Comparative Performance of Hierarchical Cell Architectures

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Abstract — **Multilayer cell systems, also known as hierarchical or overlay cell structures, are useful to accommodate high traffic densities while maintaining quality of service (QoS) objectives. These systems combine the advantages typical of microcellular systems such as increase in system capacity and also those usually derived from macro-cellular structures like the reduction in the number of handoffs causing also a decrease in signaling load. In this work we analyze, through discrete-event simulation, design aspects as, for example, spectrum sharing between the macro-cell and micro-cell layers and the performance of different strategies for vertical (across layer) handoff s. Finally, a comparison between the performances of a pure macro-cellular system and that of a hierarchical architecture is presented.**

Index Terms — **Cell Overlay, Handoffs, Spectrum Sharing, Mobile Communications**

I. Introduction

The number of cellular users has grown dramatically over the last ten years, totaling now over 1.5 billion terminals across the globe. In order to serve this fantastic demand cellular operators have to keep developing new techniques to increase their network capacity. One of these techniques is the use of micro-cells, i.e., cells that are illuminated by antennas that are lower than the rooftops. These micro-cells are essential to serve hot spots, which are common in dense urban environments, and are ideally suited for pedestrian subscribers. However, due to their size, micro-cells present a problem in addressing the characteristics of high-speed users. Terminals moving fast are required to make frequent handoffs, overloading the signaling infrastructure. There is also a significant risk in dropping calls due to excessive handoffs and street corner effects. In an attempt to overcome these difficulties, a hybrid solution was developed which is known as hierarchical cell structure. The radio network is organized in layers, typically two. One composed of micro-cells and the other of overlaying macro-cells which can accommodate fast moving terminals and illuminate difficult areas not covered by the lower layer. Reference [1] investigated the performance of three methods for resource sharing among layers taking into account the effect of co-channel interference, antenna heights and sectored antennas in the macro cells. Here a similar simulation tool is used to obtain the performance of those strategies as a function of channel distribution between lower and overlay layers. The comparative capacity advantage of the hierarchical architecture over a traditional flat structure, for the same level of quality of service, is also illustrated.

In the following section the spectrum sharing methods evaluated in this work are briefly described. The simulation tool and the environment used to assess the performance of these methods are described in Section III. Section IV offers comparative numerical results for different input traffic configurations. The superiority of a hierarchical system over a pure macro-cellular architecture is also illustrated in Section IV. Concluding remarks is the topic of Section V.

II. Resource Sharing Strategies

The three strategies here considered have already been described in the literature [2] – [6] and evaluated mostly through single cell analysis and simulation. The key features of these strategies are:

Speed sensitive method (SS): in this method users moving at a speed higher than a given threshold are placed in the overlay (macro-cell) layer. Those moving slower are assigned to the lower layer. Terminals are not allowed to change layers during the call. [5];

Overflow method: (OF): in this strategy slow users which cannot find an idle channel in the micro-cell layer are allowed to move (be handed up) to the higher layer. This overflow treatment can take place both at call origination or during a handoff. In this work, an initial layer assignment for this method is performed using speed differentiation, as in SS. In [2] an implementation where users were always placed initially in the lower layer, regardless of the speed, was investigated. It was shown that even without explicitly taking the speed into consideration a large number of the high speed users ended up in the macro-cells;

Overflow plus take back (OFTB) [6]: in this procedure slow speed terminals can be reassigned to the lower layer when a channel vacates. In this work this handoff down takes place *as* *soon as the channel becomes idle*. In other contributions [5], this so called take back is only allowed when poor signal strength forces a handoff to happen. High speed users are not transferred to the lower layer even if the macro-cell layer is congested. Management of high speed users in micro-cells is difficult. They generate excessive signaling and calls are often dropped due to lack of time to perform a handoff at a street corner, where the received signal level changes very fast [4]. Simulation results presented in [1] show that the OFTB strategy has better performance in terms of radio resource management.

In the following section the simulation tool used to evaluate these systems is described.

III. SIMULATION TOOL

The software used for the simulations was inspired in the tool implemented in [7]. The considered simulation environment is a bi-dimensional system consisting of a cluster of 7 real macro-cells and 42 virtual macro-cells, which are used to compensate the so-called border effect. Within the coverage area of each macro-cell there are 7 micro-cells which compose the lower layer of the overlay structure. The cell structure provides coverage to an urban region with a Manhattan-grid topology as shown in figure 1. Two classes of users were considered: pedestrian and vehicular. Regardless whether the user is pedestrian or vehicular, directions can only change at street corners.

