Biobjective Optimization of Radio Access Technology Selection and Resource Allocation in Heterogeneous Wireless Networks

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***Abstract*—We propose a novel optimization model for resource assignment in heterogeneous wireless network. The model adopts two objective functions maximizing the number of served users and the minimum granted utility at once. A distinctive feature of our new model is to consider two consecutive time slots, in order to include handover as an additional decision dimension. Furthermore, the solution algorithm that we propose refines a heuristic solution approach recently proposed in literature, by considering a real joint optimization of the considered resources. The simulation study shows that the new model leads to a significant reduction in handover frequency, when compared to a traditional scheme based on maximum SNR.**

I. INTRODUCTION

Nowadays, if we look at mobile subscriptions by technology, we observe a dominance of GSM/EDGE mobile standards, followed by WCDMA/HSPA and currently under deployment LTE. In the near future, as forecasted in [1], the presence of LTE and WCDMA will increase, leading to a reduction in GSM/EDGE subscriptions. LTE, in particular, will become common in metro and urban areas. Widely available EDGE will maintain its overall coverage, whereas HSPA will increase its availability steadily and cover also most of the suburban and rural areas.

A number of different standards available in the wireless environment forms a heterogeneous network with highly overlapping cells. This mix of technologies is able to bring a ubiquitous service to end users equipped with multimode terminals that are capable to switch between technologies in a seamless way. In order to fulfill the requirements of the *Always Best Connected* (ABC) paradigm [2], a number of conditions must be satisfied, namely: 1) tight cooperation between the standards enabling exchange of control information; 2) seamless handover so that a terminal can smoothly switch between the technologies and stay connected anytime and anywhere; 3) optimal selection of the Radio Access Technology (RAT) and assignment of radio resources. The last issue is the one on which we focus attention in this work.

In this paper, we address the challenge of optimal Base Station (BS) and RAT selection as well as resource allocation in heterogeneous wireless networks. Though the problem of forming clusters has been extensively discussed from a technical point of view, there is still a lack of effective optimization models for its representation and algorithms for its solution. In this work, we make a further step towards filling such gap: 1) we generalize the classical network design problem by adding handover as an additional decision dimension; 2) we propose a novel Integer Linear Programming (ILP) model that allows for a more effective and efficient utilization of network resources, including at the same time handover occurrence; 3) we define a new solution algorithm that overcomes the heuristic character of recently proposed approach in literature; 4) we assess the performance of our new model and algorithm through simulation on a set of realistic instances of a heterogeneous network including EDGE, HSDPA and LTE technologies.

We stress that the adoption of an ILP model and an exact solution approach must not be immediately interpreted as synonymous of computational inefficiency. In the last years, state-of-the-art commercial solvers like IBM ILOG CPLEX [3] have indeed greatly improved their efficacy and efficiency and they can effectively support online applications, where time is a crucial issue [4], [5], especially when used in combination with fast heuristics.

We note that several ILP models were proposed in literature to solve a RAT selection problem (e.g., [6], [7], [8]). However, currently available optimization models consider just one time scenario and do not take into account the dynamic case with a handover. As we noted, we generalize such models by inserting handover as an additional decision dimension. More specifically, we generalize the optimization model recently proposed in like [6], by including handover as additional decision variables. By introducing a penalty for occurrences of handover, our model aims at maintaining the connection of a user to an already chosen BS and RAT. In this way, we try to avoid the so-called ping-pong effect, which consists of frequent assignment changes of terminals that are highly mobile or close to a cell border. Additionally, our model considers two objectives: maximizing the minimum utility of the network and the number of connected terminals. Finally,

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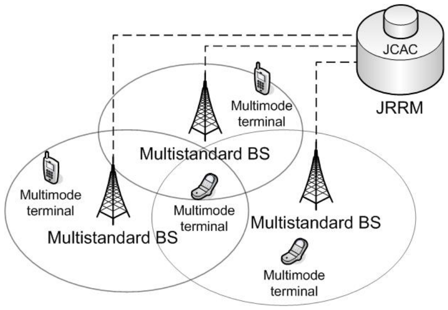

Fig. 1. An example of a network-centric RRM platform

our model also mitigates the heuristic character of models like [6]: in such models, if the available radio resources are not sufficient to satisfy the requests of all the users, some users may be dropped off according to a priority list established a priori. In our model, we do not rely on such heuristic approach based on a priority list, but we let the model choose which is the best subset of users to be served, once the number of users is fixed. Of course, such optimal selections performs much better than the heuristic one of [6], both from a theoretical and computational point of view.

