Fixed Channel Allocation Techniques Exploiting Cell Overlap for High Altitude Platforms

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Abstract : **An investigation is performed into the capacity enhancements achievable from various fixed channel allocation techniques exploiting overlap between the cells formed by the antenna beams from a High Altitude Platform (HAP). It is shown that the areas served by more than one cell (overlap areas) benefit from the multiplexing gain and as a result they have lower blocking than the areas served by one cell. A novel technique derived from the Erlang-B distribution is described, which imposes certain restrictions in order to limit the proportion of the channels allocated to the overlap areas and be retained for use in areas with no overlap, in order to maintain a more uniform blocking probability over the coverage area. This technique has significantly improved the capacity of the system and the spectrum efficiency.**

1. Introduction

High Altitude Platforms (HAPs) are airships or planes, which will operate in the stratosphere, at 17 - 22km altitude. Such platforms will have the ability to be deployed within a short period of time and have the potential to provide Broadband Fixed Wireless access services to a large number of users over a wide area [1]. HAPs achieve high capacity by using a large number of wireless transceivers, each using a directional antenna to create cells on the ground. These transceivers are co-located on the platform and they offer a line of sight communication to a geographic service area of approximately 60km diameter [2]. The cells formed on the ground are assumed to be circular and of equal size; this can be readily achieved by a careful design of the antenna beam profiles [6]. Interference between cells is largely due to the gain profile and sidelobe levels of the antennas used. It has been shown that the antenna gain profiles at the cell edges can create useable overlap between cells [3]. This technique is not generally available in the case of terrestrial systems, as the user's antenna will need to be redirected when moving between cells, a comparatively slow process, and during this time the user will be out of contact with any base station. In addition, this will require the system to be highly centralised, due to the need to exchange data about the channels available within each cell at high speed [4]. Nevertheless, the concept of overlapping cells has been investigated in the past [8][9] for terrestrial systems with schemes such as directed retry (DR), directed handoff (DH) and a variety of selective handover for traffic balance (SHOT) schemes. From work [8] it has been shown that with the DR, an increase in the overlapping between cells leads to an increase in the quality of service (QoS) provided by the system. Furthermore, the DH scheme proved to have good sensitivity properties with respect to variation in the spatial profile of the system. From work [9] it has been shown that the SHOT schemes improve traffic handling capcity and enhance frequency utilisation. The more cell overlapping the more the traffic improves. For the HAP most of the practical problems that the terrestrial systems are facing do not exist. The reason is because of the nature of the system as all transceivers are co-located on the platform and the platform itself provides a line of sight communication with the stations on the ground. This means that there will be less obstacles between the users and the platform and the cell overlap can effectively be applied in all cell of the system. The HAP itself can therefore keep track of all channels being in use within its coverage area, making use of the HAP's centralised architecture.

In this paper we will exploit this cell overlap by presenting the mathematical analysis of the problem and by proposing and developing various channel allocation schemes. These schemes then are evaluated on the basis of Monte Carlo simulation techniques. In section 2, a mathematical analysis of the size of the overlap areas formed is presented, based on the radius of the cells; this analysis shows how the size of the overlap areas develops while the cell radius increases; and in section 3, the channel allocation schemes will be evaluated, and the advantages shown in comparison to a basic channel allocation scheme that does not consider cell overlap.

2. Cell Overlap Exploitation

In this section we will present a step-by-step analysis of the cell overlap exploitation to illustrate how the cell overlap is related to the channel allocation: all the schemes presented in this paper are based on this principle. As the size of the cells on the ground increases, the area served by more than one cell also increases. The users in these overlap areas have the choice to select a channel from any of the overlapping cells. A simple example is illustrated in figure 1, where users positioned in one of the regions (highlighted) formed by three cells, can be allocated a channel from any of these three cells.

