Paris Metro Pricing for 5G HetNets

Virgilios Passas[†⋆], Vasileios Miliotis[†⋆], Nikos Makris[†⋆],
Thanasis Korakis[†⋆] and Leandros Tassiulas[‡]
[†]Department of Electrical and Computer Engineering, University of Thessaly, Greece
[⋆]Centre for Research and Technology Hellas, CERTH, Greece
[‡]Department of Electrical Engineering, Yale University, New Haven, USA
Email: {vipassas, vmiliotis, nimakris, korakis}@uth.gr, leandros.tassiulas@yale.edu

***Abstract*—Heterogeneous network access has been proposed as a solution for the continuously deteriorating congestion problem of cellular infrastructures. In this paper we focus on a multi-Radio Access Technology (RAT) environment and we provide a solution based on the Paris Metro Pricing (PMP) scheme, which was first applied in Paris metro. The concept of this pricing scheme was to provide differentiated service classes for customers who desired to avoid being congested, while maintaining the same wagons, characterized only by a different ticket price. The proposed solution extends the classic PMP policy by inducing dynamic prices formed by the congestion of each available technology. We investigate the performance of our dynamic PMP scheme taking into consideration a mobility model of the interested users. Through simulations and testbed experimentation we provide evaluation results on the average throughput, the acceptance capability of the incoming users and how these performance metrics are affected under different mobility conditions.**

I. Introduction

In recent years, global mobile data demand presents a continuous growth. According to Cisco Visual Networking Index [1], the number of mobile devices is also expected to present a vast increase, as any device from anywhere is already able to access the internet through cellular infrastructures, following the concept of Internet of Everything (IoE). These trends are already putting pressure on the mobile service providers, as the update of existing infrastructures cannot follow the growth rate of mobile data demand. Millimeter wave (mmW) radio access will increase the available spectrum for mobile devices in future 5G networks [2]. Nevertheless, until the deployment of the 5G technology infrastructure takes place, the use of multiple Radio Access Technologies (RAT) has been proposed, aiming to mitigate the congestion conditions already met by the mobile service providers. Heterogeneity will be a key feature of 5G networks [3], giving to providers the ability to offload their cellular networks to mitigate congestion and provide high quality connectivity to mobile devices.

Contemporary mobile devices are equipped with multiple radio access capabilities. At the same time multiple radio access technologies are deployed by mobile service providers (WiFi, 3G, LTE, small-cells etc), mainly in urban areas, giving to customers the option to choose and connect to different access networks. The main questions that arise in such heterogeneous environments are:

1) How a User Equipment (UE) should choose the best of the available RATs.
2) When it should change to a different RAT.
3) How changes of access decisions affect the performance of other users in the multi-RAT environment.

Aiming to tackle these questions, we propose a heterogeneous network access solution based on the Paris Metro Pricing (PMP), a service differentiation scheme that was first used in Paris metro to give to its passengers the ability to opt for less congested wagons. In this paper we extend the PMP policy by introducing a dynamic pricing scheme for each available service class and we investigate its performance under a realistic mobility model for users in an urban environment, and under real testbed experiments.

The rest of the paper is organised as follows. In Section II we present a literature overview of heterogeneous network access schemes. In Section III we present the system model of the dynamic PMP scheme. In Section IV we provide our proposed algorithms and the system architecture. Section V includes our evaluation results on the performance of the proposed scheme in terms of average throughput and acceptance capability of incoming users. Section VI concludes our work.

