The Impact of Net Neutrality on Revenue and Quality of Service in Wireless Networks

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***Abstract*—The net neutrality principle, also known as Open Internet, states that users should have equal access to all Internet content and that Internet Service Providers (ISPs) should not practice differentiated treatment on any of the Internet traffic. While net neutrality aims to restrain any kind of discrimination, it also provides exemption for a certain category of Internet traffic known as specialized services (SS), by allowing the ISP to dedicate part of the resources for the latter. In this work, we shed light on this particular case by comparing five Radio Access Technology (RAT) selection policies in heterogeneous wireless networks where SS traffic and Internet Access Services (IAS) traffic are carried. The studied policies include a non-net-neutral revenue-maximizing policy used as reference policy, and four other net-neutral policies with and without exemption to SS traffic. The results show that, even though, as expected, integrating net neutrality regulation within RAT selection policies can lead to a decrease in the generated revenue, a properly designed net-neutral policy will not only be able to reduce this decrease in revenue but also can maintain a similar level of social benefit in terms of the number of users admitted to the system.**

I. Introduction

The net neutrality debate has gained lots of attention over the past decade. The main idea behind net neutrality principle is that Internet service providers (ISPs) should treat all Internet traffic equally regardless of the content, application, device, sender or receiver. Although the net neutrality debate has targeted, at the beginning, the wired public Internet, it is clear that it will address the wireless networks as well. Opponents to wireless net neutrality argue that the characteristics of wired and wireless networks differ in many aspects and that the challenges faced by wireless networks are greater compared to the ones faced by wired connectivity. Such challenges are mainly due to the wireless medium; they include signal attenuation, interference, and handovers, among others [8]. Therefore, what applies to wired networks might not necessarily apply to wireless ones. However, considering that a significant fraction of Internet traffic is being sent over wireless connectivity, we believe that the applied regulations have to be quite similar in both wired and wireless networks.

Net neutrality principle allows the ISP to grant exemption to some non-Internet access services that require high transmission quality, known as specialized services (SS) [2]. Some examples of SS include VoLTE, linear broadcasting IPTV, and real-time health services [15]. The ISP can dedicate a certain amount of bandwidth to SS to secure that those services receive the required QoS. However, this should not lead to a degradation of the QoS experienced by the Internet access services (IAS) traffic.

In a previous work [9], we studied revenue-maximizing Radio Access Technology (RAT) selection in a Long Term Evolution (LTE) / Wireless Fidelity (WiFi) heterogeneous wireless network (HWN). The traffic with highest contribution to the revenue was granted higher priority in getting access to the network and in being served in LTE, at the expense of blocking or handing over the low-priority traffic. This way of traffic handling allows to maximize the revenue but it indeed violates net neutrality regulations, due to the fact that the low-priority traffic is treated with some kind of discrimination [14].

RAT selection is an important radio resource management component that helps tackle the problem of scarcity of wireless resources in HWNs. Despite the emergence of other solutions to deal with the same problem, such as LTE license-assisted access (LTE-LAA) which enables the operation of LTE in unlicensed spectrum [3], [11], the role of RAT selection will remain important.

In this work, we aim to investigate how applying net neutrality-compliant RAT selection policies would affect the generated revenue and the QoS perceived by both high and low-priority traffic, where the high-priority traffic is represented by SS and the low-priority traffic is represented by IAS. To the best of our knowledge, no other work has been conducted in this direction where RAT selection policies are investigated, with net neutrality integration.

The rest of the paper is organized as follows. In Section II, the motivation and related work are presented. Section III describes the system model. In Section IV, we introduce the studied RAT selection strategies and their implementation. In Section V, we provide an analysis of the obtained results. Finally, we conclude in Section VI.

II. Motivation and Related Work

Net neutrality has been heavily discussed in the past decade as a potential way to prevent the ISPs from exercising any type of discrimination on the Internet traffic. Content providers, in general, support net neutrality especially in monopolistic regimes where an ISP might have pricing power over the Internet access market. The ISPs, on the other hand, argue that service differentiation is crucial, giving them incentive to further invest in expanding their infrastructure and to provide QoS [16]. Wu in [17] expanded the net neutrality debate by suggesting that policymakers ought to consider how to apply net neutrality regulations to wireless networks. This was opposed by a number of economists (e.g. [5]) who argued that, unlike the wired market, the competition will remain high in the wireless one.

