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ABSTRACT
Cell selection in mobile radio access networks is mainly driven by efficient resource usage of the air interface. In this paper we add a new dimension to the cell selection problem by considering also the current occupancy of transport resources in the backhaul part of the network since, it is believed that, with the introduction of high speed services, this backhaul network can be a limiting factor. In such cases, we demonstrate that a cell selection algorithm using transport status information provides significant benefits over traditional schemes exclusively based on radio criteria, even under those scenarios where the selection of a cell other than the best radio server can be thought as not adequate in terms of radio resource management (e.g. single-layer/single-RAT deployments). The cell selection problem is analytically formulated and developed by means of a multidimensional Markov chain.

I. INTRODUCTION
Within a mobile radio access network (RAN), cell selection either at session set up or during a handover process is mainly driven by radio specific criteria. Hence, achieving the best radio conditions, e.g. in terms of path loss or received symbol-energy over noise-plus-interference ratio, is often used to guide the cell selection process. As well, load balancing strategies can also be applied in this context to distribute as much as possible radio load among base stations. Moreover, in case of more complex RAN deployments encompassing hierarchical cell structures and/or multiple Radio Access Technologies (RATs) new drivers such as service-based and subscription-based RAT/cell selection can be incorporated in the cell selection control. A considerable research effort has been devoted to these issues in the past and they still remain an important cornerstone in the development of advanced cell selection, and ultimately RAT selection, algorithms [1][2]. However, to the best of authors' knowledge, little attention has been paid so far to the impact that potential limitations of resources in the backhaul of the RAN can have on the cell selection problem. It is believed that with the introduction of high bit rate services (e.g. HSDPA/HSUPA in UTRAN networks) and taking into account that over-provisioning in the backhaul network may not be economically feasible (e.g. most current RAN deployments show a predominance of relatively low-speed leased lines and microwave radio links [3][4]), a new dimension must be added to the cell selection problem: the current occupancy of transport resources in the backhaul network connecting the candidate base station to the mobile network. This leads to a new paradigm where transport resources are considered not only at the network dimensioning stage but are included in a dynamic coordinated resource management scheme [5]. Resource limitations in the transport network may result in blocking of new sessions and/or service performance degradation (e.g. delay increase or packet loss in potential transport overload periods).

In this paper we develop an analytical framework to assess the benefits of including metrics related to transport resource occupancy in the decision-making process of a cell selection strategy. We focus the analysis on mobile radio access networks using a single RAT and not making use of hierarchical cell structures. This scenario is claimed to be the most critical in terms of using information different than radio metrics to control the cell selection process because the selection of the non best cell from the radio perspective can lead to some degradation in terms of, e.g., increased path loss per connection and higher interference level. In particular, we propose a novel cell selection strategy that enhances traditional attenuation-based cell assignment strategies by considering transport status information. Results demonstrate that the proposed strategy can achieve a given trunking gain in transport limited scenarios while reducing the probability of having excessive path loss increase per connection when compared to traditional schemes based only on radio criteria. The cell selection problem is formulated by means of a multidimensional Markov model where the different analysed cell selection strategies can be captured.

The paper is organised as follows. Section II describes the envisioned cell selection framework and introduces the cell selection algorithm using transport status metrics. Then, Section III and Section IV develop the analytical model and relevant metrics aimed at comparing the performance of different cell selection strategies. Results are provided in Section V and finally Section VI draws the main conclusions.

II. CELL SELECTION FRAMEWORK
Fig. 1 illustrates the envisioned cell selection framework where decisions are expected to be taken considering radio and transport resource status. In this way, the scenario under evaluation comprises multiple cells with overlapped coverage in a given service area. Thus, some terminals would be able to be connected through more than one candidate cell in case that a proper operation of the radio interface can be assured (see terminal (b) in Fig. 1). Here, as shown in the figure, it is important to remark that this framework is very generic and can be applied from 2G/3G networks with TDM/ATM backhauling solutions such as GERAN/UTRAN up to evolved architectures such as the addressed in Evolved-UTRAN [6] where backhaul networks can be deployed over IP/MPLS networking technologies.
loss does not exceed that of the best server plus a given path loss that is not saturated. The exact formulation of this strategy is given in section III.