II. Related Work

Many research groups have recently proposed different access schemes to exploit the coexistence of multiple access technologies, aiming to improve the Quality of Service (QoS) of mobile users and to mitigate the network congestion. In [4], the authors provide an extensive classification of published research works on network selection for heterogeneous networks, mainly regarding the utility functions and the mathematical models that were used. A survey on key parameters for handover decisions in heterogeneous networks is presented in [5]. A reward based algorithm is presented in [6], where mobile users autonomously update the fraction of their traffic through each available access technology, based on the rewards received by the base stations. These rewards are sent to each user, representing the impact of their traffic on the cell load. The authors in [7] formulate the multi-user RAT selection problem as a non-cooperative game, where each user tries to selfishly maximize its own throughput, and they investigate the impact of a user's decisions on other users performance and the convergence of the system to Nash equilibria. An incentive mechanism that aims to motivate WiFi Access Points (APs) to participate in heterogeneous networks, by providing an access class to the existing cellular infrastructure, is proposed in [8]. The pricing strategy for the inclusion of third party WiFi APs is formulated as a Stackelberg game between the mobile network provider and the third party WiFi APs. Another model that creates on-demand multi-RAT conditions is proposed in [9], where mobile users form short range mesh networks to collaborate, by sharing their internet access with provision for proper routing policies with load-balancing and fairness. The authors also propose a virtual currency to create incentives and facilitate the cooperation of users. A pricing-based proportionally fair scheme for concurrent uplink access through LTE and WiFi is proposed in [10]. The seminal work for the application of PMP in the context of packet delivery networks was provided in [11] where the use of PMP was presented as a solution to the congestion control problem for differentiated classes of service levels. The authors in [12] consider a general model of congestion externality for the PMP and investigate sufficient conditions of congestion functions that guarantee the viability of the PMP scheme. Inspired by these two works, we propose an extended PMP scheme with dynamic pricing, where users entering a multi-RAT environment decide which technology they prefer to access, depending on its current price and their sensitivity to congestion. In [13], the authors focus on pricing different classes of services from the service providers perspective and show that if prices are not chosen properly, matching the service qualities of the available classes, the system may settle into an undesirable equilibrium similar to the Prisoner's Dilemma game. Furthermore, they show that dynamic pricing based on users' preferences over different service classes can lead to stable equilibrium. This work is a step towards the direction of future 5G deployments, which are envisioned with dense multi-RAT heterogeneous networks [14], creating the challenge for the development of mechanisms that efficiently aggregate the capacity and coverage of diverse existing access technologies.

III. System Model

We consider the existence of M classes of radio access services that belong to the same cellular network provider. Every access class m corresponds to a radio access technology (e.g. 4G, 3G, WiFi) and has a capacity C_m. Hence, the total system capacity is equal to $C = \sum_{m=1}^{M} C_m$. We focus on UEs that are under the coverage of all provided radio access technologies as depicted in Fig. 1. Every UE is characterized by its type $\theta_i \in [0,1]$, representing its sensitivity to congestion. A UE$_i$ with congestion sensitivity θ_i, using access class m has a utility equal to:

$$U_i(m) = V - p_m - \theta_i f(Q_m, \bar{C_m}) \tag{1}$$

where V is a flat-rate valuation of accessing the multi-RAT service, p_m is the access charge for a UE served at class m and $f(Q_m, \bar{C_m})$ is a function for the perceived congestion at class m. The mass of users choosing class m is denoted by Q_m, and the available capacity of the access class m is denoted by $\bar{C_m}$. Without loss of generality, we assume that there is a total mass of UEs equal to 1. The mass of users that do not participate

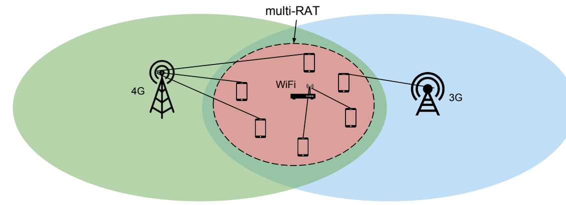


Fig. 1: Multi-Radio Access Technology Environment.

in the proposed service is equal to $Q_0 = 1 - \sum_{m=1}^{M} Q_m$. We also assume that $V \geq p_1 > p_2 > ... > p_N$ and therefore a UE$_i$ of type θ_i will choose the service class that maximizes its utility:

$$m(\theta_i) = \underset{1 \leq m \leq M}{\operatorname{argmax}} \, U_i(m) \tag{2}$$

or no service if $U_i(m) = 0, \forall m \in (1, ..., M)$. This leads to a two-level (Stackelberg) game, where the provider first decides the prices per class, which are a function of the already allocated capacity per access technology, and then the UEs distribute themselves over classes, selecting the most appropriate for them. The provider can play by anticipating the distribution of UEs over the provided service classes. The distribution of UEs over the provided access technologies will be a Wardrop equilibrium [15], at which no UE will have an interest in changing access classes. When equilibrium of distribution of UEs over available access classes is reached, a given UE of type θ_i will prefer class m over k if

$$V - p_m - \theta_i f(Q_m, \bar{C_m}) \geq V - p_k - \theta_i f(Q_k, \bar{C_k}) \tag{3}$$