Martínez et al. in [14] provided an initial analysis of the impact of net neutrality on quality of experience based differentiation in mobile networks. In [6], the authors focused on the content provider discrimination and discussed the impact of some of the disruptive network applications on net neutrality. Some other works, e.g. [12], [16], proposed alternative regulations to net neutrality. Authors in [13] studied the paid prioritization where the content providers decided to pay for this priority in monopolistic access market. They showed that, with ISP's optimal pricing, the service differentiation became efficient and the social welfare among the different content providers was close to its maximum. Altman et al. in [1] presented a bargaining framework to decide how much the ISP should charge the content provider.

In our work, we focus on one ISP and study how the generated revenue as well as the social benefit and the blocking probability of the offered traffic would be affected when net-neutrality regulation is integrated within the applied RAT selection policies in heterogeneous wireless networks.

III. System model

We consider a heterogeneous wireless network consisting of LTE and WiFi that coexist in the same geographical area. The traffic arrivals to the different base stations (BSs) are independently distributed. Hence, and without loss of generality, we can shift our focus to a single cell that corresponds to the coverage area of one cellular BS. The cellular RAT has global coverage, overlaying the WLAN i.e. within the coverage of the considered BS, one or more WLAN access point(s) might be found. This is similar to the model considered in [9].

Two types of traffic are carried, namely SS and IAS traffic, where IAS is charged a price P_l, while SS is charged the same price P_l in the case where this latter is not granted any preferential treatment, and a price $P_h > P_l$ otherwise. Naturally, this pricing differentiation affects the traffic distribution among SS and IAS. In this paper, we adopt that, and the percentage of traffic that is being sent as SS traffic can be computed with the help of the following demand function that was proposed in [4] and has been adopted in the literature e.g., [7]:

$$D[P_h] = e^{-(\frac{P_h}{P_l}-1)^2}. \qquad (1)$$

IV. RAT selection strategies

We consider five RAT selection strategies for the admission of SS and IAS traffic. The first strategy is revenue-maximizing and does not take into account net neutrality restrictions, while the four others are net neutrality-compliant. Our objective is to give insight into how the revenue and the QoS are affected when net neutrality regulations are applied. A comparison of the considered RAT selection policies is provided in Table I.

A. Description of the RAT selection strategies

- *Policy A - Revenue-maximizing policy:* With this policy, the decision of traffic admission is taken based on the generated revenue solely, i.e. neither net neutrality nor QoS requirements are taken into consideration. For its higher contribution in the generated revenue, SS is granted high priority in getting admitted to the network and in getting served in LTE. A handover of one or more IAS sessions might be performed between LTE and WiFi in case there was need to re-distribute the traffic, allowing to accommodate more sessions in the system. In return, the price charged to SS traffic is P_h. Due to the preferential treatment granted to SS traffic over IAS traffic, Policy A is considered a non-net-neutral one [10].
- *Policy B - LTE-First policy and strictly net-neutral:* This policy is strictly net-neutral in the sense that no privileges are granted to any type of traffic; arriving SS and IAS sessions are admitted and served with equal priority. The admission is LTE-first based, where the arriving traffic is admitted first to LTE as long as LTE has enough free resources, and afterwards to WiFi when LTE becomes overloaded. SS and IAS are charged the same price P_l.
- *Policy C - LTE-First net-neutral policy with exemption to SS:* This policy follows the net neutrality regulations which allow to grant exemption to SS traffic. Similar to Policy B, the traffic admission is also LTE-first based. In addition, a part of the resources pool in LTE is reserved to SS traffic, while the remaining LTE resources and the whole WiFi resources can be accessed and used by both types of traffic. With policy C, SS traffic is charged P_h for the reserved bandwidth it is granted in LTE, while IAS traffic is charged P_l. Fig. 1 provides an abstraction of the system model where a portion of the LTE capacity is dedicated to SS traffic i.e. LTE resources are divided into two parts: reserved capacity (for SS traffic only) and common capacity (for both SS and IAS traffic).
- *Policy D - WLAN-First policy and strictly net-neutral:* This policy admits the arriving traffic on a WLAN-first basis i.e. traffic is admitted to WLAN until this latter becomes overloaded, and to LTE afterwards. Policy D treats both SS and IAS traffic equally, and both are charged the same price P_l.
- *Policy E - WLAN-First net-neutral policy with exemption to SS:* Similarly to policy D, the traffic is admitted on WLAN-first basis. However, part of LTE resources is reserved for SS traffic, while the remaining LTE resources and the entire WiFi resources can be occupied by both SS and IAS traffic. SS traffic is charged P_h and IAS traffic is charged P_l.

