Multi-radio Resource Allocation Strategies for Heterogeneous Wireless Networks

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Abstract— **In this paper we present algorithms for dynamic channel allocation with QoS support. In particular, we focus on the integration of networks with different Radio Access Technologies (RATs), as is currently subject of investigation within the novel concept of Ambient Networks. On this matter, we investigate the introduction of collaborative channel assignment, which exploits service elasticity and the tunability offered by QoS management. To this end, the comparison between non cooperative and cooperative resource allocation is briefly discussed and simulations are performed to demonstrate how collaborative strategies are able to improve system performance.**

Keywords: Radio Resource Management, Cooperation, Packet Allocation, Utility, Economic Performance.

1. INTRODUCTION

The Ambient Networks paradigm [1] includes the provision of seamless communication through heterogeneous radio interfaces. Moreover, it is expected that the presence of multiple Radio Access Techniques (RATs) is able to improve the system performance by means of the so-called RAT-diversity, i.e., the co-existence of different accesses might be beneficial for the entire system, in particular for the degree of QoS provided to the users. The integration of multiple radio interfaces in order to obtain a Multi-Radio Resource Management (MRRM) is currently one of the key issues researched by the scientific community [2–6]. In particular, strategies to fully exploit the presence of multiple networks thanks to the internetworking cooperation are currently sought. To this end, it is assumed that collaborative allocation strategies improve system performance by allowing e.g., higher system capacity, or higher degree of satisfaction with respect to more trivial channels allocation techniques, independently applied to each network.

The main goal addressed in this work is the investigation about strategies which aim at allowing mobile users in coverage of more networks to fully exploit this multi-RAT co-presence. To this end, we propose a comparison between resource allocation strategies, where either the allocation is simply performed without interworking between different networks, or a degree of cooperation is allowed. We focus on single-hop and infra-structured wireless networks with fixed Access Points (APs); however, this analysis can be extended to more general scenarios, e.g., multi-hop and Ad Hoc-like networks by considering at first aggregation procedures of the terminals [7, 8] and then following the same approach presented here.

We assume that each network owns a given amount of channels, available on its whole coverage area, and the APs, interconnected each other by a high-speed backbone network, are responsible to decide the channels to use. We suppose to have an area completely covered by two radio network technologies, which could represents real multiplexing technology such as cellular UMTS or WLAN 802.11. This type of scenario is taken into consideration in many other works present in literature [9, 10]. Each network provides a certain number of channels available in the whole area; to give a sort of QoS support each mobile terminal can communicate with more parallel channels at the same time, also belonging to different radio technologies, having an instantaneous bit rate allocation. The AP has to decide if the user may send the packet with the required QoS or not. This decision is taken by negotiating the allocation with all the other APs, in order to avoid collisions between adjacent APs. The channel allocation follows a Per-Packet approach, by allocating resources for every single packet, instead of a classic per-call method.

We address a way to find satisfactory QoS for users thanks to traffic splitting between multiple radio access for a single terminal. Having at disposal more different wireless networks, we propose channel allocation algorithm that exploit a collaboration between different networks, in order to reduce drop probability and to increase system throughput. The investigation is performed by simulation, based on snapshots.

We also consider the allocation in microeconomic terms. This means that, besides the technical efficiency of the cooperation among different RATs, we also consider at first the welfare of the management, seen as utility perceived by the users when the allocation is satisfactory.

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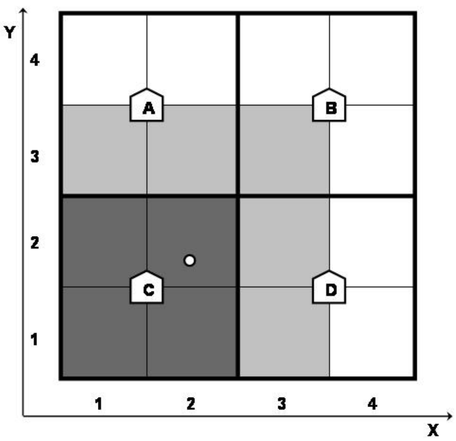

Fig. 1. Example of scenario: area with L=4, four Access Points (A, B, C, D)

Secondly, we also account for the revenue earned by the provider, evaluated through a model which is able to take into account the trade-off between quality and price.

