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A Base Station Assignment Strategy for Radio Access Networks with Backhaul Constraints

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Abstract: Existing base station (BS) assignment methods in mobile networks are mainly driven by radio conditions. This is because it is assumed that the limiting factor in the access network is basically on the air interface. However, a growing concern is that the transport part of the mobile network can also represent a bottleneck. Thus, mechanisms only based on radio conditions may assign a user to a BS with an overloaded transport, which in turn may result in a degradation of the end user throughput and quality of service. In this paper we analyse a BS assignment strategy that incorporates transport capacity constraints in the decision making process of assigning the most suitable BS to mobile users. The strategy is compared to two common schemes which are exclusively based on air interface aspects. Provided results show that the proposed BS assignment strategy can effectively accommodate more connections than traditional techniques so that both radio and transport requirements are fulfilled in backhaul limited RAN deployment scenarios.

Keywords: backhaul, base station assignment, resource management.

1. Introduction

Within the radio access network (RAN), the mobile backhaul network is the infrastructure that interconnects base stations (BS) with network controllers or switching equipments in the core network. Most of current 2G/3G backhaul networks are realised by means of point-to-point T1/E1 links, typically employing star/tree topologies, and microwave radio as the most common transmission technology. It is widely recognised that the backhaul represents one of the major contributors to the high cost of building out and running a mobile network since it is nearly one-third of the total network operating cost [1]. During the early stages of 3G systems, operators reused as much as possible existing infrastructure in order to minimize the cost of the transition from 2G to 3G. Nowadays, however, as traffic continues increasing and new air interface technologies are deployed, bandwidth demand in mobile backhaul networks is drastically growing. For instance, the move towards enhanced air interface technologies, such as High Speed Data Packet Access (HSDPA), means that cell sites are likely to increase about seven times their current capacity requirements [1]-[3].

Therefore, operators are currently challenged to look for viable ways to optimize their backhaul networks in order to reduce costs, alleviate technical and operational complexities, and enable the faster rollout of new services. Keeping these perspectives in mind, academic and industrial communities have started to look anew into the mobile backhaul network focusing on different aspects ranging from network and protocol architectures to more cost-efficient transmission technologies. In this sense, a strong effort is being devoted to progress towards innovative packet-based network architectures where IP (Internet Protocol) technologies serve as cornerstone, whereas commercial solutions from different vendors (e.g. [4], [5]) are appearing to enable mobile operators to aggregate and compress backhaul traffic in order to make more efficient use of available transport resources in the RAN. In addition, new transmission technologies are positioning as promising proposals for interconnecting RAN network elements in the backhaul. This is the case, for instance, of multihop mesh networks that use short high bandwidth optical wireless links to interconnect network entities [6]. It is worthy to remark that it is believed that fiber access will take a larger role in many networks in the future. However, deploying fiber to each single cell site in the backhaul will be very costly and challenging, even in dense urban areas where fiber is most prevalent [3].

Taking into account the above context, it should not be precluded the idea that bottlenecks in practical RAN deployments may arise not only at the air interface but also due to resource limitations in the backhaul network [7], [8]. Thus, as a complementary solution to the aforementioned ones, we propose to take into account information about the available capacity in the backhaul network in the decision making process of radio resource management (RRM) strategies, and particularly in the process of assigning mobile users to BSs. It is worth noting that current BS assignment strategies assume that the limiting resource in RANs is always the air interface between mobile terminals and BSs. This assumption has been proven to be very reasonable when circuit voice was the dominant service and backhaul capacity provisioning accounting for the peak rate at the BSs was an economically feasible option. However, as argued before, this assumption may not be valid in some practical 3G/4G RAN deployments.

In this paper, we propose a BS assignment strategy for mobile access networks where potential backhaul constraints are considered in the process of assigning the most suitable BS to mobile users. This leads to a new paradigm where transport resources are taken into consideration not only at the network dimensioning stage but are included in an integrated and dynamic resource management framework. In this sense, it will be shown that employing backhaul-aware BS assignment strategies the impact of a limited backhaul capacity in a given BS can be diminished by conveniently re-allocating some users to other BSs with available resources in both air interface and transport network links. In particular, we focus our analysis on the provisioning of delay sensitive services where it is important to guarantee a given data rate in both air interface and transport network simultaneously.