Therefore, if $p_m - p_k \leq \theta_i \left(f(Q_k, \bar{C_k}) - f(Q_m, \bar{C_m}) \right)$ and for monotonic $f(Q_m, \bar{C_m})$, class m will be preferred over k if

$$\begin{aligned} &\theta_i \geq (p_m - p_k)/(f(Q_m, \bar{C_m}) - f(Q_k, \bar{C_k})), \text{when } k > m \\ &\text{and if} \\ &\theta_i \leq (p_m - p_k)/(f(Q_m, \bar{C_m}) - f(Q_k, \bar{C_k})), \text{when } k < m \end{aligned} \tag{4}$$

This creates thresholds of θ values, $\theta_1 > \theta_2 > ... > \theta_M > \theta_{M+1} = 0$, such that at equilibrium, for $1 \leq m \leq M$, $\forall \theta_i \in (\theta_{m+1}, \theta_m)$, class m is chosen, while no class is preferred for $\theta_i > \theta_1$. The thresholds $\theta_1, ..., \theta_{M+1}$ are defined by using the fact that, at any of these specific threshold, a UE is indifferent between choosing one of the two adjacent classes. A UE, at threshold θ_1, is also indifferent between using the provided service or not.

We let the congestion perception function $f(Q_m, \bar{C_m})$ of the UEs to be

$$f(Q_m, \bar{C_m}) = \frac{Q_m}{\bar{C_m}/C_m} \tag{5}$$

We introduce a dynamic pricing scheme for each access class m. The maximum price for each class $p_m^{\max}$, is set for accessing class m when its total capacity C_m is allocated, and the minimum price $p_m^{\min}$ is set when the total capacity of class

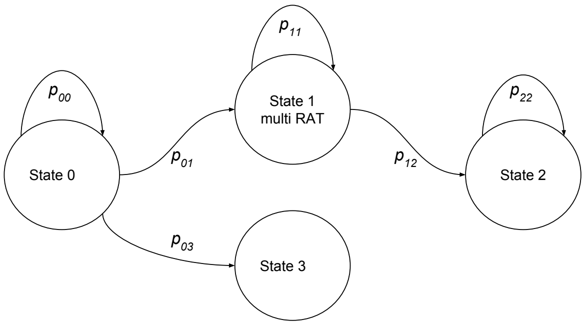


Fig. 2: Mobility States of the UEs.

m is available. The price as a function of available capacity $\bar{C_m}$ is expressed in (6).

$$p_m = \max\left(p_m^{\min}, p_m^{\max}\left(1 - \frac{\bar{C_m}}{C_m}\right)\right) \tag{6}$$

Regarding the mobility model of the UEs, we consider that they follow routes of diverse connectivity conditions to the available radio access technologies, according to the model proposed in [16]. In Fig. 2, we present the states of the Markov model for the mobility of a UE. A UE in State 0 will pass through the multi-RAT area (State 1) that we focus on with probability p_{01}, it will stay in State 1 with probability p_{11} and will leave the multi-RAT area with probability p_{12}. A UE starting from State 0 may not pass through the multi-RAT environment with probability p_{03} and stay at State 0 with probability p_{00}. Following, we provide the system architecture that was considered for the evaluation of our dynamic PMP scheme, and the algorithms designed for the multi-RAT operation.