B. Implementation of the RAT selection strategies

Policy A aims to distribute the traffic among LTE and WiFi in a way that maximizes the generated revenue. This scenario can be modeled with the help of MDP. In the following, the notation RAT i will be used to identify the available RATs,

TABLE I
Comparison of the Studied Policies.

Policy A	Policy B	Policy C	Policy D	Policy E
Priority for SS Revenue-maximizing SS charged P_h Non-net-neutral Handover of IAS traffic allowed	Equal treatment for SS & IAS LTE-first admission Equal pricing Net-neutral No handover	Reserved capacity for SS LTE-first admission SS charged P_h Net-neutral No handover	Equal treatment for SS & IAS WLAN-first admission Equal pricing Net-neutral No handover	Reserved capacity for SS WLAN-first admission SS charged P_h Net-neutral No handover

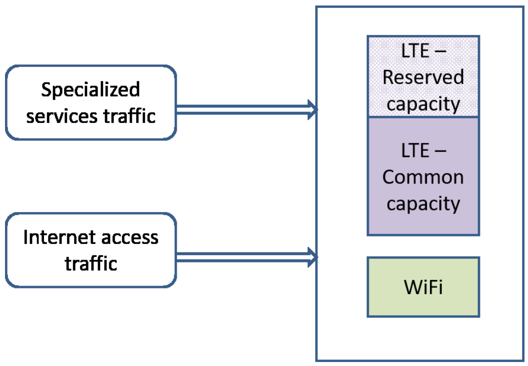

Fig. 1. System model - Net-neutral policy with exemption to SS traffic.

where RAT 1 designates LTE and RAT 2 designates WiFi. Similarly, class j traffic represents SS for $j = 1$ and IAS for $j = 2$.

The MDP model is identified by the following components:

- State space:

$$S = \left\{ \boldsymbol{s} = [s_1, s_2] = [n_{1,1}, n_{1,2}, n_{2,1}, n_{2,2}] \in \mathbb{Z}_+^4 \right\} \quad (2)$$

where $n_{i,j}$ represents the number of ongoing sessions of class j traffic in RAT i, $i \in \{1, 2\}$ and $j \in \{1, 2\}$.

- Action space: the action space of the MDP model is defined as the set of vectors $\boldsymbol{a}$ as follows:

$$A = \{\boldsymbol{a} = [a_1, a_2], a_1 \in \{-1, 0, 1\}, a_2 \in \{-1, 0, 1\}\} \quad (3)$$

A vector $\boldsymbol{a} = [a_1, a_2]$ represents the action taken following each decision epoch, where a_j denotes the action resulting from the arrival of a class j session. A decision can be either to admit the arriving session to LTE, admit it to WiFi or block it. We define a_j as follows:

$$a_j = \begin{cases} -1, & \text{if the session is admitted to LTE.} \\ 1, & \text{if the session is admitted to WiFi.} \\ 0, & \text{if the session is blocked.} \end{cases}$$

- Policy: For each state $\boldsymbol{s} = [s_1, s_2] \in S$, an action $\boldsymbol{a} \in A_s$ is chosen according to a policy $\pi_s \in \Pi$, where $A_s \subset A$ represents the set of feasible actions for state $\boldsymbol{s}$ and Π is a set of admissible policies defined as:

$$\Pi = \{\pi : S \rightarrow A | \pi_s \in A_s, \forall \boldsymbol{s} \in S\} \quad (4)$$