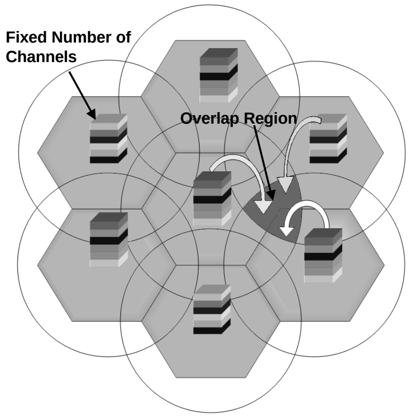

Figure 1: Illustration of Overlap Areas

The overlap occurs because of the way the power decreases away from the boresight of the antenna. The size of the overlapping area can be determined by setting a minimum received power limit or Carrier to Interference Ratio (CIR), which can be determined from the link budget and is related to the power roll-off with angle from the antenna gain profile [7,8]. In this paper we have assumed that CIR is sufficient to maintain a call over the coverage area; this can be achieved by a suitable choice of cluster size.

Figure 2 depicts a hexagonal layout of cells, and marked on one of the cells are the inner and outer circles whose radii are R_i and R_e respectively.

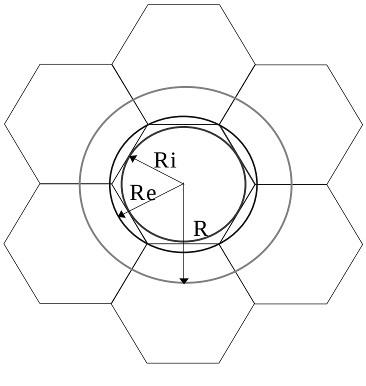

Figure 2: Overlapping Radii

The value of the overlap radius R varies within limits: the minimum value of the radius of the overlapping cell is equal to the original radius of the cell R_e in order to avoid leaving any areas without service (if R was less than R_e); and the maximum value is taken here to be equal to $1.5R_e$ radius, in order to limit the maximum number of overlapping cells to three. In theory, four or even more cells can overlap if the cell radius is increased sufficiently, assuming the co-channel interference and received power levels remain acceptable.

Before moving on to the detailed analysis of the mathematical model, we will first define what we mean by regions and areas. Individual regions are a contiguous section of land formed whenever more than one cell overlaps: these regions can be categorised into three types of overlap (A, B or C) meaning that they might be formed by one, two or three cells. They can therefore be assigned a channel from one, two or three cells respectively. A cell contains many regions. If we sum up the regions in one cell according to the three types of degrees of overlap (A, B and C), we then have what we call areas. In other words, an area contains one or more regions of the same type. For example, figure 3 illustrates a case where three cells overlap each other symmetrically. As a result, various regions are formed: A_1, A_2 and A_3, B_1, B_2 and B_3 and region C. In terms of areas (e.g. for cell 2), Area A is equal to region A_2, area B is equal to the sum of regions B_1 and B_2 and area C is equal to region C.

Regions are distinguished from areas because it has been easier to calculate mathematically the size of the areas in order to measure the degree of overlap. This technique has been particularly helpful when implementing schemes based on cell overlap.

In general, areas can be assigned different numbers of channels C_A, C_B, and C_C. This can be achieved as the user will effectively scan through all frequencies to find which cell has the best signal. The user will therefore know how many base stations are covering his position and he will signal that information up when he applies to join the system. This allows a channel allocation scheme to be implemented while minimising the blocking probability *P(Block)*. The task is to decide how to allocate different numbers of channels to the respective areas**,** so that the blocking probability will be the same in every part of the cell. It is not directly obvious how the channels must be distributed to the areas to achieve this result.

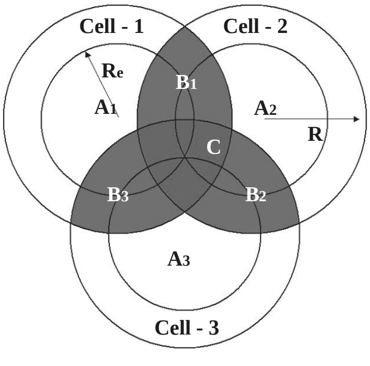

Figure 3: Illustration of areas A, B and C

For the case where we are considering one cell, the blocking probability in terms of an Erlang-B distribution can be expressed as a function of the number of channels available and the Offered Traffic (OT) in the cell.

$$P\,(\text{Block}) = f\,(OT_{\text{N-Total}}, C_{\text{N Total}}) \qquad \text{Eq. 1}$$

Here, $OT_{\text{N-Total}}$ denotes the total OT within the cell and $C_{\text{N-Total}}$ the total number of channels within the cell, and *f (OT, C)* is the Erlang-B distribution.