Next two sections formulate this problem analytically so that the three considered cell selection strategies can be compared in terms of transport capacity gain and radio degradation.

III. ANALYTICAL MODEL

In order to assess the benefits of a coordinated cell selection strategy we adopt an analytical approach to find the trunking gain that can be accomplished. Assuming some simplifying hypothesis, like having an infinite population of users with a single common service, Poisson distribution of call arrivals and exponential call service time, the trunking gain (in the sense of minimum transport blocking probability) can be obtained by solving the flow equations of a multi-dimensional Markov model. The model is mainly intended to capture session blocking due to transport saturation.

In the general case of a scenario where some terminals could have up to a maximum of \( N \) candidate cells, the state diagram of the corresponding \( N \)-dimensional Markov chain looks as shown in Figure 2. The coordinates of each state are the number of transport resources currently occupied at each of the cells. We call \( C_i \) (\( i=1, \ldots, N \)) the transport capacity of the links serving each candidate cell, which is measured in terms of the required throughput of a single connection of the kind of service requested by the users. Using queueing system naming conventions we may say that cell \( i \) has \( C_i \) servers.

![Figure 1. Cell Selection Framework](image)

Assuming that over-provisioning is not a feasible solution for the backhauling resources, sessions can be blocked in certain cells due to transport overloading. It is worth to mention that this situation would be especially critical when focusing on high bit rate services because few connections can be supported in each cell due to capacity limitations. For instance, the planned transport capacity for data traffic in a UMTS cell can be calculated over the basis that the radio interface will support up to 3 simultaneous 384kbps DCH users in the downlink [7]. This radio interface capacity would depend on the radio environment under consideration (e.g. cell size, delay profile, user mobility, etc.). Thus, from the transport network point of view, this means that transport capacity can be provisioned to support peak rates of 1152kbps plus transport protocol overheads. However, as radio conditions could in certain periods differ from those planned (e.g. active terminals are located near the base station or they require less \( E_b/N_0 \) due to more favourable mobility conditions), the cell would potentially support a new connection attending to radio resource usage but transport capacity may preclude it.

Attending to aforementioned considerations, three different cell selection strategies are analysed in the paper:

- **Best Server** Cell Selection (BS_CS). Under this strategy, terminals are only allowed to connect to the best radio server (defined, in this study, the cell with minimum path loss). However some sessions can be blocked due to transport saturation of the best server while having spare transport capacity in neighbouring cells. This case is used as a reference case for the next two strategies.

- **Radio Prioritised** Cell Selection (RP_CS). In this case, a set of additional candidate cells besides the best radio server can be available for cell selection. The criterion used to select those candidate cells is related to the amount of radio degradation that the system is able to tolerate due to the selection of a cell other than the best radio server. In particular, we consider as candidate cells those whose path loss does not exceed that of the best server plus a given Path Loss Margin (PLM). Then, the connection can be served by the cell with the lowest path loss in the candidate set that is not saturated. This mechanism can clearly result in a trunking gain for the transport resources but at the expenses of accepting certain radio degradation due to the potential selection of non optimal cells, otherwise unavoidable when targeting at low blocking probabilities in transport-limited networks. Notice that this strategy is the most common one used in legacy networks.

- **Transport Prioritised** Cell Selection (TP_CS). This is the strategy we propose to better exploit potential transport network limitations while reducing the impact on radio degradation. Now, like RP_CS strategy, a set of potential candidate cells are identified based on tolerable radio degradation, that is the PLM criterion. But then, unlike RP_CS, candidate cells are prioritised according to the transport occupancy instead of choosing the cell with lowest path loss that is not saturated. The exact formulation of this strategy is given in section III.

