Modelling Virtual Radio Resource Management with Traffic Offloading Support

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Abstract - **This paper proposes a new model for the management of virtual radio resources with traffic offloading support. The model has two key components: the estimation of network capacity and the data rate allocation. In the first one, the probability description of Signal-to-Interference-plus-Noise Ratio is used to obtain cumulative and density functions for the total network throughput. The primary objective in the second one is to achieve the maximum weighted throughput, subject to global network constraints. By using weights in an objective function, a prioritisation among services is achieved. The total network capacity, the SLAs (Service Level Agreements) of Virtual Network Operators, and fairness, are the constraints in this optimisation problem. The novelty of this paper is the addition of support for traffic offloading by considering the collision rates in Wi-Fi. The aim is to prioritise services with higher data rate per session in the offloading procedure, since it leads to a lower collision rate and a higher network throughput. A practical heterogeneous network is considered as a case study, in order to evaluate the model performance. Results show an increase of 2.5 times in network capacity, by implementing an access point at the centre of each cell. The good performance of the model and the VNOs' SLAs effect is demonstrated through numeric results.**

I. INTRODUCTION

Due to the increase of mobile data demand coming from the proliferation of smart devices and traffic-hungry applications, the monthly global data traffic is predicted to surpass 10 ExaByte in 2017 [1]. Hence, operators using scarce radio resources have to find a practical, flexible, and cost-efficient solution for their networks. The deployment of dense base stations to increase cellular networks' capacity is fundamental in any possible approach. In addition, traffic offloading, e.g., to Wi-Fi Access Points (APs), has recently proved to be a valuable complementary solution. Late studies [2, 3] suggest that an acceptable portion of traffic can be offloaded to APs just by allowing users to delay their delay-tolerant data for a maximum pre-specified interval, until reaching an AP. Since almost all Mobile Terminals (MTs) today have other connectivity capabilities, offloading approaches are based on using them instead of expensive cellular bands whenever it is possible. Furthermore, [4] analysed this approach from the energy-saving perspective, the economics of traffic offloading being discussed in [5].

Operators are facing not only a shortage of capacity, but also drastic variations of traffic, both geographically and temporally [6]. The common provisioning approach used in Radio Access Networks (RANs), i.e., considering only busy hours, is no longer acceptable, since it leads to an inefficient resource usage with relatively high CApital and OPerational Expenditure (CAPEX and OPEX) costs. In contrast, operators are looking for more flexible and elastic solutions, where they can also share their physical infrastructure.

Recently, the sharing of network infrastructure using Network Function Virtualisation (NFV) has become an active research topic, being meant to transform the way operators architect their networks [7]. Based on this, in [8, 9] one has proposed the concept of radio resource virtualisation and a management model. The goal of this approach is to serve multiple Virtual Network Operators (VNOs) over the same infrastructure, while offering isolation and flexibility in addition to network element abstraction and multi-RAT (Radio Access Technology) support. It is suggested to aggregate and manage all radio resources, instead of splitting them among VNOs. VNOs request wireless capacity from a set of physical network providers to serve their subscribers, thus, not having to deal with the physical infrastructure. Applying virtualisation of radio resources increases usage efficiency, while reducing the operational and maintenance costs. It integrates multiple radio access technologies, combines cellular networks and WLANs, and increases the flexibility of handling network traffic changes in RANs. In addition, it offers pay-as-you-go Connectivity-as-a-Service (CaaS) to VNOs, while enabling new business models for network operators and infrastructure providers.

However, Virtual Radio Resource Management (VRRM) is a non-trivial task, since it has to serve multiple VNOs with different requirements and Service Level Agreements (SLAs) over the same infrastructure. Furthermore, wireless links are always subject to fading and interference, hence, their performance is variable. The novelty of this paper is the proposition of a VRRM model with traffic offloading support. The model provides multiple VNOs with CaaS, considering Wi-Fi coverage in addition to the cellular heterogeneous access network. An analytical description of the model is provided, followed by the evaluation for a practical scenario.

This paper is organised as follows. Section II describes the proposed model for virtual radio resource management. The scenario for the evaluation of the proposed model is stated in Section III. In Section IV, numeric results are presented and discussed. The paper is concluded in Section V.

II. RADIO RESOURCE MANAGEMENT IN V-RAN

A. Estimation of Available Resources

The management hierarchy of virtual radio resources, consists of VRRM on the top of the usual radio resource management entities of heterogeneous access networks [10], Common Radio Resource Management (CRRM) and local RRMs. The role of VRRM is to translate VNOs' requirements and SLAs into a set of polices for lower levels [8].