In the case where we have more than one cell forming the coverage area and these cells overlap, then the blocking probability of a cell can be expressed in terms of the overlap. The blocking probability of a cell must now be calculated based on the fact that users are capable of choosing a channel from one cell in the case of a user in area A, or two cells in the case of a user in area B or from three cells for area C. The aim is to maintain the same lowest possible blocking probability in each and every area and as a result in the whole cell. This can be feasible only having assigned the optimum number of channels to each of these areas. It is important to note that the percentages of the coverage areas with respect to the cell area do not change while the height of the HAP changes. It is the ratio R/R_e that controls the degree of overlap and as a result these percentages, and hence this optimum ratio must be decided during the system design.

Multi – Overlapping Cell System

Having presented the initial definition of the model, we can now calculate the overlap areas as a function of the varying radii of the overlapping circles. This task requires finding the percentage of these areas that cover the total area of the cell. The following figure illustrates a typical HAP communication system of 121 cells [1]. The coverage area is defined as the area enclosed within the bold circle.

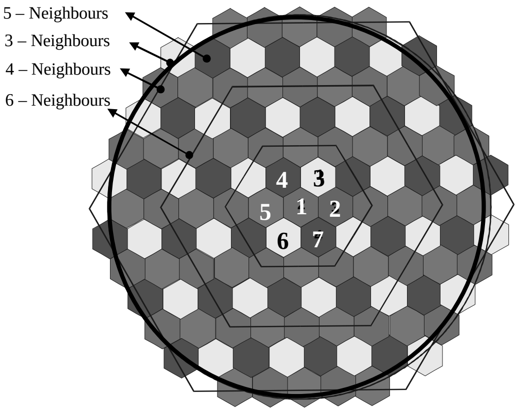

Figure 4: 121 Cell formation and the four types of overlap

The cells marked with the number of neighbours represent the cases that need to be considered when calculating the overlap areas. In this paper however, the case of 6 neighbours will be considered when describing the channel allocation schemes, since it is the most common and generally applicable case.

All cells inside the coverage area have 6 neighbouring cells, which overlap with each other. This means that each cell consists of 6B and 6C regions plus one region A as shown in figure 5. Notice that there are no areas formed by 4 or more overlapping cells.

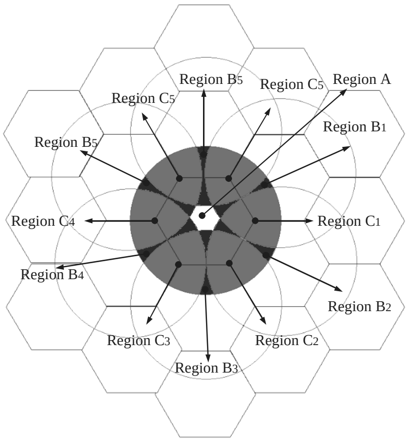

Figure 5: Illustration of Regions within Inner Cells

The final equations related to the type of cells presented above will be presented rather than the full mathematical analysis of the problem due to its length. Table 1 represents all relevant mathematical equations for calculating the size of the three types of areas in terms of the size of regions while varying the radius of the cells.

Region A	$2pR^2$ - (6 Region B + 6 Region C)
Region B	$\left[\left(R^2 \cdot a\cos\left(\frac{R_i}{R}\right) - R_i \cdot \left(\sqrt{R^2 - R_i^{\,2}}\right)\right) - Area\,C\right]$ $-2\,\frac{R^2}{2} \cdot \left[\sqrt{3} \cdot \left(1 - \cos(q_C)\right) + 3 \cdot \left(q_c - \sin(q_c)\right)\right]$
Region C	$\frac{R^2}{2} \cdot \left[\sqrt{3} \cdot \left(1 - \cos(q_C)\right) + 3 \cdot \left(q_c - \sin(q_c)\right)\right]$
q_c	$q_c = \arccos\left(1 - \frac{3 \cdot \left(\sqrt{R^2 - R_i^{\,2}} - \frac{R}{\sqrt{3}}\right)^2}{2 \cdot R^2}\right)$
Also $R_e = \frac{2R_i}{\sqrt{3}}$ **or** $R_i = \frac{\sqrt{3}R_e}{2}$	