The paper is organized as follows: the next Section presents the problem of RAT selection and resource allocation more in detail whereas Section III introduces the optimization model proposed in this paper. Section IV discusses the simulation setup used for evaluation purposes including network architecture and utility function. Simulation results are presented in Section V and finally Section VI concludes the paper.

II. RAT SELECTION IN HETEROGENEOUS NETWORKS

To provide ubiquitous service, very tight cooperation between the network entities of different standards is expected. In order to manage the operation of multistandard networks in the best way, a number of Radio Resource Management (RRM) systems have been proposed, such as Common RRM (CRRM) [9] or Joint RRM (JRRM) [10]. They are based on a centralized approach, where common or joint network entities are responsible for the overall heterogeneous network control, as depicted in Fig. 1.

A network entity called Joint (or Common) Call Admission Controller (JCAC) is responsible for setting up, managing the connections and allocating the radio resources for all the terminals present in the network. The control entity gathers and maintains all the necessary information about the terminals, such as their capabilities, signal quality reports, required service type, radio parameters etc. It has also access to the characteristics of BSs that are present in its control region, such as the number of available resources and all the inter-RAT configuration information. Based on these, it makes the decisions on assigning terminals a serving BS, RAT and a number of resources helping to balance the network load and utilize the network resources in an efficient way.

It is worth noting that RRM systems of a more distributed character were also proposed, such as Multiaccess Radio Resource Management (MRRM), where a set of cooperating agents take control over the network. Depending on RRM architecture then, the entity responsible for call admission control and resource allocation serves a number of cells and manages a certain area more globally for centralized RRM system or locally if it's distributed. This entity could be also used in the management of future Cloud Radio Access Networks (C-RAN) [11] and can then reside as a module in the baseband (BB) pool and control the connections of user terminals to particular Remote Radio Heads (RRH).

In this paper we present an optimization model that can support management entities like JCAC in their decisions; it is described in detail in the following section.

III. OPTIMIZATION MODEL

In this section, we present our new optimization model and solution algorithm for RAT selection and resource allocation in heterogeneous networks. For an overview of the use of optimization models in wireless network design, we refer the reader to [12] and [13]. Before discussing the model in detail, we first describe the elements of the model and the corresponding notation.

We consider the design of a cellular network made up of a set B of BSs that provide a telecommunication service to a set of user terminals T. Each BS $b \in B$ installs a set R of RATs and each RAT makes available I resource units. A BS $b \in B$ offering services through a RAT $r \in R$ has a capacity of C_{br} that is limited by the number of resources I. The assignment of a quantity of resources to a terminal generates a utility that reflects the satisfaction of the user. A terminal is covered with service if it is assigned a subset of resources that guarantees its minimum required utility U^t_{min}. Similarly to [6], we assume that the utility gained by a user depends on the RAT and in general increases as the number of assigned resources increase. Furthermore, we also introduce a dependency upon the BS that provides the resources, since in this way, we can discriminate among different BSs (for example, we can penalize the utility of BSs that are far away from the terminal, in contrast to closer BSs). The utility value U^t_{bri} gained by a terminal t is thus indexed over the BSs $b \in B$, the RATs $r \in R$ and the resources $i \in I$.