- Reward function: the reward function that we want to maximize reflects the revenue achieved by the admission of both classes of traffic. Hence, the reward function for choosing action $\boldsymbol{a} \in A_s$, when the system is in state $\boldsymbol{s} \in S$ can be defined as follows:

$$\begin{aligned} r(\boldsymbol{s}, \boldsymbol{a}) = w_{1,1} \cdot \delta(-a_1) - k_{c,w} \cdot n_{h,2} \cdot h \\ + w_{2,1} \cdot \delta(a_1) - k_{w,c} \cdot n_{h,2} \cdot h \\ + w_{1,2} \cdot \delta(-a_2) + w_{2,2} \cdot \delta(a_2) \end{aligned} \quad (5)$$

where:
$w_{i,j} \in \mathbb{R}_+$ is the weight associated with the admission of a class j session into RAT i, $\mathbb{R}_+$ being the set of non-negative real numbers,
$k_{c,w}$ is the cost associated for handing off an IAS session from LTE to WiFi and $k_{w,c}$ is the cost associated for handing off an IAS session from WLAN to LTE,
$n_{h,2}$ represents the number of IAS sessions handed off from one RAT to another,
h is a variable that takes 1 as value if a vertical handover was performed, and 0 otherwise,
and $\delta(x)$ is a function defined as:

$$\begin{cases} 0, & \text{if } x \leq 0 \\ 1, & \text{if } x > 0 \end{cases}$$

Since our objective is to maximize the revenue, the weights $w_{i,j}$ in the reward function are assigned the value P_h for $j = 1$ and P_l for $j = 2$. For more details about the MDP modeling, the reader is referred to [9].

To implement Policies B, C, D and E, a 4-dimensional Markov chain has been used where the transitions between states are defined according to the definition of the policies (either LTE-first or WLAN-first), and the resource reservation for SS traffic is also taken into account for Policies C and E.

V. Numerical Results

The values of the different system parameters used in this work are summarized in Table II. The total arrival requests follow a Poisson process with traffic intensity ρ. Each of these requests may randomly choose SS or IAS due to pricing and to the probability to choose SS which is given by (1). As a result, the traffic intensities of SS and IAS, denoted by ρ_1 and ρ_2, can be respectively found as:

$$\rho_1 = D[P_h] \cdot \rho$$

$$\rho_2 = (1 - D[P_h]) \cdot \rho$$

where $D[P_h]$ is found from (1). As for the call holding time, it is assumed to be inelastic, i.e. the average duration of the

TABLE II
SYSTEM PARAMETERS

Parameter	Symbol	Value
Average session holding time - SS traffic	$1/\mu_1$	200 s
Average session holding time - IAS traffic	$1/\mu_2$	150 s
Total traffic intensity	ρ	2-12 Erlang
Price charged for high-priority traffic	P_h	1.6 MU
Price charged for low-priority traffic	P_l	1 MU

service is independent of the allocated number of channels. Particularly, it follows an exponential distribution with mean $1/\mu_1$ and $1/\mu_2$ for SS and IAS traffic respectively. For Policies C and E, the value of 15% is assigned to the ratio of reserved capacity in LTE for SS traffic.

A. Revenue

The term revenue, as used in this paper, designates the charges paid by the users in exchange for the services they are receiving. It is hence the amount paid by them for transmitting their traffic over the network in monetary unit (MU).

The revenue achieved when applying the different RAT selection policies is depicted in Fig. 2. With Policy A, which is the revenue maximizing policy, SS sessions are charged P_h and are granted, in return, higher priority in getting admission to the system and in using LTE network over the IAS traffic. Moreover, a handover of IAS traffic is also allowed whenever there is the need to re-distribute the traffic among LTE and WiFi in order to admit more sessions. Policy A is hence the one that allows to achieve the highest revenue among the five studied policies. With Policies C and E, SS sessions are also charged P_h in exchange for the reserved resources they are getting in LTE. The results show that Policy C is able to achieve higher revenue than Policy E. This is because Policy C fully exploits LTE resources before admitting traffic to WiFi, while Policy E admits the traffic to WiFi first which has local coverage and this can result in loss of some of the traffic sent to WiFi and, consequently, a decrease in the revenue. Policies B and D offer equal treatment to both SS and IAS traffic which are also charged equally. Both achieve lower revenue than the other policies with some advantage to Policy B which admits the traffic on LTE-first basis, unlike Policy D.