IV. System Architecture and Algorithms Design

The proposed scheme is considered for three available radio access technologies, namely 3G, 4G and WiFi, and is evaluated by means of extensive simulations. Taking into consideration the significant shortfalls of simulations, identified in [17], in comparison to real-life experimentation, we provide results based also on testbed experimentation implemented on the Future Internet (FI) facility provided by NITOS [18]. NITOS is a heterogeneous testbed, located in the premises of University of Thessaly, in Volos, Greece. The rich heterogeneity of resources allows us to conduct the designated experiments. We employ an LTE base station of NITOS, along with a UMTS femto-cell and the respective Core Network [19]. We use a testbed node as a WiFi Access Point, located inside the coverage of both LTE and UMTS, and six nodes as the UEs located inside the Multi-RAT system. The overall topology that we use for our experiments is depicted in Fig. 3.

For the simulations we consider a basic system setup and demonstrate how the proposed pricing policy performs in certain representative scenarios. The mobile service provider has 3 classes of RAT and specifically cellular 3G, 4G and WiFi services. We assume that the maximum speed for each RAT is 42.4 Mbps (UMTS/HSPA+), 150 Mbps (IEEE802.11n SISO) and 300 Mbps (LTE Cat4 2x2 MIMO).

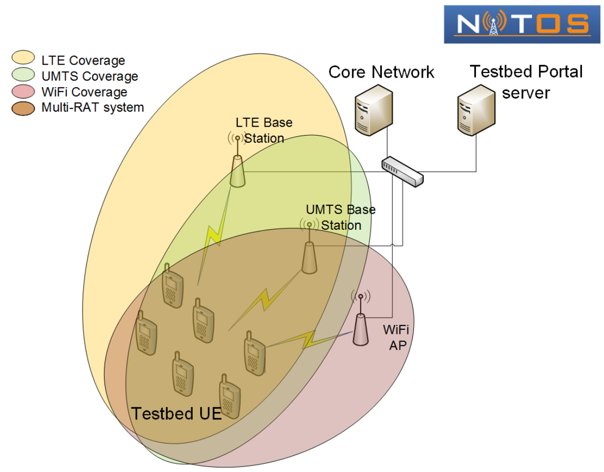


Fig. 3: Testbed topology used for the experiments

In order to evaluate the proposed pricing scheme, we came up with two algorithms, running at the UEs and the Core Network. In Algorithm 1, we present the operation of a UE that enters or is already situated in the multi-RAT environment. Initially, a UE receives a system report message containing the price, the available capacity and the mass of connected users to every RAT, and it calculates its utility for each class. If it decides to change or connect to a RAT, it sends a change/connect message to the Core Network. When a UE is connected and until it leaves State 1, if it receives a new system report, it recalculates its utility function for each class and examines if a change of RAT maximizes its utility. Based on its decision, the UE sends a message to the Core network to inform for a change (or for no change) and continues its operation as long as it stays in State 1.

In Algorithm 2, we provide the functionality of the Core

Algorithm 1 Algorithm for UEs

```
Receive system report (p_m, C̄_m, Q_m) ∀ RAT
Calculate Utility Function for each RAT
if UE decides to change/connect to RAT then
    Send change/connect message to Core Network
else
    Send OK to Core Network
end if
while 1 do
    if UE decides to leave State 1 then
        Send leave message to Core Network
    else
        Wait for system report
        Calculate Utility Function for each RAT
        if UE decides to change RAT then
            Send change message to Core Network
        else
            Send OK to Core Network
        end if
    end if
end while
```

Network. At first, the Core Network randomly distributes the UEs situated in State 1 to the available RATs, and it calculates the prices, the available capacities and the mass of connected users to every RAT. Thereafter, it sends an updated system report to each UE sequentially, and following it examines if the system is stable. The system is considered stable, when no UE desires to switch to another RAT. In the case when a UE leaves the multi-RAT, the Core Network updates the system values and communicates them to the State 1 UEs for further calculation of their utility functions, in order to determine whether they will change their RAT. In the case that a UE enters State 1, the Core Network calculates the available capacity to decide if it can serve its needs, otherwise the access is denied to the specific UE.