The VRRM procedure consists of two key components: the estimation of the available resources, and their allocation. In the former, the model maps the number of available Radio Resource Unites (RRUs) (e.g., time-slots in GSM, codes in UMTS, resource-blocks in LTE, and radio-channels in Wi-Fi), onto the Probability Density Function (PDF) of the network capacity. By using a realistic estimation, the VRRM allocates a portion of this capacity to each service of each VNO. The goal in the estimation of the available virtual radio resources is to obtain a probabilistic relationship between the set of available resources and the total network capacity. In general, the data rate achieved by allocating an RRU to an MT depends on various parameters, such as RAT, modulation, and coding scheme, among others. In a certain configuration (e.g., certain modulation) the data rate of an RRU is a function of Signal-to-Interference-plus-Noise Ratio (SINR), as given below:

$$R_{b_{RAT_i[\mathrm{Mbps}]}}(\rho_{in}) \in [0, R_{b_{RAT_i[\mathrm{Mbps}]}}^{max}] \tag{1}$$

where:

- $R_{b_{RAT_i}}$: data rate of an RRU from the *i*-th RAT,
- ρ_{in}: SINR,
- $R_{b_{RAT_i}}^{max}$: maximum data rate of an RRU from the *i*-th RAT.

Based on [8], the PDF of $R_{b_{RAT_i}}$ can be given as:

$$p_{R_b}\left(R_{b_{RAT_i[\mathrm{Mbps}]}}\right) = \frac{\frac{0.2}{\alpha_p}\ln(10)\left(\sum_{k=1}^{5} k a_k \left(R_{b_{RAT_i}}\right)^{k-1}\right) e^{-\frac{0.2}{\alpha_p}\ln(10)\sum_{k=0}^{5} a_k \left(R_{b_{RAT_i}}\right)^{k}}}{e^{-\frac{0.2}{\alpha_p}\ln(10)a_0} - e^{-\frac{0.2}{\alpha_p}\ln(10)\sum_{i=0}^{5} a_i (R_{b_{RAT_i}}^{max})^{i}}} \tag{2}$$

where:

- $\alpha_p \geq 2$: the path loss exponent,
- a_k: coefficients in a polynomial approximation of SINR, as a function of data rate in each RAT; for cellular networks, they are presented in [8], while for Wi-Fi, they are based on [11], the values being $a_0 = -93.35, a_1 = 0.142, a_2, a_3, a_4, a_5 = 0$.

The total data rate from a single RAT pool is:

$$R_{b_{tot}}^{RAT_i} = \sum_{n=1}^{N_{RRU}^{RAT_i}} R_{b_n}^{RAT_i} \tag{3}$$

where:

- $N_{RRU}^{RAT_i}$: number of RRUs of the *i*-th RAT,
- $R_{b_{tot}}^{RAT_i}$: data rate from a *i*-th RAT pool,
- $R_{b_n}^{RAT_i}$: data rate from the *n*-th RRU of the *i*-th RAT.

Assuming that channels are independent, data rates random variables, R_{bi}, are also independent. The total data rate is equal to the sum of all random variables, thus, based on [12], the PDF of a RAT's data rate is equal to the convolution of all RRUs' PDFs:

$$p_{R_b}\left(R_{b_{tot}}^{RAT_i}\right) = p_{R_{b1}}\left(R_{b_1}^{RAT_i}\right) * \dots * p_{R_{bn}}\left(R_{b_n}^{RAT_i}\right) \tag{4}$$

In the deployment of heterogeneous access networks, the resource pools of different RATs can be aggregated under the supervision of CRRM. The total data rate from all RATs is the summation of the total data rate from each of the individual ones:

$$R_{b\,[\mathrm{Mbps}]}^{CRRM} = \sum_{i=1}^{N_{RAT}} R_{b_{tot}[\mathrm{Mbps}]}^{RAT_i} \tag{5}$$

The PDF of (5) is also computed using (4). By having the number of the available resources mapped onto probability functions, the VRRM has an estimation of the total network capacity.