In comparison with what is achieved by the revenue-maximizing non-net-neutral policy, i.e. Policy A, the difference in revenue highly depends on the adopted net-neutral policy, which varies from less than 10% up to 30% as shown in Fig. 2.

Regardless of the adopted RAT selection policy, the achieved revenue is affected by the ratio P_h/P_l. To illustrate this, we plotted in Fig. 3 the revenue obtained by Policy C for different ratios P_h/P_l. It is shown that the achieved revenue first increases with the increase of P_h/P_l, then starts to decrease. This is because when the price P_h of SS traffic becomes too high compared to P_l, the users will tend to send the majority of traffic as low-priority traffic as can be deduced from (1), which will result in a decrease of the revenue.

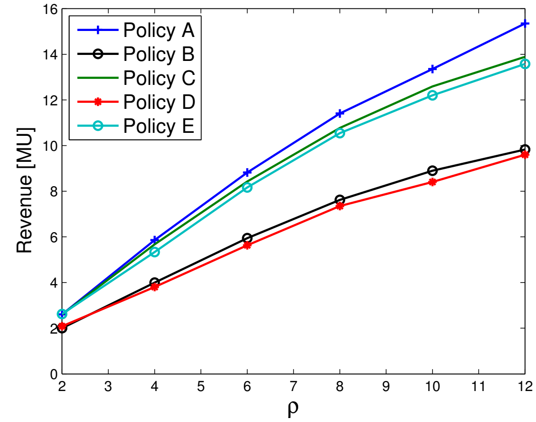

Fig. 2. Revenue achieved in monetary unit [MU].

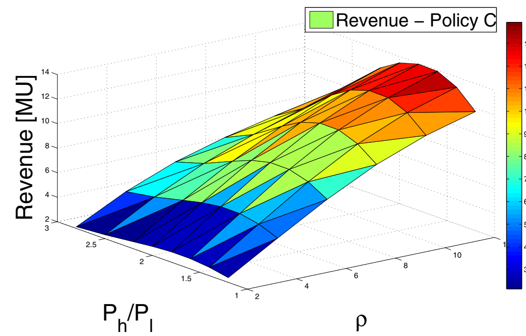

Fig. 3. Revenue of policy C for different pricing ratios $\frac{P_h}{P_l}$.

Another important parameter that affects the revenue achieved by applying Policies C and E is the share of bandwidth that is reserved to SS traffic. This parameter will be further investigated in Section V-D.

B. Social benefit

We define the social benefit as the total number of admitted sessions into the network regardless of the traffic type. This metric offers insight into the user experience. Fig. 4 depicts the number of admitted sessions realized by all five RAT selection policies. Policy A is able to admit the highest number of sessions. Policy B comes in the second place despite its low achieved revenue observed in Fig. 2. This indicates that Policy B performs well in terms of session admission and the low revenue is mainly due to the difference in pricing between the two types of traffic. A similar observation can be noticed with Policy E in the sense that the relatively high revenue achieved by this policy is also due to the difference in pricing, which indicates that Policy E admits mostly SS sessions, resulting in high revenue but low number of total admitted sessions.

The results show also that the policies that offer equal traffic treatment perform better in terms of social benefit than their respective policies that reserve capacity to SS traffic (i.e. Policy B outperforms C, and D outperforms E). Nevertheless, the difference in terms of social benefit achieved by the studied policies is generally small, e.g. less than 5% shown in Fig. 4.

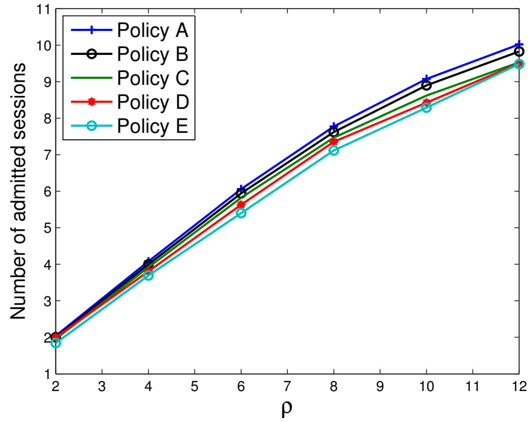

Fig. 4. Social benefit.