The *heterogeneous network resource assignment problem* (HNRAP) consists of assigning resources to terminals in order to cover with service the maximum number of users, while maximizing the minimum utility of the system (i.e., we want to maximize the utility of the user obtaining the minimum utility). We stress that we do not limit our attention to this problem, but we add a further level of generalization by considering the possibility of operating a handover. So, in our problem we look at two consecutive time periods and we introduce an additional index $p \in P = \{1, 2\}$ to represent a generic period among the two. Of course, we want to contain handover, so we penalize its occurrence for a terminal $t \in T$ by a value $w_t > 0$. To model these four decisions, we introduce four types of decision variables:

1) a binary *resource assignment variable* $y^{tp}_{bri} \in \{0,1\}$, $\forall\, t \in T, b \in B, r \in R, i \in I, p \in P$ that is equal to 1 if terminal t is assigned i resources by BS b through RAT r in period p and equal to 0 otherwise,
2) a binary *service variable* $x_{tp} \in \{0,1\}$, $\forall\, t \in T, p \in P$ that is equal to 1 if terminal t is served in period p and equal to 0 otherwise,
3) a binary *handover variable* $w_t \in \{0,1\}$, $\forall\, t \in T$ that is equal to 1 if terminal t experiences handover and to 0 otherwise,
4) a single continuous *utility variable* $u \in [0,1]$ that coincides with the lowest utility gained by a served terminal of the network.

We summarize the complete notation in Table I.

TABLE I
NOTATION

$t \in T$	set of terminals
$b \in B$	set of base stations
$r \in R$	set of radio access technologies
$i \in I = 1,...,\lvert I\rvert$	set of assignable units of resources
$p \in P = [1,2]$	set of time slots
U^t_{bri}	utility value of terminal t towards BS b and RAT r if i resources are assigned
U^t_{min}	minimum utility requirement of terminal t
π_t	handover penalty for terminal t
M	sufficiently large positive constant, $big-M$
y^{tp}_{bri}	resource assignment variable of terminal t served by BS b through RAT r with i resources
x_{tp}	service variable of terminal t in period p
w_t	handover variable of terminal t
u	minimum utility value

The original optimization model that we introduce is the following:

$$\max u \tag{1}$$

$$\max \sum_{t\in T}\sum_{p\in P} x_{tp} - \sum_{t\in T} \pi_t \cdot w_t \tag{2}$$

$$u \le \sum_{b\in B}\sum_{r\in R}\sum_{i\in I} U^t_{bri}\, y^{tp}_{bri} + M\,(1 - x_{tp}), t \in T, p \in P \tag{3}$$

$$\sum_{b\in B}\sum_{r\in R}\sum_{i\in I} U^t_{bri}\, y^{tp}_{bri} \ge U^t_{\min}\, x_{tp}, t \in T, p \in P \tag{4}$$

$$\sum_{t\in T}\sum_{i\in I} i\, y^{tp}_{bri} \le C_{br}, b \in B, r \in R, p \in P \tag{5}$$

$$\sum_{b\in B}\sum_{r\in R}\sum_{i\in I} y^{tp}_{bri} \le x_{tp}, t \in T, p \in P \tag{6}$$

$$\sum_{i\in I} y^{t1}_{\beta\gamma i} + \sum_{b\in B\setminus\{\beta\}} \sum_{r\in R\setminus\{\gamma\}} \sum_{i\in I} y^{t2}_{bri} \le 1 + w_t,$$

$$t \in T, \beta \in B, \gamma \in R \tag{7}$$

$$y^{tp}_{bri} \in \{0,1\}, t \in T, b \in B, r \in R, i \in I, p \in P \tag{8}$$

$$x_{tp} \in \{0,1\}, t \in T, p \in P \tag{9}$$

$$w_t \in \{0,1\}, t \in T \tag{10}$$

$$u \in [0,1] \tag{11}$$

The problem has a biobjective function and includes: 1) the maximization of the lowest utility of a terminal; 2) the maximization of the difference between the total number of served terminals and the total penalization coming from handovers. The connection between the utility variable u and the utility gained by each terminal is described by constraints (3). Each of these constrains activates only when the included variable x_{tp} is equal to 1. If $x_{tp} = 1$, the presence of a sufficiently large value $M > 0$, the so-called *big-M coefficient* (see [13], [14]), makes the constraint redundant. As noted in Section I, we stress that the adoption of these big-M constraints is an improvement with regard to the model proposed in [6]: if the number of terminals to be served is fixed, the served terminals are not chosen a priori by a priority list as in [6], but the choice is operated directly by the optimization model in the best possible way.