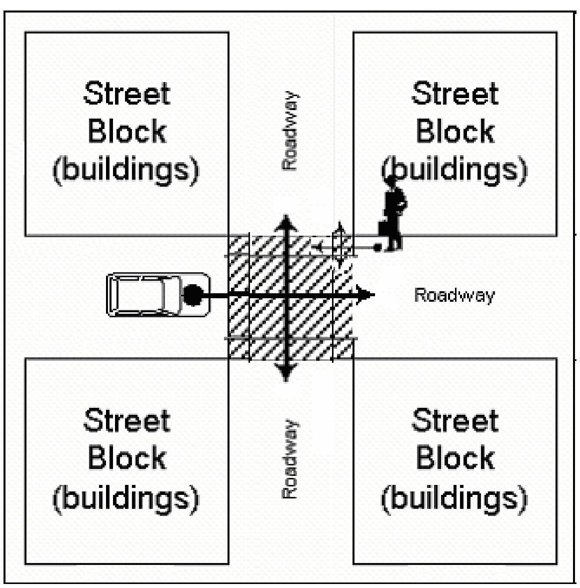

Fig. 1: Mobility Model

The user speed is defined as a random variable for each class:

- Pedestrian: speed assumed to be uniformly distributed between 2.5 and 5 Km/h.;
- Vehicular: speeds obey a Gaussian distribution truncated at 10 and 90 km/h with a 50Km/h average speed and a standard deviation equal to 10 Km/h.

In the traffic model adopted, new calls are generated according to a stationary Poisson process. The new call rate remains constant during the simulation and the calls are distributed uniformly over the simulation environment. The average duration of each call, in the simulation, is an exponential random variable.

The propagation loss model adopted was that of Walfisch-Ikegami [8], also known as COST 231. A log-normal fading component was added with a standard deviation of 8 dB. Three sector antennas were used in the macro-cell layer and omni-directional antennas were adopted for the micro-cells. Since a cluster size of seven is used in both layers, if y channels are allocated for each macro-cell sector and x channels are deployed in each micro-cell, the total number of channels required in the system is $3 * 7 * y + 7* x$.

In the following section this simulation too is used to evaluate the performance of the three resource management techniques introduced in Section II.

IV. SIMULATION RESULTS

The results presented here were obtained generating 20000 (including) calls from pedestrian and vehicular users. The average call duration was set to 2 minutes. Two scenarios were considered to evaluate the performance. Scenario A consists of a 50-50 split between pedestrian and vehicular users. Scenario B is defined by having 75% of the users being pedestrians. In this work every pedestrian user is initially assigned to the micro-cells while vehicular users are assigned to the macro-cells. It is assumed also that the system correctly assigns every user to its respective layer. Initially we will analyze design aspects such as spectrum sharing between the macro-cell and micro-cell layers for the OFTB strategy. Then a comparative analysis of the behavior of the resource management strategies introduced in section II is presented. Finally, we compare the performance of a hierarchical system to that of a purely macro-cellular system.

The performance measures adopted were the average number of active users in the system and the new-call blocking probability. For both scenarios the performance was assessed for 5 different spectrum partitions between the layers. Table I presents the partitions evaluated. It is important to stress that in the tables and in the following comments the notation adopted was: xmyM, where x is the number of channels per micro-cell and y is the number of channels in each macro-cell sector. Note also that for all configurations considered the total number of channels in the system is the same, namely 420.

TABLE I
SPECTRUM PARTITIONS USED IN THE SIMULATION

Spectrum Partition	Total Number of Channels Micro-cell Layer	Total Number of Channels Macro-cell Layer
6m18M	42	378
9m17M	63	357
12m16M	84	336
15m15M	105	315
18m14M	126	294

In Tables II – VI numerical results are given as a function of the input traffic measured in calls per hour in the coverage area of one micro-cell. The influence of the input traffic on the average number of active users in a system employing the OFTB strategy is analyzed in Table II. It is observed that as the input traffic increases, the number of active users increases too. However when a certain value is exceeded, the behavior tends to saturate due to an increasing blocking probability of new users. It can be noticed that for high loads the 12m16M was the best spectrum partition.