Table 1 - Equations for Regions A, B and C as a function of the internal radii R_i and overlap radius R

Figure 6 represents the size variation for areas A, B and C for the case of an internal cell (6 neighbours). Note that the overlap radius (R) of the internal cell is normalised with respect to the initial external radius of the cell (R_e). As mentioned before, if the radius of the cells becomes smaller than the external radius R_e, then some areas will be left without service; therefore, the overlap radius can only be equal or larger than R_e. Also, users in area A can be assigned channels only from one base station, users in area B can be assigned channels from two base stations and users in area C can be assigned channels from three base stations.

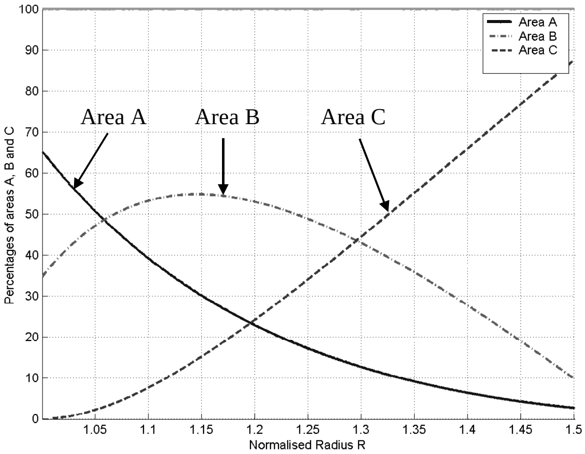

Figure 6: Size of areas (%) formed due to overlap Vs Cell radius for the case of an internal cell

From figure 6, it can be clearly seen that for as little as 5% increase on the initial radii of this type of cell, area B becomes equal to the size of area A; and for a 20% increase, area C becomes equal in size to area A and finally for an increase of 30%, area C becomes equal in size to area B. This plot has been useful when implementing the overlap based channel assignment schemes.

3. Scenario and Channel Assignment Strategies

Cell overlap can improve the system performance as the multiplexing gain of the channels in the overlap regions allows greater efficiency in spectrum use [5]; and the aim of any channel assignment strategy is to improve the guaranteed Quality of Service (QoS). In a HAP system that is using cell overlap, the charging rates for all users are based on the worst blocking level the provider can offer. Since the overlap improves the blocking in some areas but not others, with a distribution of channels based on areas only, some areas would have higher blocking levels than other areas. It is evident that by increasing the blocking in the regions with lower blocking levels, the worst-case blocking can be reduced. For constant-bandwidth traffic (for example video) applications considered here, this optimum situation can be achieved by minimising the worst blocking level within the coverage area.

The ideal situation is to be able to guarantee uniform QoS over the coverage area by maintaining uniform blocking levels in all areas. This can be achieved by controlling the number of channels available in each area formed due to the overlap. Uniform QoS means that all regions must have the same blocking levels without favouring any region for the sake of maintaining lowest possible average blocking levels in the system.

3.1. Scenario - Parameters and Assumptions

To ensure realistic results a set of 37 circular cells instead of 121 was considered with statistics only collected from the centre cell. This is because the majority of the cells in a 121-cell scenario (see figure 4) have six neighbours (e.g. centre cell). Each of these thirty-seven cells is using a different group of 30 channels within its coverage area and therefore co-channel interference is ignored. We have also assumed that there is direct line-of-sight communication between the user and the HAP. 100,000 users have been assumed with 500,000 conversations to be made. The arrival process is a poisson distribution and the length of the phone calls has a negative exponential distribution. The users are uniformly distributed within the coverage area, and the offered traffic (OT) is quantified in terms of Erlangs per square unit area. The total OT in the 37-cell coverage area ranges from 8 - 10 Erlang per square unit times the actual size of the coverage area (one unit of length is taken to be the external radius of the cells, R_e).