The rest of the paper is organized as follows: in Section 2 we describe in detail the channel allocation strategies for both cooperative and non cooperative cases. In Section 3 we explain the application of micro-economic models, including evaluation of users' satisfaction determined by QoS and price. Section 4 shows the results obtained by means of simulations. Section 5 draws the conclusions.

2. CHANNEL ALLOCATION: BASIC ASSUMPTIONS AND STRATEGIES

In this section we present in detail the studied scenario, the basic assumptions and the per-packet allocation approach, as well as two different MRRM channels allocation strategies, with and without cooperation between the wireless networks present in the whole area.

2.1. Scenario and Per-Packet Approach

For the sake of simplicity, the studied scenario is a square area subdivided into $L \times L$ square sectors; the side of the area is composed by $L = 2l$ sectors. A total number of l^2 APs are present in the whole area and they are placed on a grid with constant distance from one to the other. We assume the coexistence of $N = 2$ distinct RATs operating in the same area, with all APs having the availability of both RATs. We consider that the coverage areas of different APs are perfectly non-overlapping: this assumption is not restrictive as it might be avoided by exploiting the paradigm of Always-Best-Connected networks [4]. Each AP is connected through a wired infrastructure with the adjacent APs through a backbone network; each AP coverage area is split into four square sectors. Mobile terminals (MTs) are uniformly distributed in the area; each AP can localize a MT in one of the four sectors of its coverage area. A total number C of channels belonging to each of the two networks are available in the system; channels of one network do not interfere with channels belonging to the other network. Each AP can use up to $2C$ independent transmission channels at the same time. To achieve the desired QoS, a mobile terminal might request a given amount of channels to be received on both networks.

The transmission system is time slotted in order to simplify the AP activity. All the packets may be transmitted by the APs or terminals on a slotted structure. In any case no direct communication between stations is performed, so a packet travels from an AP to a terminal or vice versa.

The channel allocation follows a Per-Packet approach, by allocating resources for every single packet. The strategy followed to admit or drop a communication request is based on some interference considerations; the AP has to decide, through a MRRM strategy, if the user may communicate with the required QoS (number of requested parallel channels) or not. This decision has to be taken by negotiate the allocation with all the other APs, in order to avoid collisions between adjacent APs. The Per-Packet Channel Allocation algorithm is separately applied to both the two types networks since we suppose that channels of the two types do not interfere with each other. To describe how Per-Packet Channel Allocation algorithm works we refer to the scenario in Figure 1. The total area in the example is a square of side $L = 4$; we localize each single sector by referring to a couple (x, y) of a cartesian diagram. Consider a user located in the sector $(2, 2)$ requiring a communication with ch_{req} parallel channels of a certain type to support QoS (in Figure 1 the user is represented by the white point in the sector $(2, 2)$). Channels can be released to a user if they are *free* in that slot. A channel requested for a given direction (uplink or downlink) is said to be *free*, e.g., for the sector $(2, 2)$ if this channel is not used at the same time in the same or opposite communication direction in sectors (x_d, y_d) with $1 \leq x_d, y_d \leq 2$ (dark grey sectors in Figure 1) and if it is not used in the opposite direction in sectors $(3, y_o)$ with $1 \leq y_o \leq 3$ and $(x_o, 3)$ with $1 \leq x_o \leq 3$ (light grey sectors in Figure 1).

2.2. Cooperative and Non Cooperative MRRM Strategies

Let us refer to the two RATs present in the whole square area as 1 and 2. The users' requests consist of a two-dimensional vector (c_1, c_2) which corresponds to the requested allocation on both networks.

Without any possibility of collaboration between the two available networks, the MT request could be accepted only if its related AP can offer to the MT a vector of free channels (d_1, d_2) where $d_1 = c_1$ and $d_2 = c_2$. We call this strategy as Non Cooperative, since the communication request is accepted only if the number of channels obtained by each network is exactly the same expressed by the communication request.

By considering the possibility of intercommunication between the two networks and thanks to the availability also for each mobile terminal of more and different radio technologies interfaces, we could think some possible exploitation of this networks heterogeneity in order to improve network admission and to reduce drop probability. In a cooperative view, we assume it is possible that the degree of service is kept equal if the allocation is performed by allocating the same resource on aggregate. In other words, the allocation is still satisfactory if the same total number of channels of the request is achieved on either the first or the second access technique only, or with a mixed allocation on both access techniques. In the context of a Cooperative strategy, each user is assumed to be satisfied if the network allocator can provide him with any vector (d_1, d_2) such that $c_1 + c_2 = d_1 + d_2$.