The rest of the paper is structured as follows. Section II presents a generic framework where BS assignment strategies considering backhaul constraints can be applied. In order to analyse the proposed BS assignment approach, the problem is formulated for a WCDMA access network in section III. The evaluation methodology that comprises the use of heuristics and utility functions, as well as the considered BS assignment strategies are detailed in section IV. In section V numerical results and discussion are presented, and finally section VI draws main concluding remarks.

2. Generic Framework

Here we introduce a generic framework where BS assignment strategies considering backhaul constraints can be applied. In a typical RAN deployment (e.g. see Figure 1) the infrastructure involved in the backhaul network is very complex since there could be hundreds of cell sites that need to be interconnected using different topologies and transmission technologies. This generic framework can be applied to 2G and 3G networks, as well as in 4G networks where it is expected that the number of BSs will be even larger. A typical RAN deployment is likely to have multiple cell coverage in some locations of the service area and some mobile users could have more than one candidate BS to be connected to. In this context, there have been an important number of papers that have studied the problem of BS assignment in RANs, but mainly in terms of air interface resource optimization (e.g. see [9]-[12] for CDMA networks). However, when addressing BS assignment strategies that consider criteria other than radio, the main challenge is to keep under control the amount of degradation of the radio interface due to not always connecting users to their “best” radio serving BS (e.g. increased path loss and higher interference level) so that the overall performance can be definitively enhanced (e.g. higher number of connections can be served satisfying both radio and transport constraints).

In this context, we focus in a homogeneous RAN scenario with a single radio access technology (RAT) and frequency reuse factor of one, which is claimed to be the most critical in terms of using information other than radio metrics to control the BS assignment process. Notice that in scenarios with multiple frequency layers or heterogeneous RAT’s, mobile users can be assigned to a given frequency layer or RAT considering backhaul constraints as well, but the total or partial decoupling of the radio resource pools used in each frequency/RAT could make this decision less critical in term of radio degradation.

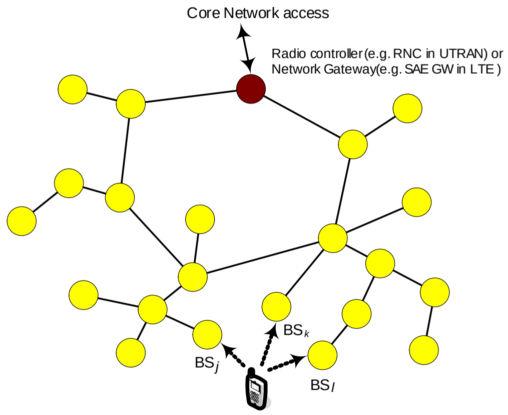

Figure 1: Typical RAN Deployment

3. System Model

For the reasons stated in previous section, the performance analysis of backhaul-aware BS assignment strategies will be addressed considering a single frequency WCDMA network. Specifically, we focus on the downlink because it is usually considered the more restrictive link due to the asymmetric bandwidth demand between the downlink and the uplink data services [9]. The network consists of N BSs that cover a geographical area in which, at a given instant, there are M users that have to be served. It is assumed that resources in any BS in the system are constrained by two factors: the maximum power limit in the radio interface and the provisioned capacity in the backhaul network.

The system state is characterized by a M x N matrix, hereafter referred to as $B = \{b_{ij}\}$, that denotes the BS assignments at a given instant. In particular, $b_{ij} = 1$, if BS j is assigned to user i, and $b_{ij} = 0$, otherwise. A given B matrix is considered feasible solution if radio and transport constraints are fulfilled. Details of these constraints are given in the following.