Constraints (4) ensure that a served terminal is guaranteed a minimum utility value so that its Quality of Service (QoS) requirements are fulfilled. Constraints (5) express the limit on the capacity C_{br} of BS b and RAT r and make sure that it is not exceeded. An important model assumption is that a terminal is allowed to set up a connection to only one BS/RAT at a time. Constraints (6) impose that a terminal receives resources only if it is served. Finally, constraints (8) control the handover procedure: we incur a handover penalization when a terminal is served in both periods and there is a variation in the serving couple (β, γ) BS-RAT passing from period 1 to period 2 (this means that the second group of summations excluding β and γ assumes unitary value, thus forcing w_t to 1). Thanks to this approach, our model can be used for multiple consecutive time instances and support the decisions of JCAC.

Concerning the solution approach, we adopt a standard way to deal with a biobjective function: we consider a convex combination of the two objectives by a parameter $\alpha \in [0,1]$ (we use $\alpha \max u + (1-\alpha) \max \sum_{t\in T}\sum_{p\in P} x_{tp} - \sum_{t\in T} \pi_t \cdot w_t$). The value of α thus controls the relative importance of the two objectives.

IV. SIMULATION SCENARIO

The optimization model that we propose is very generic and can be applied to numerous network scenarios, including multiple telecommunication standards, deployments with small cells (pico, femto) so-called HetNets, and C-RAN. It can be also used in a scenario where traffic offloading is considered. All of the above are subject to proper utility function definition.

Due to the observations described in the introduction, we consider a wireless scenario where three RATs are available, namely EDGE, HSPA and LTE. The goal is to provide the multimode terminals the best possible connection by choosing the most appropriate RAT and assigning necessary resources so as to and meet their QoS requirements.

We develop the test scenario in OPNET Modeler [26]. Furthermore, the network simulator is interfaced with GAMS [27] which uses CPLEX [3] as an ILP solver. Network parameters are periodically extracted from OPNET and automatically sent to GAMS. Later on results of optimization are returned as an input to the network simulator. Following sections will present the network model considered in this paper more in detail.

A. *Network Architecture*

We consider a target area covered by three standards offering service to a number of terminals. Mobile users with multimode terminals (MTs) are randomly distributed and move around the coverage area with a uniformly distributed speed. BSs send control information over their broadcast control channel specific for each RAT. Every multimode MT is equipped with three radio interfaces, one per RAT. MTs monitor the system information and perform periodic reporting of their Channel Quality Indicators (CQIs) over a specific control channel towards a particular BS and RAT. This information is further forwarded to the centralized JCAC entity. We assume perfect synchronization between the RATs and error-free transmissions of CQIs.

MTs generate call requests, as described in IV-C. JCAC processes them periodically and assigns MTs to particular BSs and RATs using the optimization procedure described in III. Once a MT transits from an idle to a connected mode, data transfer over a data traffic channel starts. If during an ongoing call the assignment of BS/RAT changes, we assume that a seamless vertical handover occurs.

B. *Network Resources*

For the evaluation purposes we will consider one cell served by a multistandard base station. We focus on the downlink transmissions and the resources available in the network are 7 carriers, 15 codes and 25 resource blocks for EDGE, HSDPA and LTE, respectively. The multimode terminals are capable to operate in all three standards and in case of HSDPA we assume a terminal cat. 16 which can use up to 15 codes.

All the standards enable Adaptive Modulation and Coding (AMC), the terminals perform measurement of the received Signal-To-Noise (SNR) ratio and map it to an appropriate Modulation and Coding Scheme (MCS). The values of SNR thresholds are adopted from [15] for EDGE and HSDPA. Mapping for LTE is based on [16] and presented in Table II. Transport Block Size (TBS) is determined based on the MCS and is done according to the tables specified in the documentation of the standards [17], [18], [19].

C. *Traffic Model*

According to [20] video comprise of 30% of the mobile traffic traffic on laptops, tablets and smartphones. Another 30 to 40 % consists of web browsing including social networking, e-mail and file sharing. The remaining part we allocate to Voice over IP (VoIP) services. In this scenario we consider three types of traffic, as aforementioned. As for the VoIP traffic characteristics, we model 16 kbps with G.728 codec, 32 kbps with G.726 and 64 kbps with G.711 codec based on [21]. Video traffic is modeled according to the specification [22] whereas http traffic model is adopted from [23]. Traffic models are summarized in Table III.