B. Allocation of the Resources

In the next step, the services of the VNOs have to be granted with a portion of the network capacity. The allocation of the resources has to be based on services' priority and SLAs. These SLAs can generally be categorised into three main groups:

- Guaranteed Bitrate (GB), in which the VNO is guaranteed a minimum and a maximum level of data rates, regardless of the network status. It is expected that subscribers always experience a good QoS (Quality of Service) in return to relatively more expensive services.
- Best effort with minimum Guaranteed (BG), where the VNO is guaranteed with a minimum level of service. The request for higher data rates than the guaranteed level is served in the best effort manner, hence, the minimum guaranteed data rate is the one received during busy hours. On the other hand, from the subscribers' viewpoint, services are offered with an acceptable quality and relatively lower cost.
- Best Effort (BE), in which the VNO is served in the pure best effort approach. Hence, operators and their subscribers may suffer from low QoS and resource starvation during busy hours.

The key goal in the allocation procedure is to increase the total network throughput, while considering the priority of different services and the other constraints. As a consequence, the objective function for VRRM, $f_{\mathbf{R_b}}^{v}$, is the total weighted network data rate (e.g., in Gbps), being expressed as:

$$f_{\mathbf{R_b}}^{v}\left(\mathbf{R_b^{Srv}}\right) = f_{\mathbf{R_b}}^{cell}\left(\mathbf{R_b^{cell}}\right) + f_{\mathbf{R_b}}^{WLAN}\left(\mathbf{R_b^{WLAN}}\right) - f_{R_b}^{f}\left(\mathbf{R_b^{f}}\right) \tag{6}$$

where:

- $f_{\mathbf{R_b}}^{cell}$: objective function for cellular RATs,
- $\mathbf{R_b^{cell}}$: vector of serving data rates from cellular networks,

- f_v^{WLAN}: objective function for APs,
- $\mathbf{R}_\mathbf{b}^{\mathbf{WLAN}}$: vector of serving data rates from WLAN,
- $f_{\mathbf{R}_\mathbf{b}}^{f}$: fairness function,
- $\mathbf{R}_\mathbf{b}^{\mathbf{f}}$: vector of intermediate fairness variables,
- $\mathbf{R}_\mathbf{b}^{\mathbf{Srv}}$: vector of serving data rates.

The objective function for cellular RATs in (6) is given by:

$$f_{\mathbf{R}_\mathbf{b}}^{cell}\left(\mathbf{R}_\mathbf{b}^{\mathbf{cell}}\right) = \sum_{i=1}^{N_{VNO}} \sum_{j=1}^{N_{srv}} W_{ji}^{Srv} R_{b_{ji}\,[\text{Mbps}]}^{cell} \tag{7}$$

where:

- N_{VNO}: number of served VNOs by this VRRM,
- N_{srv}: number of services for each VNO,
- W_{ji}^{Srv}: weight of serving unit of data rate for service *j* of VNO *i* by VRRM, where $W_{ji}^{Srv} \in [0{,}1]$,

The weights in (7) are used to prioritise the allocation of data rates to services, being based on the SLAs between VNOs and VRRM; it is a common practice to have the summation of all of them equal to unit. It is desired that the services with the higher serving weights receive higher data rates than the ones with the lower serving weights. The equivalent function for WLANs is:

$$f_{\mathbf{R}_\mathbf{b}}^{AP}\left(\mathbf{R}_{\mathbf{b}[\text{Mbps}]}^{\mathbf{WLAN}}\right) = \sum_{i=1}^{N_{VNO}} \sum_{j=1}^{N_{srv}} \left(W_{ji}^{Srv} R_{b_{ji}}^{WLAN} + W^{SRb} \frac{\overline{R_{b_j}}}{\overline{R_b^{max}}} R_{b_{ji}}^{WLAN} \right) \tag{8}$$

where:

- W^{SRb}: weight for session average data rate, where $W^{SRb} \in [0, 1]$,
- $\overline{R_b^{max}}$: maximum average data rate among all network services,
- $\overline{R_{b_j}}$: average data rate for service *j*.

In (8), W^{SRb} is introduced to give priority to services with a higher data rate per session. Assigning these services to a Wi-Fi network reduces collision rates, leading to a higher network throughput. Obviously, assigning zero to this weight completely eliminates the average data rate effect (i.e., the effect of collision on network throughput) and converts the objective function of WLANs in (8) to the cellular one presented in (7).