3.1 Air Interface Formulation

In the downlink of a WCDMA air interface, the signal to interference and noise ratio (SINR) observed by the i-th user has to fulfil the following expression [13]:

$$SINR_i = \frac{\dfrac{P_{ij}}{L_{ij}}}{\dfrac{(P_j - P_{ij})}{L_{ij}}(1-\alpha_i) + \sum_{k=1,k\neq j}^{N} \dfrac{P_k}{L_{ik}} + P_N} \geq \frac{R_i}{W}\left(\frac{E_b}{N_0}\right)_{\min,i} = \gamma_i \qquad (1)$$

where $(E_b/N_0)_{\min,i}$ is the minimum bit energy over noise power spectral density requirement, P_{ij} is the required transmit power devoted to user i being served by BS j, P_N is the noise power at the user terminal, R_i is the bit rate of user i, W is the chip rate, P_k is the total transmit power of BS k, L_{ik} is the path loss between BS k and user i, and α_i is the orthogonality factor seen by user i ($\alpha_i = 1$ means perfect orthogonality). Hence, attending to (1), the required transmitted power for user i being served by BS j can be expressed as:

$$P_{ij} = \frac{\gamma_i}{1+\gamma_i(1-\alpha_i)}\left[(1-\alpha_i)P_j + \sum_{k=1,k\neq j}^{N} \frac{L_{ij}}{L_{ik}} P_k + L_{ij} P_N\right] \tag{2}$$

From (2), the required total BS transmission power can be obtained by summing up the power of each served individual user and the radio constraint is formulated as:

$$P_j = \sum_{i\in\{i|b_{ij}=1\}} P_{ij} \ \leq \ \mathrm{P}_{T,\max} \qquad j = 1 \ldots N \tag{3}$$

where $P_{T,max}$ is the maximum power limit of BSs. Solving (3) for a fixed BS assignment is a well studied problem so that feasibility conditions and optimal power allocation can be obtained following the algorithm described in [14]. Nevertheless, it is also worth noting that when focusing on the joint power control and BS assignment problem there is not always a Pareto optimal power vector in the downlink as is the case in the uplink.

3.2 Transport Capacity Formulation

In practical RAN deployments, the transport capacity provisioned for a given BS is normally dimensioned in accordance to the amount of traffic that this BS can serve over the air interface. A common used approach to estimate the air interface downlink capacity is based on the computation of the downlink load factor n_{DL} defined as [15]:

$$\eta_{DL} = \sum_{i=1}^{K} \frac{R_i}{W}\left(\frac{E_b}{N_0}\right)_{\min,i} \left((1-\alpha_i) + f_{DL,i}\right) \tag{4}$$

where K is the number of users served by a given BS, $f_{DL,i}$ is the other-to-own cell received power ratio for the i-th user at the position where it is located. This means that as the load factor move towards one, the downlink capacity approaches to its maximum pole air capacity value. Over such a basis, focusing on one important special case where all mobile users have similar characteristics (i.e. service type, bit rate and E_b/N_0 requirements), it is easy to show that the air pole capacity denoted here as C_{air} can be estimated using the following expression:

$$C_{air} = K \cdot R \leq \frac{W}{\left(\frac{E_b}{N_0}\right)_{\min} \left((1-\alpha) + f_{DL}\right)} \tag{5}$$

where $\alpha = \frac{1}{K}\sum_{i=1}^{K} \alpha_i$ is the average orthogonality factor in the cell and $f_{DL} = \frac{1}{K}\sum_{i=1}^{K} f_{DL,i}$ is the average ratio of other-to-own cell BS power received by users. Therefore, in our analysis, the transport capacity C_{trans} of BSs is related to the air pole capacity C_{air} by means of a multiplicative factor β, as shown below:

$$C_{trans} = \beta \cdot C_{air} \tag{6}$$

A value of $\beta = 1$ would mean that the transport capacity has been dimensioned to satisfy the downlink air pole capacity estimated in the planning process. Hence, the transport constraint of a given BS j in the system is expressed as:

$$\sum_{i\in\{i|b_{ij}=1\}} R_i \leq C_{trans} \tag{7}$$

3.3 Methodology

The analysis is conducted using the "snapshot" technique [16]. In a given snapshot of the system there are M active users, and the objective is to find a feasible BS assignment so that constraints (3) and (7) can be fulfilled. In order to look for feasible assignments, a utility function u_{ij} is defined to express the degree of fulfilment to the constraints that each user-BS combination provides. The summation of the utilities of all assigned users in the system represents the system utility U. In our analysis, the considered utility functions are monotonically decreasing and concave functions, although different forms of expressing utilities are possible [17]. In this type of functions, the absolute value of its derivative progressively increases as moving towards a condition of minimum utility. Conversely, these functions exhibit softer variations when they are close to the region of maximum utility. Over such a basis, a simulated annealing-based algorithm targeted to maximize system utility U is used to find a feasible assignment solution. Repeating this process for a large number of snapshots allow us to determine the average number of users that can be assigned correctly by a particular BS assignment strategy.

4. Base Station Assignment Strategies

The analysed BS assignment strategies are referred to as Load Balancing Radio (LBR) and Joint Radio and Transport (JRT). The former is a strategy that is exclusively based on radio aspects, while JRT is the proposed strategy to account for potential backhaul limitations. Details of the utility functions of these strategies and the description of the simulated annealing-based algorithm are given in next sub-sections.

4.1 Load Balancing Radio

The LBR strategy aims to distribute terminals among BSs in order to balance the transmitted power of BSs, whenever propagation losses between terminals and candidate BSs do not exceed a given margin Δ above the minimum path loss. To that end, the utility function of LBR is formulated as:

$$u_{ij} = \left(1 - \left(\frac{\min\left(L_{ij} - L_{i,bs}, \Delta\right)}{\Delta}\right)^2\right) \cdot \left(1 - \left(\frac{\min(P_j, P_{T,\max})}{P_{T,\max}}\right)^2\right) \tag{8}$$

where $L_{i,bs}$ is the path loss attenuation between user i and its best server and $L_{i,j}$ is the attenuation that this user would have if it is served by BS j. Thus, as observed in expression (8), as the total power of BS j increase towards its maximum power limit $P_{T,max}$, the resulting utility u_{ij} to connect user i to BS j decreases. Similarly, the utility is decreased by assigning a user to a BS with a path loss approaching Δ above the minimum.

4.2 Joint Radio and Transport

The JRT approach extends the LBR strategy to include transport restrictions in the utility function. Thus, the utility function of this strategy can be written as follows:

$$u_{ij} = \left(1 - \left(\frac{\min\left(L_{ij} - L_{i,bs}, \Delta\right)}{\Delta}\right)^2\right) \cdot \left(1 - \left(\frac{\min(P_j, P_{T,\max})}{P_{T,\max}}\right)^2\right) \cdot \left(1 - \left(\frac{\min(R_j, C_{trans,j})}{C_{trans,j}}\right)^2\right) \tag{9}$$

where R_j is the aggregated rate of all users being served by BS j, while $C_{trans,j}$ is the associated transport capacity of the BS j. The rightmost term in (9) takes into account the transport occupancy of BS j. Thus, if a user is assigned to a BS with high transport/power utilization, the resulting utility will be lower. Although some degree of coupling exists between the BS transmitted power and the served aggregate rate, different situations can arise where one constraint could become more restrictive that the other. For instance, for the same aggregate traffic load, different power levels may be required depending on how far from the BS users are located.