TABLE II
AMC IN LTE [16]

SNR [dB]	MCS	Modulation	Coding
-6.5	MCS 1	QPSK	1/12
-4.5	MCS 2	QPSK	1/9
-2.5	MCS 3	QPSK	1/6
-0.1	MCS 4	QPSK	1/3
1.5	MCS 5	QPSK	1/2
3.5	MCS 6	QPSK	3/5
5.0	MCS 7	16QAM	1/3
7.0	MCS 8	16QAM	1/2
9.0	MCS 9	16QAM	3/5
11.0	MCS 10	64QAM	1/2
12.5	MCS 11	64QAM	1/2
15.0	MCS 12	64QAM	3/5
16.5	MCS 13	64QAM	3/4
18.0	MCS 14	64QAM	5/6
20.0	MCS 15	64QAM	11/12

TABLE III
TRAFFIC MODEL DETAILS

Traffic	Parameter	Characteristics
Video	Frame size [packets]	8
	Frame interarrival [s]	Deterministic: 0.1
	Packet size [bytes]	Truncated pareto: mean 50, k=40, α=1.2
	Packet interarrival [s]	Truncated pareto: mean 0.006, k=2.5, α=1.2
VoIP	ON time [s]	Exponential: mean 1.34
	OFF time [s]	Exponential: mean 1.67
G.728	Packet size [bytes]	60
	Packet interarrival [s]	0.03
G.726	Packet size [bytes]	80
	Packet interarrival [s]	0.02
G.711	Packet size [bytes]	160
	Packet interarrival [s]	0.016
Http	Packet size [bytes]	Pareto: mean 81.5 α=1.1
	Packet interarrival [s]	Normal: mean 0.0277, st.dev. 0.01
	Session size [packets]	Normal: mean 25, st.dev. 5
	Reading duration [s]	Exponential: mean 5

D. *Utility Function*

In the available literature, there are many proposals of the utility function definition for RAT selection purposes, for example [6], [7], [8], [24], [25]. These definitions take into account a number of various factors, such as terminal capability, cell load, service cost or link quality among others. Our definition is strongly related to user mobility and radio conditions measurement, which every user performs periodically. As explained in IV-B all the standards considered in the simulation scenario use AMC, where particular channel quality in terms of SNR is mapped to an MCS. Consequently MCS translates to TBS and achievable throughput. Because of that we decided to make our utility function solely dependent on throughput. For this purpose we modify the utility function proposed in [8] to the form given below.

$$U = \frac{min\{T_{net}, T_{max}\} - T_{req}}{T_{max} - T_{req}} \tag{12}$$

where T_{net} is the throughput offered by the network which is estimated based on the radio conditions of the terminal and the number of resources to be allocated with a given

TABLE IV
SIMULATION PARAMETERS

Parameter	Value
Number of cells	1 with 1 multistandard BS
Cell radius	1 km
Number of RATs	3: EDGE, HSPA, LTE
Resources	7 carriers, 15 codes, 25 resource blocks
Number of MTs	70
MT mobility model	Random Waypoint
MT max. speed [km/h]	3, 5, 10, 20, 60
Simulation duration [s]	300
Optimization time interval [ms]	100

MCS. T_{req} represents the throughput requested by a terminal and T_{max} is the maximum throughput available for a given application.

Let us note that this definition takes into account the number of assigned resources, and uses them in an efficient way. The formulation guarantees the requested throughput with minimum number of resources, since as soon as $T_{net} > T_{max}$ the utility equals 1. Until that stage, it explores the potential of a terminal to increase its utility by assigning more resources.

In the simulation run, we calculate the utility for every possible resource assignment for each terminal based on reported CQI. Thus, users have a chance to be assigned maximum number of resources a terminal is capable to manage. The utility function presented here could be further enhanced with other decision factors, as mentioned at the beginning of this section. It wouldn't affect the general principle of the proposed procedure, though.

V. RESULTS

In this section, we will evaluate network throughput and handover frequency reduction resulting from the proposed model as a part of the control platform of a heterogeneous network introduced in previous sections. The simulation parameters are summarized in Table IV.