3. ECONOMIC EVALUATION OF THE COOPERATION

In order to evaluate, besides the technical performance, also the impact of the cooperative allocation from the economic point of view, we apply here a model, which aims at integrating the QoS perceived and the price paid by the users. In the model, price and utility tune the degree of satisfaction perceived by the users: the key idea is to define an *Acceptance value*, that depends on the utility u_i and on the paid price p_i, assigned to each user i. Several expressions are possible an appropriate acceptance function. In [3] we proposed the following expression:

$$A(u_i, p_i) \triangleq 1 - e^{-k \cdot (u_i/\psi)^{\mu} \cdot (p_i/\phi)^{-\epsilon}}, \qquad (1)$$

where k, μ, ϵ, ψ, ϕ are appropriate positive constants.

Note that both u_i and p_i depend on the allocated resource r_i, which in our study is related to the number of allocated channels. Thus, the shape of the acceptance probability as a function of r_i depends on the functions $u_i = u(r_i)$ and $p_i = p(r_i)$. For example, we take $u(\cdot)$ equal to a sigmoid-shaped function (i.e., it increases and then saturates for large values of r_i) and $p(\cdot)$ is assumed to be linearly related to r_i. However, these choices can be replaced with other ones, without affecting what follows. According to this assumption, $p_i = \alpha_i r_i$, and the unit price α_i depends on which kind of resource is actually allocated. Note that for the sake of fairness, α_i will be equal for all users i belonging to the same class of service. Thus, in general, α_i depends on the used RAT (it might even be the same for both RATs).

By giving A_i a probabilistic meaning, the model allows a simple and direct evaluation of the statistical average revenue coming from each user allocated with utility u_i and paying price p_i, which is determined as $p_i A(u_i, p_i)$. Thus, the total revenue is:

$$R = \sum_{i=1}^{N} p_i A(u_i, p_i) \, . \qquad (2)$$

It is also possible to conceptually invert the roles of utility and price in order to determine the total network utility, defined as:

$$U = \sum_{i=1}^{N} u_i A(u_i, p_i) \, . \qquad (3)$$

Note that, while the revenue R is a possible objective function from the point of view of a network provider, the total utility U might be seen as the users' goal, or the objective of a network provider which has interest in regulating the market fairly (e.g., an arbitrator or a public institution).

In this sense, alternative goals for the RRM might be the maximization of the total network utility, or the maximization of the provider's revenue. As shown in [2], these approaches might lead to quite different conclusions. Equation (2) implicitly represents the following intuitive property: too high prices drive customers away, since A_i decreases, and therefore yield very little revenue. Conversely, too low prices can easily be afforded by the users, but also results in low revenues. This can be formalized by stating the existence of an optimal price choice, i.e., an expression for $p_i(\cdot)$, which corresponds to the highest revenue. However, when the resource to allocate is scarce, as is usually assumed, this optimal pricing is also achieved when the capacity is fully utilized.

The model can be exploited for different aspects of the Radio Resource Management. In particular in the following we will focus on rate assignment for packet networks. That is, r_i will be the transmission rate allowed to terminal i, which is between 0 and the maximum value C. Also for the sake of simplicity, we will consider sigmoid-shaped utilities, which are bound in the range $[0, 1]$.

We depict the QoS perception of the users by assuming that the sigmoid functions representing users' utility are randomly generated for every user. The framework presented above is useful to exploit the simplicity of a direct evaluation of collected tariffs, which allows in fact a simple test of performance by means of simulation.

4. NUMERICAL RESULTS

To compare the technical behavior of the Cooperative and the Non Cooperative solutions we refer to two performance metrics:

- the dissatisfaction probability, i.e., the probability that a given user results to be not sufficiently served for what concerns the total requested resource;
- the number of channels effectively released to users with respect to the total amount of channels requested, which might be related to the system throughput.