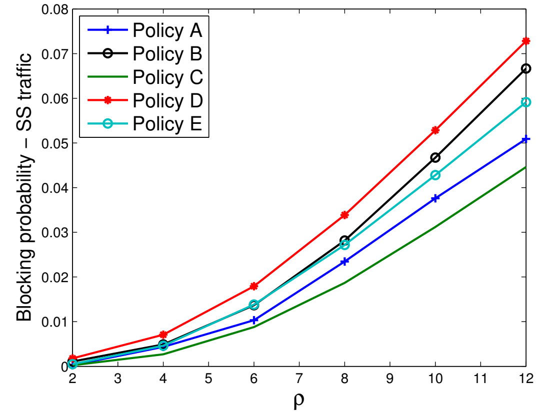

Fig. 5. Blocking probability - specialized services traffic.

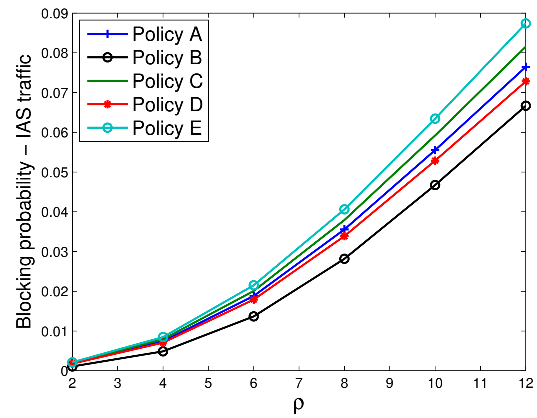

Fig. 6. Blocking probability - Internet access traffic.

C. Blocking Probability

1) SS traffic: The blocking probability of SS traffic obtained with the studied RAT selection schemes is depicted in Fig. 5. Policy D, which admits the traffic on WLAN-First basis without bandwidth reservation for SS traffic, performs the worst. This is due to the possibility of loss of traffic when admitted to WLAN. Policies B and E have comparable performance when the traffic load is low. However, when the traffic load increases, Policy E outperforms Policy B. This is mainly due to the capacity reservation in LTE for SS traffic that Policy E allows. As for Policy A, despite granting priority to SS traffic, it does not outperform Policy C. This is due to the way the reward function (5) is built, where only revenue maximization has been considered without taking QoS into account. Policy C allows to realize the lowest blocking probability for SS traffic among all studied policies and this is because it combines both bandwidth reservation for SS traffic and LTE-First admission.

2) IAS traffic: Fig. 6 depicts the blocking probability of IAS traffic obtained with the considered RAT selection policies. With Policy B, where the two classes of traffic receive equal treatment, the blocking probability of IAS traffic is the lowest. The result of Policy A is in the middle, while the policies that reserve capacity for SS traffic (Policies E and C) perform the worst, which shows that reserving bandwidth for SS traffic has clear effect on the blocking probability of IAS traffic. The results show also that the blocking probability obtained by the WLAN-First based policies D and E is higher than that by their respective LTE-First based Policies B and C.

D. Proportion of reserved capacity for SS traffic

When studying the performance of Policies C and E, we have to take into account that the obtained results are dependent on the share of the reserved capacity in LTE for SS traffic. It is hence interesting to investigate how varying the proportion of the reserved capacity for SS would affect the revenue and the blocking probability of both SS and IAS traffic. Since Policy C achieves higher revenue than Policy E, we shift our focus to Policy C to study its performance with three values of the proportion of reserved capacity : 10%, 15% and 20%.

1) Revenue: The revenue obtained by Policy C for the different proportions of reserved LTE bandwidth is depicted in Fig. 7. It is shown that when we increase the share of reserved capacity in LTE, the revenue starts to increase in the beginning. Then when this share becomes relatively high, the revenue starts again to decrease. The reason is that, when large portion of bandwidth is reserved, this will result in "wasted" resources, and consequently, a significant portion of IAS traffic will be rejected. This results in loss of the revenue that could have been realized if the resources were better managed to allow the accommodation of a higher number of IAS sessions.