4.3 Algorithm Description

The implemented algorithm for finding a feasible BS assignment under a given snapshot is realized using the simulated annealing technique [18]. The algorithm aims to maximize the system utility $U = \sum_{i=1}^{M}\sum_{j=1}^{N} u_{ij} b_{ij}$ while it searches for a feasible BS assignment. As depicted in Table 1, the algorithm begins the search from an initial BS assignment *B* and an initial temperature value *T*. The initial assignment *B* is obtained using a minimum path loss (MPL) criterion. For each temperature, the inner loop is performed until a feasible BS solution is found or the maximum number of iterations has been reached. The new solution *B'* and the variation between the corresponding system utilities, denoted as δ, are computed in each iteration. Note that the new solution replaces the previous one if $\delta > 0$, that is if the new solution increases *U*. The same happens with probability $e^{(-\delta/T)}$ in case the new solution decreases *U*. It is worth here to explain that the method for generating the new solution *B'* is based on an estimation of the utility increment that users would have if they are reallocated to a new BS. Thus, users with highest utility increment are potentially considered for generating a new assignment. The utility increment of a user is computed as the difference between the utility obtained when it is assigned to a given BS, under the current allocation, and the estimated utility if this user is moved to a different BS. We have seen that using this approach to generate a new solution *B'* is a good tradeoff between avoiding local minima and reducing the overall number of iterations, in comparison to generate *B'* in a completely random fashion.

5. Simulation Results

We consider a cellular deployment with 19 hexagonal cells including a central cell and the cells in its first and second tier. A wrap around technique is used to avoid border effects. The parameter Δ is assumed to be 6 dB. Users are uniformly distributed in the service area. It is assumed that users are served by a single BS, i.e. macrodiversity is not considered. As mentioned before, the analysis is focused on delay sensitive services. In particular, simulations are performed for data service under three different user bit rates: 64 Kbps, 128 Kbps, and 384 Kbps. A summary of the main simulation parameters is provided in Table 2.

Table 1: Simulated Annealing Algorithm

```
Compute initial solution B and temperature T
while thermal equilibrium or stopping criterion
is not reached
    while max number of iterations or stopping
    criterion is not reached
        Obtain new solution B';
        Compute δ = U(B') – U(B)
        if δ > 0 then
            B = B';
        else
            if random(0,1) < e^(-δ/T) then
              B = B';
            end_if
        end_if
        increase number of iterations;
    end_while
    Decrease T according with the annealing
    schedule;
end_while
```

Table 2: Simulation Parameters

Parameter	Value		
User bit rate, R_i	64 Kbps	128 Kbps	384 Kbps
E_b/N_0 target	5.3 dB	5.3 dB	5.2 dB
Air pole capacity, C_{air}	960 Kbps	1024 Kbps	1152 Kbps
Cell radius	1 Km		
Urban macro-cell propagation model [19]	L(dB)=128.1+37.6log[d(km)]+S(dB)		
Shadowing standard deviation, S	10 dB		
Chip rate, W	3.84 Mchips/s		
BS max. transmitted power	43 dBm		
Thermal noise, P_N	-101.15 dBm		

The downlink air pole capacity C_{air} provided in Table 2 was obtained by rounding expression (5) to the nearest multiple of the bit rate under consideration and assuming an average ratio of other-to-own interference f_{DL}=0.65 and average orthogonality factor α = 0.5

[13]. From this air pole capacity, the transport capacity of BSs is computed according to (6) and different values of β ranging from a transport capacity dimensioned to already account for the air pole capacity (i.e. β = 1) up to a transport capacity 150% higher (β = 2.5) have been considered.

Besides the LBR strategy, we also consider a second reference case in which users are assigned according to a MPL criterion. These two reference strategies are compared with the proposed JRT strategy. Results are presented in terms of the maximum number of active users in the overall service area for which a feasible BS assignment can be found for the 95 % of the cases. Fig. 2 shows the results of the three considered user bit rates. Focusing on the case of 128 Kbps, it can be seen that the JRT strategy is able to increase the feasible BS assignments about 88 % with respect to the MPL and LBR schemes, in scenarios where the transport capacity is provisioned to account for the air pole capacity obtained through a planning process (i.e. β = 1). The benefits of using JRT are also reflected in bandwidth savings, since with less provisioned transport capacity is capable to obtain similar results than non transport-aware strategies such as LBR and MPL. On the other hand, as expected, the LBR and JRT strategies tend to converge as the backhaul capacity increases because BS assignments are mainly limited by radio constraints when transport capacity can be over-provisioned. In any case, both LBR and JRT always are able to achieve some capacity gain over the classical MPL strategy in all the analysed cases.

