran, "On comparison of clustering properties of point processes," *Adv. Appl. Probab.*, vol. 46, no. 1, pp. 1–20, 2014.



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