2) Blocking Probability:

- SS traffic: It is evident that the increase of the share of reserved bandwidth in LTE will lead to a decrease of the blocking probability of SS traffic as depicted in Fig. 8.
- IAS traffic: when the share of reserved bandwidth in LTE for SS traffic is small, the blocking probability of IAS traffic is low (Fig. 9). However, when this share increases, higher blocking probability of IAS traffic is observed.

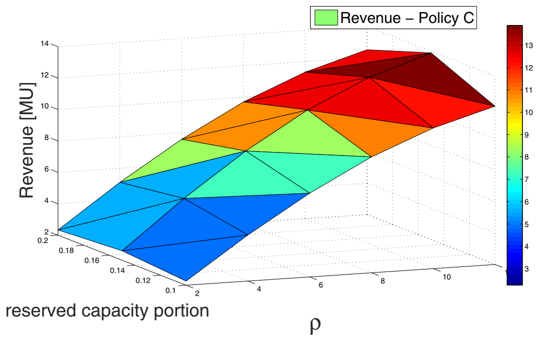

Fig. 7. Revenue in monetary unit [MU] - different ratios of reserved capacity.

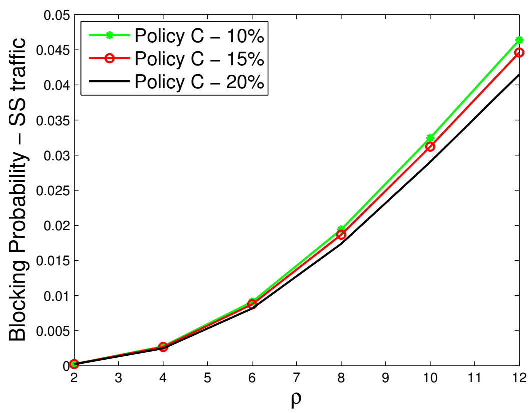

Fig. 8. Blocking probability of SS - different ratios of reserved capacity.

VI. Conclusion

In this work, we discuss net neutrality and highlight its impact on the revenue and the QoS of both SS and IAS traffic in a heterogeneous LTE / WiFi network. We study the performance of five different RAT selection policies: a revenue-maximizing policy that is not compliant to net neutrality, and four other net-neutral policies. The results show that, even though, as expected, applying net neutrality regulations can lead to a decrease in revenue, this decrease can be reduced by choosing proper net-neutral RAT selection policies. In terms of social benefit, even though a similar decrease can be observed, the decrease is so small that the difference may be neglected in deciding which policy to use. Concerning QoS, applying net neutrality regulations with bandwidth reservation for SS traffic can lead to a decrease in the blocking probability of this latter. However, for IAS traffic, the lowest blocking probability is achieved with the policies that are strictly net-neutral. Finally, the choice of the share of reserved LTE resources for SS traffic is investigated.

We conclude that in order to support net neutrality and at the same time maximize revenue and meet the QoS requirements, the RAT selection policy has to be designed / chosen carefully. We believe that, though far from exhaustive, the results in this paper on the considered policies shed light on further study along this direction.

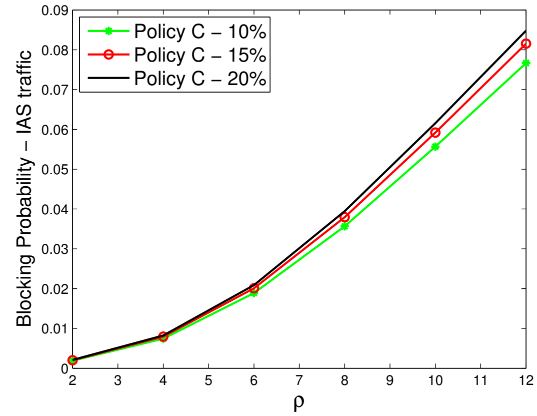

Fig. 9. Blocking probability of IAS - different ratios of reserved capacity.

Acknowledgment

This work was supported in part by the EU FP7 Marie Curie Actions under Grant Agreement No. 607584, and in part by the EU H2020 Marie Skłodowska-Curie Actions under Grant Agreement No. 699924.

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