Fairness is the other objective in the allocation procedure. As previously state, services with a higher weight get a higher data rate, but this cannot lead to a situation in which services with a lower weight are not served at all, or served in very poor conditions. A fair allocation of resources is achieved when the deviation from the weighted average for all services is minimised:

$$\min_{R_{b_{ji}}^{Srv}} \left\{ \sum_{i=1}^{N_{VNO}} \sum_{j=1}^{N_{srv}} \left| \frac{R_{b_{ji}\,[\text{Mbps}]}^{Srv}}{W_{ji}^{Srv}} - \frac{1}{N_{VNO} N_{srv}} \sum_{i=1}^{N_{VNO}} \sum_{j=1}^{N_{srv}} \frac{R_{b_{ji}\,[\text{Mbps}]}^{Srv}}{W_{ji}^{Srv}} \right| \right\} \tag{9}$$

This concept is addressed as a fairness function, being written as follows:

$$f_{\mathbf{R}_\mathbf{b}}^{fr}\left(\mathbf{R}_\mathbf{b}^{\mathbf{f}}\right) = \sum_{i=1}^{N_{VNO}} \sum_{j=1}^{N_{srv}} \left(\frac{R_{b\,[\text{Mbps}]}^{CRRM}}{\overline{R_{b[\text{Mbps}]}^{min}}} R_{b_{ji}[\text{Mbps}]}^{f} \right) \tag{10}$$

where:

- $\overline{R_b^{min}}$: minimum average data rate among all network services,
- $R_{b_{ji}}^{f}$: intermediate variable used to simplify the problem, defined as follows:

$$\begin{cases} \dfrac{R_{b_{ji}\,[\text{Mbps}]}^{Srv}}{W_{ji}^{Srv}} - \displaystyle\sum_{i=1}^{N_{VNO}} \sum_{j=1}^{N_{srv}} \frac{R_{b_{ji}\,[\text{Mbps}]}^{Srv}}{N_{VNO} N_{srv} W_{ji}^{Srv}} \leq R_{b_{ji}[\text{Mbps}]}^{f} \\ -\dfrac{R_{b_{ji}\,[\text{Mbps}]}^{Srv}}{W_{ji}^{Srv}} + \displaystyle\sum_{i=1}^{N_{VNO}} \sum_{j=1}^{N_{srv}} \frac{R_{b_{ji}\,[\text{Mbps}]}^{Srv}}{N_{VNO} N_{srv} W_{ji}^{Srv}} \leq R_{b_{ji}[\text{Mbps}]}^{f} \end{cases} \tag{11}$$

The division of the network capacity by the minimum average data rate of the services gives the maximum possible number of users in the network with a given network capacity and service set. By multiplying the fairness variable by the maximum number of users, the balance of these two objectives (i.e., network throughput and fairness) can be kept. In (11), the allocated data rate for a specific service is defined as:

$$R_{b_{ji}\,[\text{Mbps}]}^{Srv} = R_{b_{ji}\,[\text{Mbps}]}^{cell} + R_{b_{ji}\,[\text{Mbps}]}^{WLAN} \tag{12}$$

In addition, there are more constraints for VRRM to allocate data rates to various services, which should not be violated. The very fundamental constraint is the total network capacity estimated in the last section. The summation of the entire assigned data rates for all services should always be smaller than the total capacity of the network:

$$\sum_{i=1}^{N_{VNO}} \sum_{j=1}^{N_{srv}} R_{b_{ji}\,[\text{Mbps}]}^{Srv} \leq R_{b\,[\text{Mbps}]}^{CRRM} \tag{13}$$

The offered data rate to GB and BG services imposes the next constraints. The data rate allocated to these services has to be higher than a minimum guaranteed level (for both GB and BG) and lower than a given maximum (for GB only):

$$R_{b_{ji}[\text{Mbps}]}^{Min} \leq R_{b_{ji\,[\text{Mbps}]}}^{Srv} \leq R_{b_{ji}[\text{Mbps}]}^{Max} \tag{14}$$

where:

- $R_{b_{ji}}^{Min}$: minimum guaranteed data rate for service *j* of VNO *i,*
- $R_{b_{ji}}^{Max}$: maximum data rate for service *j* of VNO *i.*

Based on this model, the objective function presented in (6) has to be optimised subject to constraints addressed in (11), (12), (13), and (14). In this paper, the optimisation is done based on interior-point method using the linprog function of MATLAB [13].

III. SCENARIO

In order to evaluate the performance of the proposed model, a realistic scenario, in which coverage is provided through a set of Radio Remote Heads (RRHs) [14], is assumed. RRHs are capable of supporting multiple RATs, which are OFDMA (LTE-Advanced), CDMA (UMTS HSPA+), and FDMA/TDMA (GSM). VRRM is in charge of a service area, as described in TABLE I.