During the evaluation we will focus on network throughput and handover frequency measurement. If during an ongoing service, a change of BS/RAT assignment occurs, it is counted as a handover. In our scenario, we have a multistandard BS, so only vertical handovers are considered. Furthermore, if no resources for data transmission are assigned, we maintain a connection to the last chosen BS/RAT only for control purposes. All the simulation results are presented with 95% of confidence interval.

A. Comparison With Max SNR Scheme

First we compare the proposed RAT selection and resource allocation scheme with the one based on maximum SNR, where terminals are associated with the BS/RAT that offer the best downlink radio channel conditions indicated by the highest SNR.

Fig. 2 presents the average network throughput for a number of scenarios with varied maximum terminal speed (from 3 to 60 kmph). We observe that RAT selection and resource allocation based on Max SNR provides higher network throughput than our proposed optimization model.

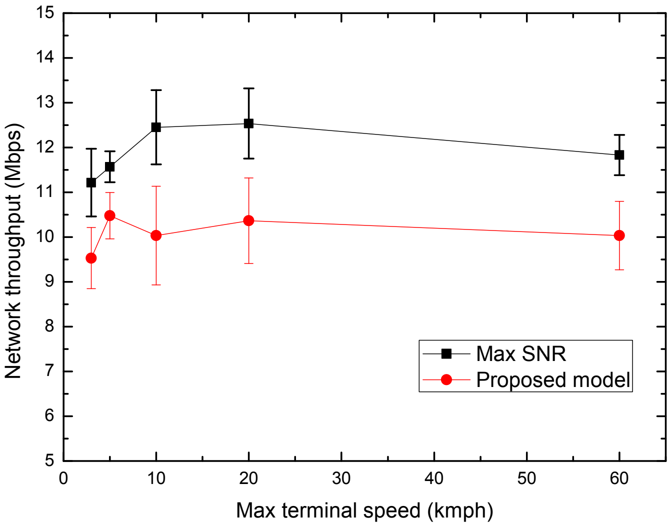

Fig. 2. Average network throughput, α 0.5, π_t 0.5

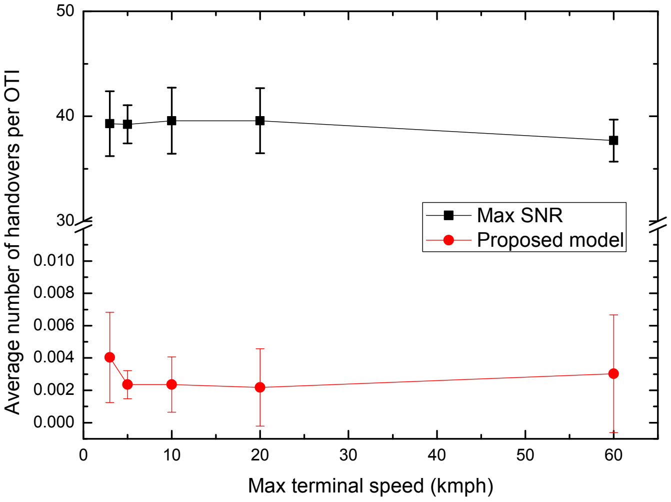

Fig. 3. Average number of handovers, α 0.5, π_t 0.5

However, while comparing the number of handovers depicted in Fig. 3 it can be clearly seen that our scheme highly outperforms the classical one. Please note that to present the significant difference in terms of number of handovers between the two schemes precisely, the scale of the Y axis had to be adjusted. Max SNR enforces a handover much more frequently, and on average 50% of terminals change their assignment every Optimization Time Interval (OTI) whereas our scheme maintains the connection to a particular BS and RAT as long as it is feasible. The average number of handovers per OTI is less than 0.01, more stable assignments and handover reduction is achieved at a cost of slight throughput degradation as discussed above.