![Figure 2. Generalized state diagram for an N-dimensional Markov chain](image)
The general expression for $\gamma_i$ (i=1,..,N) can be written, for any state, as:

$$\gamma_i = \lambda_i + \sum_{n=1}^{N} \alpha_{in} \lambda_n + \sum_{n=1}^{N} \sum_{m=1}^{N} \alpha_{im} \lambda_{imn} + \sum_{n=1}^{N} \sum_{m=1}^{N} \sum_{p=1}^{N} \alpha_{imn} \lambda_{imnp} + \cdots + \sum_{n=1}^{N} \sum_{m=1}^{N} \sum_{p=1}^{N} \cdots \sum_{q=1}^{N} \alpha_{imnq} \lambda_{imnqp} \tag{1}$$

where $\lambda_{imnq}$ [calls/s] is the call arrival rate for terminals whose set of candidate cells is $\{i, n, m, q\}$ and the constants $\alpha_{imnq}$ are the state dependent load steering coefficients that must be chosen to optimize the system capacity. The terms in (1) stem from the fact that the full set of terminals in our scenario can be classified into N different disjoint subsets, $\{T_1, T_2, \ldots, T_N\}$, where a terminal belongs to the subset $T_j$ (j=1,..,N) if it has exactly j candidate cells. Each subset $T_j$ can be further subdivided into $\binom{N}{j}$ disjoint traffic classes, where two terminals from a given subset $T_j$ belong to the same traffic class if both share the same set of candidate cells. Any given traffic class is uniquely identified by the sequence of j different subsets in $\lambda_{imnq}$. By convention, the first subscript (i) in $\lambda_{imnq}$ means the cell where the fraction of traffic $\alpha_{imnq}$ is directed to. That is, $\alpha_{imnq}$ is the probability that any new session of class $\lambda_{imnq}$ is directed to cell i. The order of subscripts in $\lambda_{imnq}$ is not relevant. e.g., $\lambda_{i123}=\lambda_{213}=\lambda_{312}$. Expression (1) is written in such a way that any traffic class which has cell i as a candidate cell appears only once. We call $\lambda$ to the global system rate of arrivals, which is the addition of the call rates of all the $2^N-1$ different traffic classes.

For the state $(S_1, S_2, \ldots, S_N)$ and for the traffic from terminals belonging to subset $T_j$ and class $\lambda_{imnq}$, we calculate $\alpha_{imnq}$ in one of two ways:

$$\alpha_{imnq}(S_1, S_2, \ldots, S_N) = \frac{1-\delta(C_i - S_i)}{\sum_i \left[ 1-\delta(C_i - S_i) \right]} \tag{2}$$

$$\alpha_{imnq}(S_1, S_2, \ldots, S_N) = \frac{E(C_i - S_i)}{\sum_i E(C_i - S_i)} \tag{3}$$

In (2) $\delta(n)$ means Kronecker’s delta. In (3) $g(i)=i$, $g(2)=m$, $g(3)=n$, $g(j)=q$ and $E(x)$ means the free Erlang capacity (given the desired system blocking probability) of a cell with $x$ free servers. Expression (2) models a scenario where all terminals connect to their best server unless the cell is saturated and assumes symmetric coverage, so that traffic originated in the overlapped coverage regions is equally shared by all the overlapping cells. Expression (3), in turn, makes use of transport occupation information to send a bigger fraction of the traffic from the terminals that can choose towards the cell with more free transport resources at any given moment. Notice, in (2) and (3), that in the limiting states no traffic is sent towards the saturated cells, but the traffic is still served by the cells with free resources, since the sum of all the load steering coefficients for a given traffic class equals unity.

Our design proposal for the TP_CS strategy is to use expression (3) only at the states where $C_{i-S_i}<L$ for at least one value of $i$ (i=1,..,N). In the rest of the states we will apply expression (2). So L is a parameter of the TP_CS strategy. For the RP_CS strategy expression (2) is always used.

Since the total probability rate departing from any of the states must be zero, it is possible to write a linear system of equations to find the probability of being at any of the states, and so the system blocking probability. By reversing the procedure (using a numerical root-finding algorithm) it is possible to fix the desired system blocking probability and find the value of $\lambda$, that leads to that blocking probability. By repeating this method for the cases of RP_CS and TP_CS cell selection and for the reference case, the trunking gains are found as:

$$t\lambda_{RP-CS}=100 \left( \frac{\lambda_{TP-CS}}{\lambda_{RP-CS}} - 1 \right) \% \tag{4}$$

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The reference strategy for calculating the trunking gain is the case where all new sessions are connected always to their best-server. If the best-server is saturated then the session is dropped. This means that only $\lambda_1, \lambda_2, \ldots, \lambda_N$ are different from zero and $\gamma=\lambda_i$ (i=1,..,N). In the reference case, and assuming equal transport capacity per cell, the blocking probability, for a given $\lambda$ and a given number of servers per cell, can be obtained with the classical Erlang-B expression.