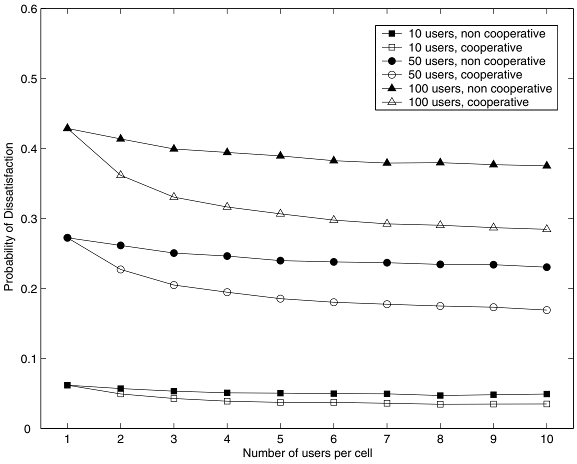

Fig. 2. Comparison between Non-cooperative and Cooperative allocation in terms of users dissatisfaction probability.

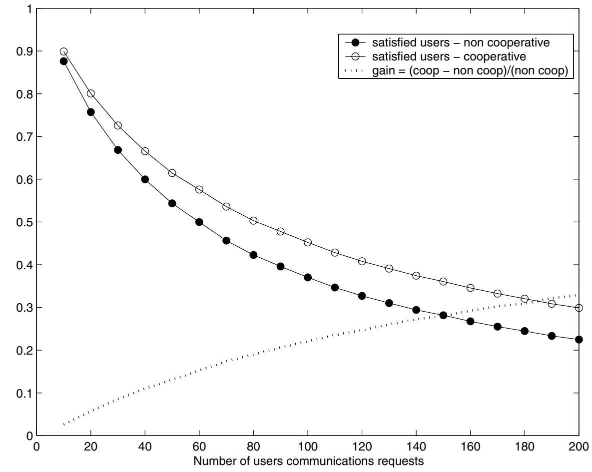

Fig. 3. Comparison between Non-cooperative and Cooperative allocation in terms of system throughput.

Result about dissatisfaction probability is plotted in Fig. 2. Note that the high dissatisfaction rates shown should be intended as resulting from network saturation, i.e., we intentionally select congested cases, where the number of users requiring access is quite high, hence resulting in heavy dissatisfaction rates. As it is visible from the figure, the probability of dissatisfaction is clearly decreased by allowing network cooperation. This means that cooperative MRRM strategies are able to exploit the co-existence of multiple access techniques, with respect to allocation strategies which treat different access techniques independently. Note also that the trend of both cooperative and non-cooperative strategies is a decreasing dissatisfaction probability as a function of the number of available channels in the network; however, around 5 channels a saturation occurs. By comparing the saturation value, we see that cooperation allows a decrease in the dissatisfaction probability ranging from 20% to about 30%.

In Figure 3 we plot the percentage of accepted allocation requests versus the total number of communication requests. This might be related in some way to the system throughput. We report both the comparison between the performance of Cooperative and Non Cooperative MRRM and the gain obtained with Cooperative solution with respect to the Non Cooperative one. Figure 3 refers to a scenario with $C = 5$ available channels for each network. As expected the allocation efficiency decreases as the network density increases. However, thanks to Cooperative MRRM the performance is improved and the gain is higher in scenarios with higher density.

In Fig. 4 another comparison is reported in order to highlight the benefit of economic nature coming from the cooperative network management of multiple RATs. Here, a scenario with $n_{AP} = 19$ APs and $N = 5$ networks has been considered. The number of available channels is 10 for each RAT type. A total number of 300 users is considered: the reason of this increase is explained below. The parameters of the acceptance probability, defined in Eq. (1), are: $\psi = 1.0$, $\phi = 25.0$, $\epsilon = 2.0$, $\mu = 4.0$, $k = -\log 0.9$.

Differently from Fig. 2, three cases are compared: the single-network case corresponds to a situation where the users both request and are allocated on a single RAT. Then, the cases with MRRM are distinguished between Non-cooperative and Cooperative as before.