TABLE I. DIFFERENT RAT CELL RADIUS.

RAT	**Number of Cells**	**Cell Radius [km]**	**System**	$N_{RRU}^{RAT_i}$
OFDM	16	0.08	Wi-Fi	40
OFDMA	16	0.4	LTE	8 000
CDMA	1.7	1.2	UMTS	80
TDMA	1	1.6	GSM	75

In addition to cellular networks, Wi-Fi (OFDM) coverage is considered. In the centre of each OFDMA cell, an IEEE802.11ac AP is placed. The APs are facilitated with beam forming and MU-MIMO, in order to support up to 8 spatial streaming channels. They are configured to work over a 80 MHz channel bandwidth (due to European Union regulations, there are only five available channels for 80 MHz APs [15]). In contrast to cellular RATs, Wi-Fi uses the same set of links for up- and downlinks. In order to achieve coherency among all RATs, the total Wi-Fi throughput is equally divided between up- and downlinks. Hence, the number of OFDM RRUs in each link in TABLE I. is half of the total number of available channels.

Three VNOs are assumed to operate in this area, each one with a different SLA, i.e., GB, BG, and BE. All of them offer the same set of services as listed in TABLE II. The serving weights are based on general service classes: 0.4 for Conversational, 0.3 for Streaming, 0.2 for Interactive, and 0.05 for Background. In (8), the average session weight, W^{SRb}, is heuristically chosen to be 0.05.

Each VNO has 500 subscribers, where each one requires the average data rate of 6.375 Mbps [16]. Hence, the contracted data rate for all operators is 3.11 Gbps, and each service receives a portion based on the volume percentage in TABLE II.

TABLE II. NETWORK TRAFFIC MIXTURE.

Service		**Volume [%]**		W_{ji}^{Srv}	$\overline{R_{b[\text{kbps}]}}$
Mobile Video	Video Calling (ViC)	59.7	95.4	0.3	5 120
	Video Streaming (ViS)		4.6	0.4	384
File Sharing (FTP)		3.5		0.2	1 024
Web Browsing (WWW)		11.9		0.2	500
Social Networking (SoN)		14.4		0.2	384
M2M	Smart Metres (MMM)	5.9	25	0.05	200
	e-Health (MME)		25	0.2	200
	Int. Transp. Serv. (MMI)		25	0.4	200
	Surveillance (MMS)		25	0.3	200
Email (Ema)		1		0.05	100
Music (MuS)		3		0.3	64
VoIP (VoI)		1		0.4	12.2

On the ground of each service data rate, the SLAs of these VNOs are defined as follows:

- VNO GB: the data rates allocated to services are guaranteed to be in the range of 50% to 100% of the corresponding service data rate.
- VNO BG: it has best effort with a minimum 25% of the service data rate guaranteed by the SLA.
- VNO BE: it has all services served in the best effort approach, without any guarantee.

IV. RESULTS

In a first step, the capacity of cellular networks is computed by using (5); then, the same method is used to obtain the Cumulative Distribution Function (CDF) of the extended capacity by joining WLANs. The results for cellular network is presented in [8] for three common path loss exponents (2 for free space, 3.8 for regular urban environments, and 5 for high attenuation dense urban ones [17]). The increase of attenuation when collision effects are neglected leads to an increment of capacity, because interference is much more reduced than the signal itself, the same procedure being used for WLANs. From numeric results, the median capacity offered by APs is 1.76 Gbps for free space, increasing up to 6.8 Gbps when $\alpha_p$is 5.

Fig. 1 presents the allocated data rate to each service from cellular networks and WLANs. As expected, Conversational services (VoIP, Video Call, and M2M – ITS), which are the ones with the highest serving weights, receive the highest data rates, Streaming (Music, M2M – SV, and Video Streaming) being placed second. The lowest served services are the Background ones (email and M2M – SM). The effect of W^{SRb}can be observed in the balance in data rates between cellular networks and WLANs, e.g., it can be seen that the allocated data rate to Video Streaming in WLANs is 6.5 times higher than the one in cellular networks, while, in contrast, Email (a service with a low average data rate), is allocated a higher data rate in cellular networks than in WLANs. However, VoIP is not following the same rule, since it has a relatively high serving weight, which overcomes the higher effect of the average data rate in (8) for this service, hence, being allocated a comparatively high data rate from both type of networks. The same phenomenon can be observed among M2M services; the ones with high serving weights, e.g., M2M – ITS, received relatively high capacity from WLANs comparing to the others.