IV. ASSESSING THE PATH-LOSS INCREASE STATISTICS

In this section we present the method for assessing the path-loss increase statistics in a single-RAT scenario using a regular hexagonal cell deployment with uniform user distribution per square meter. The analysis is focused on the coverage region of three sector cells (see Fig. 3) served by the access points AP1 (C1 servers), AP2 (C2 servers) and AP3 (C3 servers) respectively. In Fig. 3 the best-server area of an AP is the region where that AP is the closest one. In this case, the global rate of arriving calls ($\lambda$) can be distributed into the following traffic classes: $\lambda=\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+\lambda_{123}$, where the exact distribution of rates is found by numerical integration of the areas of overlapped coverage, that is, the grey and the pink dashed areas in Fig. 3. Obviously, the width of the overlapped coverage regions increases for increasing values of the PLM [dB]. In order to find the boundaries of the overlapped coverage regions a simple exponential power decay law has been assumed, i.e.: $P_r=P_0 e^{-k d^\beta}$. Where $P_r$ and $P_0$ are, respectively, the power transmitted by the serving AP and the power received at the terminal, $d$ is the distance from the terminal to the serving AP, $k^d$ is the attenuation for $d=1$ and $\beta=3.5$. 

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In this section the results obtained for the scenario described in the previous section are presented. The desired system blocking probability is 1% in all cases. Figure 4 is a comparison of RP_CS and TP_CS cell selection strategies for symmetric AP transport capacities. In particular, a number of servers equal to 8 has been considered for the three cells (this can be a high number when focusing on high data rate services over cellular cells, e.g. 384 kbps in a UMTS cell). The curves are parameterized by the value of \( L \), which was explained in section III (\( L=\text{ALL} \) means that expression (3) is used at all the states). In the leftmost graph we realize that the higher the PLM the higher is the trunking gain (more terminals can choose among several cells), but the TP_CS strategy clearly outperforms the RP_CS strategy. It is also evident that the TP_CS strategy with \( L=3 \) achieves almost the same trunking gain as the TP_CS with \( L=\text{ALL} \) but leads to less path-loss increase. In the central graph we see that the trunking gain is achieved at the cost of certain path-loss increase. But if we compare the RP_CS strategy and the TP_CS strategy for the same trunking gain (see dashed lines), the path-loss increase of both strategies is almost the same. So, even taking into account our estimation of the radio degradation, the TP_CS strategy still outperforms the RP_CS strategy. Finally, the rightmost graph allows comparing the 1% percentile of the path-loss increase for the \( \lambda_{123} \) traffic. At the same trunking gain we can expect almost 2dB less path-loss increase, for the worst case calls, with the TP_CS strategy.

Figure 5 shows the trunking gains that can be obtained assuming an asymmetric distribution of transport resources, that is \( C_2=C_1=8 \) and \( C_3=C_1+n \) \( (n=0,2,4) \). These results address the case where one of the candidate cells (cell 3) has an upgraded backhaul link while the others don’t. The same comments already given for Figure 4 apply also here, but notice how the trunking gain of the RP_CS strategy is independent of the asymmetry in the number of servers, while an increased asymmetry leads to an increased trunking gain of the TP_CS strategy. Finally, Figure 6 shows the dependency of the trunking gains with the number of servers for symmetric and asymmetric transport capacities. For a low number of servers (low capacity links and high speed services) the trunking gains of the TP_CS strategy can be quite high.

VI. CONCLUSIONS

In this paper we have developed an analytical framework to assess the benefits of including metrics related to transport resource occupancy in the decision-making process of a cell selection strategy. It has been shown that, under mobile radio access network scenarios where transport network resources can get saturated, it is possible to make use of the transport status occupation to drive cell selection, even in those scenarios where a cell selection other than the non best radio server can be considered a priori as not appropriate. In particular we have seen that the proposed algorithm is able to mitigate transport limitations by conveniently allocating those connections that have less impact on the radio degradation.
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