Algorithm 2 Algorithm for Core Network

1: Assign randomly UEs to 3 RATs
2: Calculate prices, available capacities and mass of users
3: Create system report $(p_m, \bar{C_m}, Q_m)$ $\forall$ RAT
4: **for** UEs in system **do**
5: Send system report to UE
6: Wait for response
7: Update system report
8: **end for**
9: **if** System is stable **then**
10: Continue
11: **else**
12: Go to 4
13: **end if**
14: **while** 1 **do**
15: Wait update from UEs in State 1
16: Wait for new UEs
17: **if** Available capacity **then**
18: Assign new UE to RAT
19: **else**
20: Deny access to new UE
21: **end if**
22: Calculate prices, available capacities and mass of users
23: Create system report $(p_m, \bar{C_m}, Q_m)$ $\forall$ RAT
24: **for** UEs in system **do**
25: Send system report to UE
26: Wait for response
27: Update system report
28: **end for**
29: **if** System is stable **then**
30: Continue
31: **else**
32: Go to 24
33: **end if**
34: **end while**

V. System Evaluation

For the evaluation of our proposed policy, we employ both simulation methods, as well as real testbed experiments. For our simulations, we evaluate our model for 10 users, who are initially placed in State 1 and 20 users in State 0. In order to validate our simulation results, we cross-reference them with results that we received from executing our proposed policy under a real testbed environment, with initially 2 users in State 1 and 4 users in State 0.

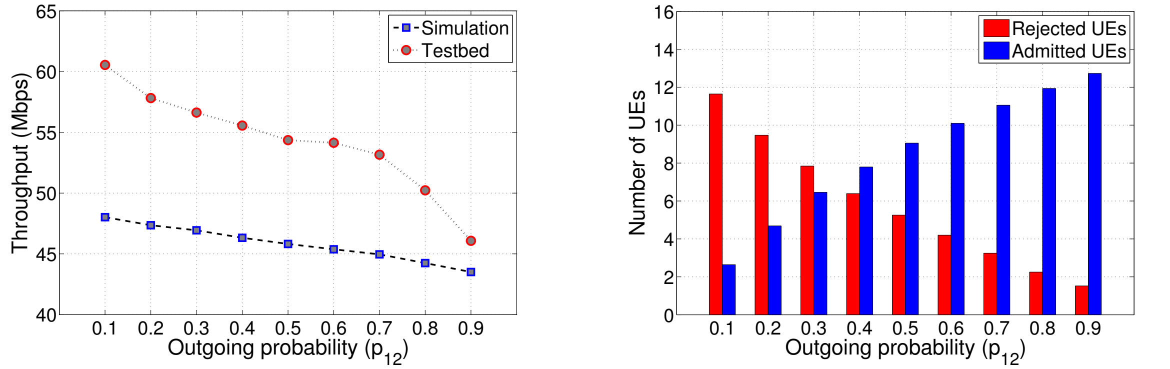
For the testbed tests, we logged RSSI and RSRP values for the LTE network equal to -53 dBm and -76dBm respectively. Similar values where observed for the UMTS and WiFi networks as well, inside the multi-RAT environment. Rate adaptation algorithms were disabled, and set to the highest Modulation and Coding Scheme for all the technologies involved, meeting the same maximum throughput requirements as set in our simulator. Moreover, we conduct our experiments in an isolated environment of external interference. We measure the capacity of our links by using packet sizes of 1500 bytes. The maximum and minimum prices of each class are selected to be proportional to the maximum available capacity of each RAT. We use a static probability p_{03} equal to 0.2, representing the probability that UEs on State 0 follow a route outside our system across all our experiments (simulations and testbed experiments). In other words, the selected mobility pattern includes a more common passage from the multi-RAT State 1 than avoiding it through State 3.

We organize our evaluation in three different experiments, during which the prices are constantly recalculated based on our model, and transmitted to the UEs of the network. The first experiment targets to monitor the throughput and acceptance ratio of the UEs in the multi-RAT system, when tuning the probability of exiting the system. The second experiment evaluates the same metrics when configuring the probability of a UE entering the multi-RAT system. Finally, the third experiment details our results for different congestion sensitivities of the UEs.