The size of the *coverage area (CA)* for 37 circular cells is equal to:

$$CA = 37pR_e^2 - 180 \cdot \left(R_e^2 \cdot a\cos\left(\frac{R_i}{R_e}\right) - R_i \cdot \left(\sqrt{R_e^2 - R_i^2}\right)\right)$$

Eq. 2

Assuming that R_e is equal to 1 unit, then R_i is equal to $\sqrt{3}/2$ units, and the total coverage area is equal to 99.9 square units. This value remains fixed for any overlap radius despite the fact the cell radius might change. This is to ensure constant OT within the coverage area. The same parameters have been used in all channel allocation models with the only exception the way the channels are allocated.

3.2. Scheme (1) – Standard FCA Scheme (FCA)

Description

The first scheme to be presented is a standard Fixed Channel Allocation (FCA) scheme implemented primarily for terrestrial systems. In this scheme, each cell is allocated a fixed set of channels and it will only allow users to be allocated a channel from the nearest base station. No overlap is considered and hence no choices are made by the users on which cell should they be allocated a channel. The reason for implementing this model is for comparison with the overlap based scenarios implemented.

Performance

The following plot depicts how the standard FCA scheme responds to the offered traffic (OT) variations. In this example, the users can only be connected to the closest base station. Figure 7, clearly shows that the system can maintain a 4% blocking probability for an OT less than 9.5 Erlang per square unit.

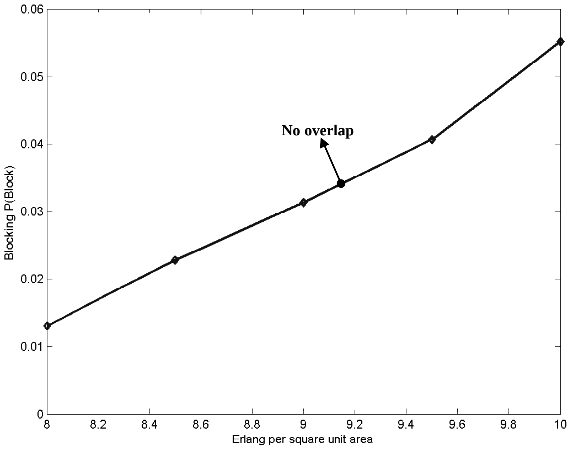

Figure 7: Nearest Base Station Scheme - No Overlap Considered

3.3. Scheme (2) – Area Based FCA Scheme (ABFCA)

Description

The second scheme is based on the standard FCA scheme. As before, each cell has a fixed number of channels, which can be allocated to any user within its coverage area. However the cell radius (R) is now equal to 1.25 times the initial cell radius (R_e). This means that any users positioned within a radius R of the centre of any cell can connect to this cell. The users will first search for the number of cells they can connect to (up to 3 cells) and then they will pick up a channel from which ever cell has the most available channels. If for example a user happens to be in area C, he can pick a channel from one out of three cells within his range that has most channels available.

Performance

In this simulation the radius of the cells defining the degree of overlap is set to R=1.25. Notice that although the overlap radius has been increased, the OT within the total coverage area remains the same (as in the previous case with no overlap). Figure 8 depicts the blocking levels for areas A, B and C in the centre cell for the case where we consider cell overlap, in contrast to the standard FCA scheme. From the plot, it can be seen that overall (considering the total cell blocking levels), the overlap scheme performs better than the one with no overlap (previous scheme); however the blocking levels for the users positioned in area A, B and C vary differently. Users in area A experience worse blocking levels than the users in area B and C. For areas B and C, where the users have the option to choose from more than one cell, the blocking levels are much lower than the case with no overlap.

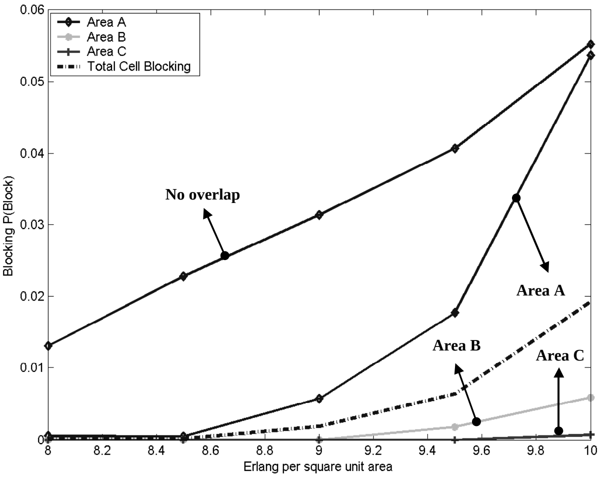

Figure 8: Area Based FCA Scheme (ABFCA).