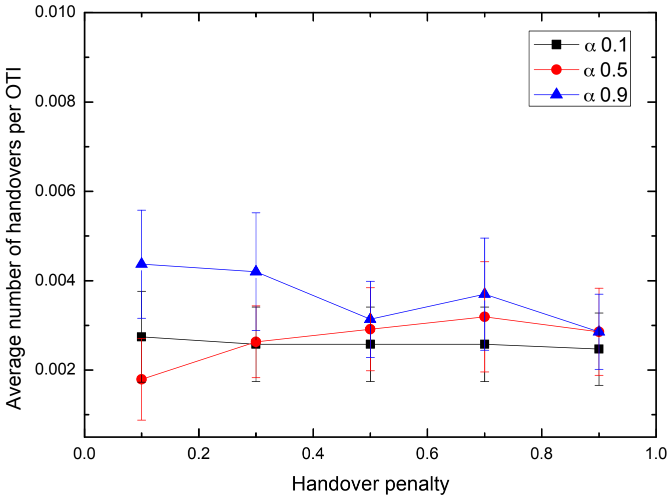

Fig. 4. Average number of handovers as a function of α and π_t

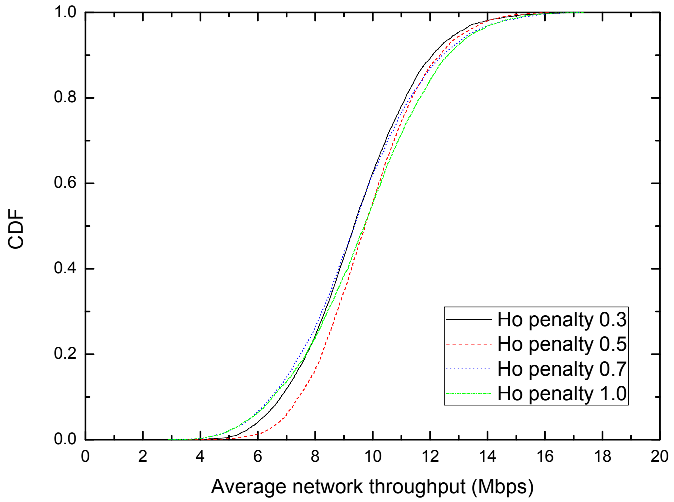

Fig. 5. CDF of the network throughput, α 0.5, max. speed 5 kmph

B. Optimization Model Evaluation

In this subsection we will characterize some of the performance properties of the proposed optimization model. Let us recall the final objective function, $\alpha \max u + (1 - \alpha) \max \sum_{t \in T} \sum_{p \in P} x_{tp} - \sum_{t \in T} \pi_t \cdot w_t$. Minimum utility u is in the range [0,1] and the other part of the sum is upper limited by the total number of users in the system. According to our computational experience the value of α parameter does not have big influence on the network performance in terms of throughput. In Fig. 4 we present the influence of α and π_t parameters on the number of triggered handovers. As expected, it decreases with the increase of π_t. Due to the formulation of the objective function higher values of α should enable more frequent handovers but the results show limited impact (highly overlapping confidence intervals).

On the contrary, handover penalty π_t, which can have different value depending on the standard or a terminal, has more influence on the final result. In Fig. 5 the lower handover penalties result in a higher network throughput. This happens because handover penalty at a low level enables more frequent assignment change. The system aims at improving the utility value and maximizing minimum utility u. On the other hand, when the handover penalty is set to higher values, the assignment is changed only in case of significant utility value improvement. As a consequence, high handover penalty leads to lower network throughput but mitigates the impact of handovers and keeps the MT-BS/RAT coupling more stable.

VI. CONCLUSION

In this paper we presented a novel optimization model of RAT selection and resource allocation in heterogeneous networks. It aims at optimizing double objectives: the minimum utility and the number of connected users. Furthermore, it takes into account two consecutive time slots and by reusing its previous solution it minimizes the occurrence of a handover.

The proposed scheme was compared with the baseline which is the maximum SNR. Through simulations we showed that our optimization model highly outperforms the classical approach. Obtained results indicate that the handover frequency can be significantly reduced at the cost of a slight overall network throughput degradation. The model can be used as an integral part of a RRM system, as taking advantage of the technology and channel state diversity leads to overall better resource utilization in heterogeneous networks. The utility function used for performance evaluation was solely based on throughput. However, it can be easily enhanced with other factors such as service price or network load. Furthermore, after adopting a suitable utility function the proposed optimization model can be applied to a number of heterogeneous wireless network scenarios, including call admission control and resource allocation in HetNets, traffic offload case and C-RAN.

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