A. Experiments for UEs exiting the system

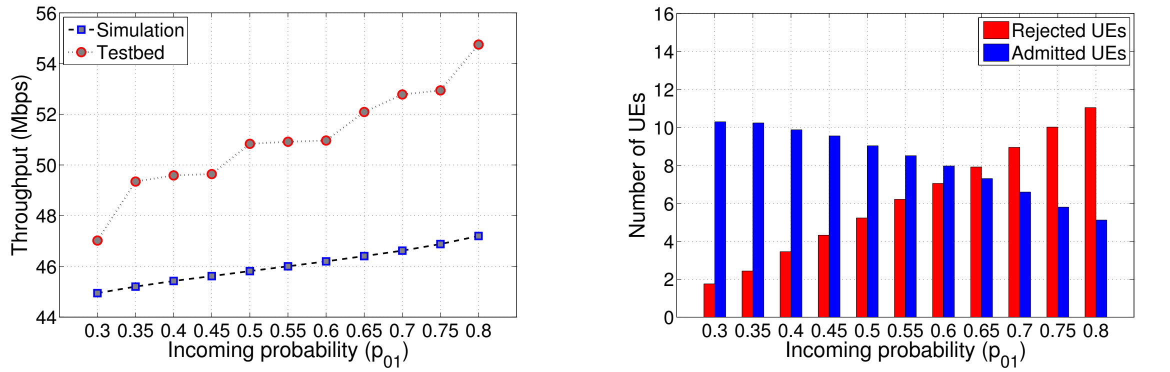
In this experiment, we seek to investigate the impact of different exiting mobility patterns, represented by the probability p_{12}, on the average throughput of the system. Furthermore, we examine how tuning this probability affects the number of incoming users from State 0, as well the number of users whose the access to State 1 was denied from the Core Network due to insufficient available capacity. For this experiment we configure the probabilities for the State 0 to have the following values: p_{00} = 0.3 and p_{01} = 0.5. In addition, we setup the highest capacity demand of each UE equal to 1/4 of the RAT with the highest capacity, in our case the LTE network. Fig. 4a demonstrates the average achieved throughput for various values of the exiting probability p_{12} used to express whether a UE leaves the multi-RAT system or not. In our simulations, we observe that as the probability of leaving the system is increasing, the total throughput is decreasing. This happens due to the fact that UEs stay at State 1 for a shorter period. On the other hand, the number of UEs that are not accepted to State 1 is decreasing as the probability p_{12} increases, meaning that more UEs enter the system as shown in Fig. 4b.

Similarly, for our testbed experiments, we observe a similar decreasing pattern as the outgoing probability rises. We would



(a) Throughput performance for UEs exiting the system (b) UEs admitted and denied for UEs exiting the system

Fig. 4: Experiment results for UEs exiting the system



(a) Throughput performance for UEs entering the system (b) UEs admitted and denied for UEs entering the system

Fig. 5: Experiment results for UEs entering the system

expect that the testbed experimentation would generate results with lower average throughput compared to simulations. Nevertheless, as the experiments are run using a lower number of UEs, we receive marginally higher average throughput.

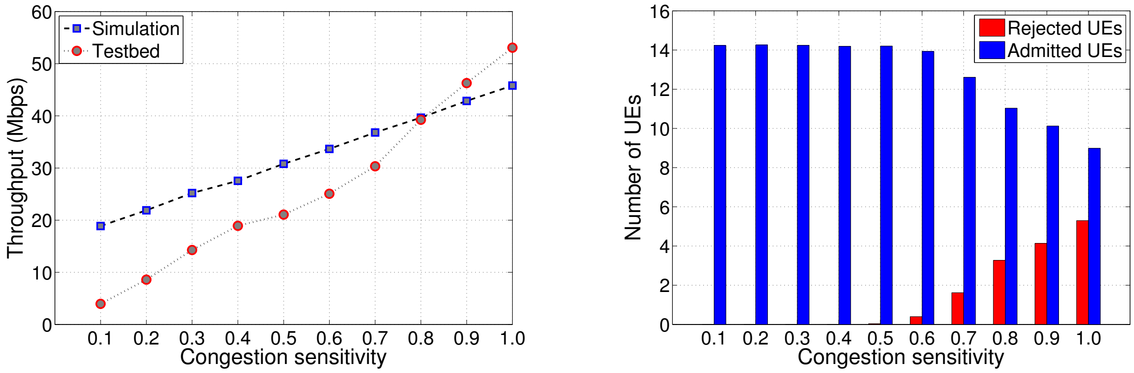
B. Experiments for UEs entering the system