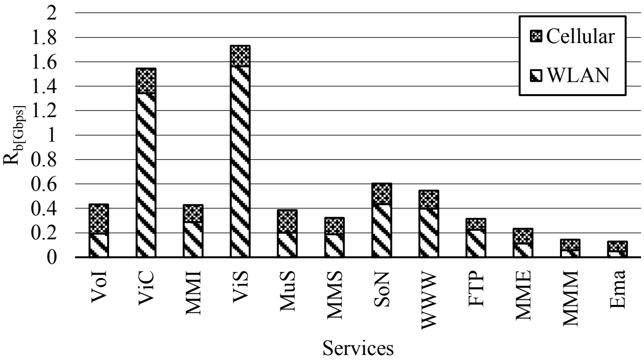

Fig. 1. Allocated data rate to different services from Cellular and WLAN.

Fig. 2 illustrates the data rates that are allocated to each service of each VNO. It is apparent that most of the services of VNO GB are served with the maximum guaranteed data rate, e.g., VoIP and Music are guaranteed to be served with a relatively global maximum of 31.87 Mbps and 95.62 Mbps, and they have been allocated the same amount. The main difference between VNO GB and VNO BG is the service maximum data rate; since the services of VNO BG have no high limit while the VNO GB ones have, the total allocated data rate to the former is higher than the latter. Obviously, the offered capacity to VNO BG is a resource shortage situation that is going to be smaller than VNO GB.

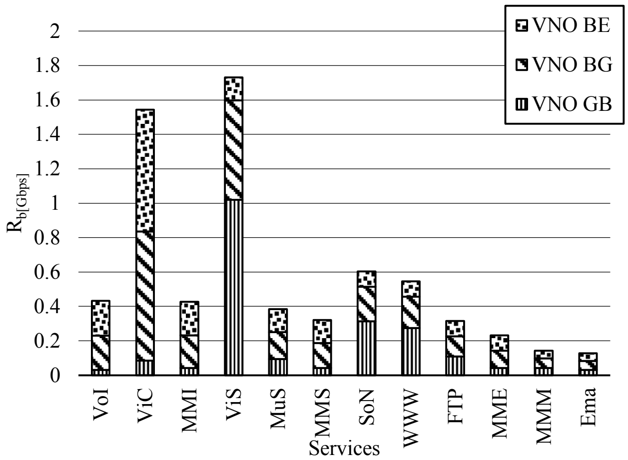

Fig. 2. Allocated data rate to different services of the VNOs.

V. CONCLUSIONS:

As a solution to extreme mobile data demand, this paper proposes to use of traffic offloading and virtualisation of radio resources together. By means of virtualisation of radio resources, it is possible to share the physical infrastructure, either cellular or WLANs, among multiple VNOs. By using this approach, VNOs can be served by a wireless capacity while they are offered isolation, element abstraction, and multi-RAT support. The offered service to VNOs is referred to as Connectivity-as-a-Service.

In addition, a model for the management of virtual radio resources with support of traffic offloading is proposed. The model is able to map the number of available resources to network capacity in a first step. Then, it optimises the allocation objective function, which is a weighted throughput of the network; the introduction of serving weights makes it possible to prioritise services. The model's guideline in traffic offloading is to serve services with low average data rate per session from cellular network and the others from WLANs to reduce the collision rates. Besides, the model also considers fairness among services; a fair allocation according to the model is when the summation of the deviation from the weighted average for all services is as small as possible. The ideal case is zero, but it may compromise the main objective, hence, there is always a trade-off between fairness and the network throughput.

Finally, the performance of the proposed model is evaluated for a practical scenario and numeric results are presented. By adding an AP to each OFDMA cell, the network capacity increases up to 2.8 times. Three VNOs with three different SLAs are considered in the scenario. Traffic offloading enables VRRM to properly serve all three VNOs: not only guaranteed services are served adequately, but best effort ones are allocated with a relatively high data rate. Services with a higher serving weight, such as Conversational ones, are provided with a higher data rate. In conclusion, it is shown that our model achieves the desired goals.

ACKNOWLEDGMENT

The research leading to these results was partially funded by the European Union's Seventh Framework Programme Mobile Cloud Networking project (FP7-ICT-318109).

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