TABLE II
AVERAGE NUMBER OF ACTIVE USERS
OFTB STRATEGY – SCENARIO A

Input Traffic (calls/h)	6m18M	9m17M	12m16M	15m15M	18m14M
100	157.72	155.46	158.11	155.65	157.87
200	232.26	232.74	233.80	234.51	233.15
300	275.30	282.05	281.79	277.27	276.69
400	297.24	305.76	*308.32*	303.55	303.29

Table III is useful to explain these results. It is observed that as the traffic increases more channels are needed in the micro-cells to prevent the extreme overflow pedestrians, but the macro-cell must have enough channels to hold the demand of vehicular users. It can also be observed in Table III that for moderate and high loads, the distributions 9m17M and 12m16M yield superior performances. Note that using the 12m16M configuration the resulting average number of users in each layer is very similar (less than 5% differential).

TABLE III
NEW CALL BLOCKING PROBABILITY (%)
OFTB STRATEGY – SCENARIO A

Input Traffic (calls/h)	6m18M	9m17M	12m16M	15m15M	18m14M
100	0.00	0.00	0.00	0.00	0.00
200	0.45	0.08	0.15	0.20	0.00
300	4.96	*0.99*	2.05	2.50	4.44
400	13.98	8.40	*7.28*	8.15	12.65

It is interesting to notice, that in the case of scenario B, the spectrum partition that presented greater capacity was 18m14M as is shown in Table IV. This can be explained by the fact of that for a greater percentage of pedestrians, it is necessary to increase the number of channels in the micro-cells to reduce the blocking probability. For vehicular users, the configuration 18m14M presented a tolerable blocking probability since in Scenario B there is a lower amount of calls originated by that class. Therefore, as expected, for a traffic profile with more pedestrians than vehicles, a bigger number of channels must be placed in the micro-cells. Table V shows that the average blocking probability was indeed lower for the configuration 18m14M.

TABLE IV
AVERAGE NUMBER OF ACTIVE USERS
OFTB STRATEGY – SCENARIO B

Input Traffic (calls/h)	6m18M	9m17M	12m16M	15m15M	18m14M
100	157.38	155.77	158.05	155.41	157.66
200	231.11	232.19	233.44	235.46	234.31
300	275.03	282.43	283.99	281.94	*283.64*
400	300.86	311.49	316.37	316.14	*318.93*

TABLE V
NEW CALL BLOCKING PROBABILITY (%)
OFTB STRATEGY – SCENARIO B

Input Traffic (calls/h)	6m18M	9m17M	12m16M	15m15M	18m14M
100	0.00	0.00	0.00	0.00	0.00
200	0.01	0.00	0.00	0.00	0.00
300	1.11	0.15	0.03	0.02	*0.02*
400	9.69	3.24	0.98	0.36	*0.36*

Table VI shows a performance comparison between the three different traffic distribution methods reviewed in Section II. The results shown were obtained for the 12m16M configuration and indicate that, as expected since it is a more complex method, the OFTB indeed has superior performance in apportioning the network resources for a given traffic demand.

TABLE VI
CALL BLOCKING PROBABILITY (%) – COMPARISON BETWEEN STRATEGIES

Input Traffic (calls/h)	OFTB	OF	SS
100	*0*	0	0
200	*0.15*	0.21	0.17
300	*2.05*	2.62	2.13
400	*7.28*	8.65	7.77

Finally, Table VII illustrates the advantage of using an overlay architecture over a traditional flat one. The gain in capacity provided by the hierarchical structure surpasses 30% for very comparable levels of blocking and forced termination probabilities. The drawback is that the number of handoff attempts in the two-layer arrangement is substantially larger, causing a corresponding increase in signaling traffic.

TABLE VII
COMPARISON BETWEEN HIERARCHICAL STRUCTURE AND SINGLE LAYER SYSTEM

	Hierarchical 12m16M	Single Layer 0m20M
Call Blocking Prob (%)	2.05	2.45
Forced Termination Prob (%)	2.74	1.48
Avg. # of users	*281.8*	210.2
# of handoff attempts	*1850*	427

V. FINAL REMARKS

Hierarchical cellular systems have been designed to combine the advantages of the micro and macro-cellular structures aiming at increasing the radio resource management efficiency. In this work we have studied the performance of three existing call management and handoff strategies namely: overflow (OF), speed sensitive (SS), overflow with take back (OFTB). Simulation results with the OFTB and the SS strategies have shown that the optimum spectrum partition, in the sense of total number of users being served simultaneously, depends on the input traffic profile. This behavior suggests that hierarchical systems with adaptive control of the radio resources should be studied. A strategy that would allow the number of channels distributed for each layer to vary according to the traffic profile could result in great improvement in resource management efficiency.

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