In this case, it is assumed that the network provider adopts a linear pricing strategy of the channel allocation, i.e., users pay a tariff proportional to the number of allocated channels, but only if the allocation is satisfactory. The satisfaction is determined by the trade-off between QoS and pricing, i.e., the probability that a user i is satisfied is given by the metric A_i as explained in Section 3. On average, with our choice of the parameters, the willingness to pay of a given user, i.e., the price which is considered fair for the service, spans between 10 and 200. This is why we considered a larger number of users than in the previous case, since now users might refuse the service also because it is considered too expensive, and henceforth we have a larger dissatisfaction probability. With these settings, the network load is comparable in both cases.

The key point in introducing the resource pricing is that in this way the revenue coming from the management can be considered; however, it is sensible to assume that only satisfied users generate revenue. Dissatisfied users, where dissatisfaction might be due to either too high a price or too low QoS, are assumed not to stay in the system on the long run. For this reason, as it is visible from Fig. 4, cooperative strategies are particularly suitable also to increase the revenue, since they improve the users' satisfaction. Estimating the revenue is a practical way to quantify the benefit of the cooperation, besides being also a fun-

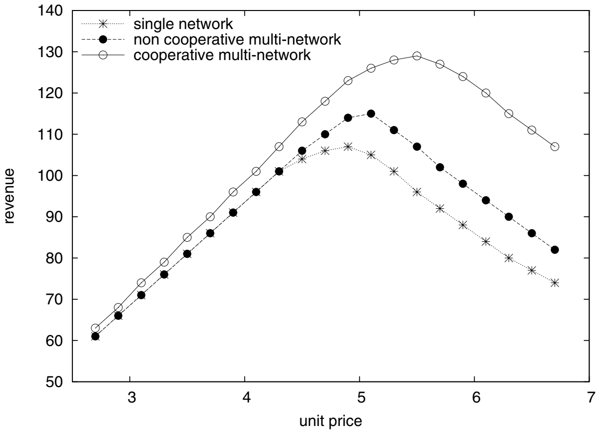

Fig. 4. Comparison between Non-cooperative and Cooperative allocation in terms of generated revenue.

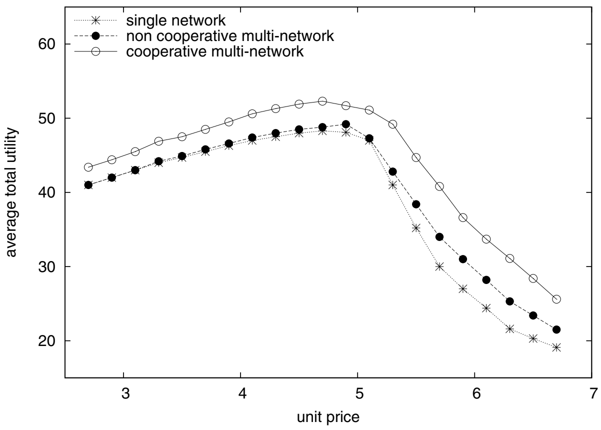

Fig. 5. Comparison between Non-cooperative and Cooperative allocation in terms of number of global network utility.

damental evaluation, since the generated income has to sustain the business model of the operator.

The revenue increase seen in Figure 4 might be seen as related to a general increase in the users' satisfaction. In order to more directly show the increase in the users' overall utility, as defined in Eq. (3), also Figure 5 has been evaluated. Here, the same three strategies seen in Fig. 4 are plotted. Even though the revenue and the total utility derive from different approaches of the optimization, in general their increases are related and the increase of the revenue seen in Fig. 4 might be seen as directly striving from the utility increase shown in Fig. 5 (which is however lower). This means that the cooperative MRRM is able to increase the allocated resource and to increase the QoS supplied to the users.

5. CONCLUSIONS

In this paper, we discussed the issue of cooperative allocation for multi-radio resource management, which is key to guarantee both QoS and economic efficiency of the network operation. We have shown results for different allocation strategies in the presence of multiple RATs and adaptive service. In general, the main conclusion is that ideal cooperation among the access techniques might severely improve the allocation. However, lack of full cooperation might decrease this gain. Henceforth, deeper study on this matter is required, and also the integration of service-perception-aware metrics in the allocation seems very promising in order to ensure a good performance both from technical and economic perspective.

For what concerns also the economic aspects of the MRRM, further research will investigate the role of pricing, and how it can be differentiated to improve the coordination among different services. The results for what concerns economic metrics for cooperative network allocation show that our approach provides understanding on how to realize an efficient MRRM which achieves satisfactory welfare and revenue.

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