When considering lower data rates such as 64 Kbps, the same trends discussed for 128 Kbps are observed but the obtained gains are lower (e.g. 60 % in front of 88 % for β = 1). The main reason for this decreased gain is that user distribution among BSs becomes more homogenous as the number of active users to be assigned is higher and, consequently, load balancing strategies have less room to improve. On the other hand, for 384 Kbps users, gains provided by LBR and JRT are now even higher due to the fact that fewer users can be served per BS so traffic distribution mechanisms between BSs becomes more imperative. It can be seen that JRT can achieve gains of 140 % and 50 % with respect to the LBR strategy for β = 1 and β = 1.5, respectively.

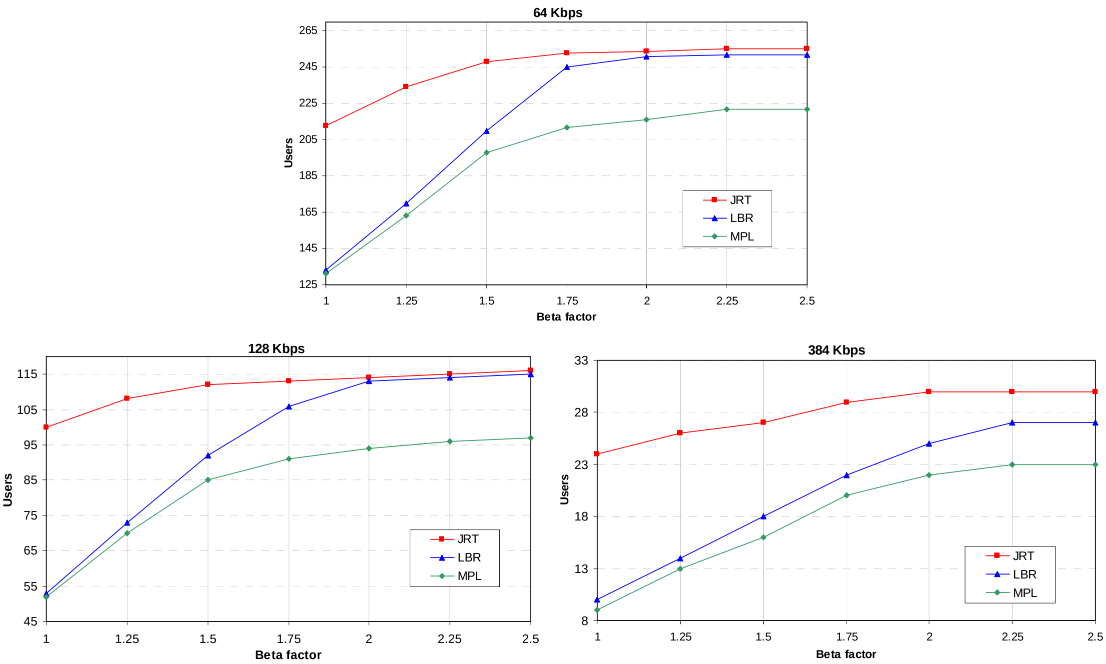

Figure 2: Feasible BS Assignments for Service Rates: 64 Kbps, 128 Kbps, and 384 Kbps

6. Conclusions

In this paper we proposed a BS assignment strategy for RANs that takes into account available transport capacity at the BSs. The strategy is evaluated and compared to more traditional approaches exclusively relying on radio aspects. Provided results show that including backhaul capacity constraints in the BS assignment process yield to a considerable gain, especially when backhaul limitations are more pronounced. We consider that the proposed approach could help mobile operators to delay the upgrade of backhaul to a later stage. Lastly, the evaluation of the proposed scheme under partially backhaul-limited scenarios, as well as the formulation of the BS assignment approach as an optimization problem to find the optimum solution are left for future work.

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