In this scenario, extensive throughput experiments were conducted under varying values of the probability p_{01}. The total throughput performance is investigated for different mobility patterns of UEs entering the multi-RAT system. The probabilities in this scenario regarding State 1 are the following: p_{11} = p_{12} = 0.5, meaning that each existing UE inside the multi-RAT has a probability of 0.5 to either stay in or exit the system. The highest capacity demand of each UE stays the same as in the previous experiment. We notice that while p_{01} increases, the same occurs to the average system throughput as illustrated in Fig. 5a. Moreover, increasing the entering probability causes more UEs to be served by the multi-RAT system as observed in Fig. 5b. In parallel, the total number of UEs choosing a transition to State 1 rises (comprising of both admitted and denied UEs). Of course, the more UEs select to enter the multi-RAT system, the more are denied access due to lack of available capacity.

Regarding the testbed evaluation, we use a similar setup as for the aforementioned experiments. We observe that as the incoming probability rises, so does the average throughput that the UEs in the multi-RAT system achieve. Higher average throughput denoted in the testbed experiments, in comparison to simulation results, is mirroring the lower number of UEs used for our experiments.

C. Experiments for different congestion sensitivities

Through this set of experiments, we aim at investigating the impact of different QoS applications to our proposed PMP scheme. More specifically, we characterize different classes of applications by their congestion sensitivity, running inside the multi-RAT environment we focus on. In order to examine how applications with different demands affect the average throughput of the system, we first configure the probabilities of State 0 and 1 with the following values: p_{00} = 0.3 and p_{01} = 0.5 and p_{11} = p_{12} = 0.5. This means that each new UE stays in State 0 with probability 0.3, enters the multi-RAT system with probability 0.5, and follows a route outside our system with probability 0.2. Each existing UE inside State 1 has a probability of 0.5 to either remain in the system or exit it. By tuning different congestion sensitivities, we simulate applications with different QoS demands in the system. A UE running an application with the maximum congestion sensitivity is depicted in Fig. 6a with the value 1.0. In our results, the throughput received from such an application with high congestion sensitivity is equal to the 1/4 of the LTE's bandwidth. We have also assumed that the values of



(a) Throughput performance with respect to different congestion sensitivities

(b) UEs admitted and denied with respect to different congestion sensitivities

Fig. 6: Experiment results subject to different congestion sensitivities

the congestion sensitivity of the UEs in the multi-RAT are uniformly distributed. Fig. 6a depicts the average throughput achieved for different values of congestion sensitivity. We observe that for low bandwidth demands, all new UEs are accepted and served by the system but the average throughput performance is low, ought to the low requested demands. As the congestion sensitivity increases, the average throughput also increases, which means that the available capacity is decreasing. Consequently, the system is starting to deny access to new UEs, as it is shown Fig. 6b. Similarly for the testbed experiments, we observe a pattern that follows the simulation trends for the overall average throughput performance.

VI. Conclusion

In this work, we proposed the utilization of an extended Paris Metro Pricing scheme with dynamic prices, as a policy for selecting a RAT when operating inside a multi-RAT environment. We formulated the problem and defined the utility functions of each client for accessing the target RAT and we investigated its performance for several mobility scenarios. We presented our experimental results from the application of our scheme both in a simulator and a real testbed environment. In the future we foresee extending our work, for the cases when a UE is concurrently connected to multiple RATs, and interchangeably selects its access technology based on the current pricing policies of the system.

Acknowledgment

The research leading to these results has received funding from the European Union's Seventh Framework Programme under grant agreement no 612050 (FLEX Project).

References

[1] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015-2020," Feb. 2016.

[2] Ericsson, "5G Radio Access," 2011, [Online],http://www.ericsson.com/res/docs/whitepapers/wp-5g.pdf.

[3] C.-X. Wang, F. Haider, X. Gao, X.-H. You, Y. Yang, D. Yuan, H. Aggoune, H. Haas, S. Fletcher, and E. Hepsaydir, "Cellular Architecture and Key Technologies for 5G Wireless Communication Networks," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 122–130, 2014.

[4] L. Wang and G.-S. Kuo, "Mathematical Modeling for Network Selection in Heterogeneous Wireless Networks – A tutorial," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 1, pp. 271–292, 2013.

[5] D. Xenakis, N. Passas, L. Merakos, and C. Verikoukis, "Mobility Management for Femtocells in LTE-Advanced: Key Aspects and Survey of Handover Decision Algorithms," *IEEE Communications Surveys Tutorials*, vol. 16, no. 1, pp. 64–91, Jan 2014.

[6] P. Coucheney, C. Touati, and B. Gaujal, "Fair and Efficient User-Network Association Algorithm for Multi-Technology Wireless Networks," in *Proc. IEEE INFOCOM 2009*, pp. 2811–2815.

[7] E. Aryafar, A. Keshavarz-Haddad, M. Wang, and M. Chiang, "RAT Selection Games in HetNets," in *Proc. IEEE INFOCOM 2013*, pp. 998–1006.

[8] X. Kang and S. Sun, "Incentive Mechanism Design for Mobile Data Offloading in Heterogeneous Networks," in *Proc. IEEE International Conference on Communications (ICC) 2015*, pp. 7731–7736.

[9] G. Iosifidis, L. Gao, J. Huang, and L. Tassiulas, "Enabling Crowd-Sourced Mobile Internet Access," in *Proc. IEEE INFOCOM 2014*, pp. 451–459.

[10] V. Miliotis, L. Alonso, and C. Verikoukis, "Weighted Proportional Fairness and Pricing Based Resource Allocation for Uplink Offloading Using IP Flow Mobility," *Ad Hoc Networks*, Oct. 2016.

[11] A. Odlyzko, "Paris Metro Pricing for the Internet," in *Proc. of the 1st ACM conference on Electronic commerce*, 1999, pp. 140–147.

[12] C.-K. Chau, Q. Wang, and D.-M. Chiu, "On the Viability of Paris Metro Pricing for Communication and Service Networks," in *Proc. IEEE INFOCOM 2010*, pp. 1–9.

[13] L. He and J. Walrand, "Pricing Differentiated Internet Services," in *Proc. IEEE INFOCOM 2005*, vol. 1, pp. 195–204.

[14] S. Talwar, D. Choudhury, K. Dimou, E. Aryafar, B. Bangerter, and K. Stewart, "Enabling technologies and architectures for 5g wireless," in *Proc. IEEE MTT-S International Microwave Symposium (IMS)*, 2014, pp. 1–4.

[15] J. G. Wardrop, "Some Theoretical Aspects of Road Traffic Research," *Proc. of the Institution of Civil Engineers*, vol. 1, pp. 325–378, 1952.

[16] A. J. Nicholson and B. D. Noble, "Breadcrumbs: Forecasting Mobile Connectivity," in *Proc. of the 14th ACM International Conference on Mobile Computing and Networking, MobiCom '08*, 2008, pp. 46–57.

[17] S. Kurkowski, T. Camp, and M. Colagrosso, "MANET Simulation Studies: The Incredibles," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 9, no. 4, pp. 50–61, Oct 2005.

[18] "NITOS - Network Implementation Testbed using Open Source platforms." [Online],http://nitlab.inf.uth.gr/NITlab/index.php/nitos.html.

[19] N. Makris, C. Zarafetas, S. Kechagias, T. Korakis, I. Seskar, and L. Tassiulas, "Enabling Open Access to LTE Network Components; The NITOS Testbed Paradigm," in *1st IEEE Conference on Network Softwarization (NetSoft), 2015*, pp. 1–6.