From the results above we can verify that the areas formed by two or more cells enjoy the advantage of higher multiplexing gain, and as a result, the blocking levels are much lower than the case where no overlap is considered. Therefore, the overall blocking levels of the ABFCA scheme are much lower than the no overlap case. Nevertheless, it is not possible to favour any area (in this case B and C) for the sake of maintaining the lowest possible overall blocking levels in the system. The ABFCA scheme however, indicates that utilising cell overlap can significantly reduce the blocking levels. In addition, there is great potential to improve the performance of ABFCA by careful analysis of the channel distribution based on the performance of the individual areas. More specifically, in this scheme it is necessary to reduce the blocking levels in area A, by increasing slightly the blocking levels in area B and C. The aim is to try to do this by keeping the total cell blocking level below the no overlap case. The following scheme to be presented has been designed and implemented based on these criteria.

3.4. Scheme (3) – Uniform FCA Scheme (FCA)

Description

The next channel allocation scheme investigated is based on the ABFCA scheme and is called Uniform Fixed Channel Assignment (UFCA). Again, each cell has a fixed number of channels, which can be allocated to any user within its coverage area. In this scheme, certain restrictions are imposed in order to prevent a proportion of the channels from being allocated to the overlap areas, to allow them to remain available to areas with no overlap (area A). The parameters chosen for this scheme take into account the performance of the ABFCA scheme shown in figure 8. The aim of this scheme is to improve the results illustrated in figure 8, so that the blocking in all regions becomes lower than the standard FCA model. From figure 8 it is apparent that more channels have to be allocated for the users in area A, and less channels for the users in area B and C.

One way of doing this without directly shifting channels from one area to the other, which requires partitioning the cell into small regions, is by blocking a proportion of users in area B and C even though there are channels available. The channels saved from area B and C can then be used in area A. As a result, the blocking of area A will be decreased and the blocking in area B and C will increase. The model proposed saves the last channel in area B and the last two channels in area C from being automatically used: instead these channels are only used on a random basis: when a random number generated is greater than a random acceptance factor (RAF). The RAF thus comes into effect every time a user in either area B or C requests a channel and there is only one (or two in the case of area C) left available for that area. After experimentation, this combination is proven to perform better than others since it was impossible to ensure uniform blocking in each region.

The optimum value for RAF was found, after a numerical investigation, to be a function of the level of offered traffic per unit area, and is given by:

$$RAF = a + b \cdot \ln\left(\frac{OT_{optimum}}{OT_{\mathrm{var}\,ying}}\right) \qquad \text{Eq. 3}$$

where a defines the probability that the last channel will be saved by blocking the user in the area of reference (area B or C) and *ß* is a scaling factor for the RAF to optimise it for a range of offered traffic. $\mathrm{OT}_{\mathrm{Optimum}}$ is defined as the OT for which the blocking probability is the minimum possible while uniform within the same cell and as an extent to the whole cellular system when *ß* is set to zero. Initially, *ß* is set to zero in order to find the best probability factor a by requiring the blocking levels in all three areas to be as close as possible to each other. For example, in figure 8, it can be clearly seen that the blocking of area A increases exponentially. We therefore need to increase individually the blocking in area B and area C using different RAF scaling factors and as a result decrease the blocking in area A. This technique enables us to control the number of channels being allocated into certain areas without partitioning the group of channels of a cell into smaller groups, and retaining the maximum number of channels to be available for localised “hot-spots” in traffic demand.

Performance

As before, the radius of the cells defining the degree of overlap is set to R=1.25. The parameters a, *ß* and the $\mathrm{OT}_{\mathrm{Optimum}}$ used in this simulation are given in table 3.

Area Type	**a**	**ß**
B	0.405	1.7
C	0.045	1.7
$\mathbf{OT}_{\mathbf{Optimum}}$	8.8	

Table 2 a, *ß* and $\mathrm{OT}_{\mathrm{Optimum}}$ parameters used for overlap radius R=1.25

From the results shown in figure 9 we can clearly see that the total cell blocking has been reduced. Furthermore, the blocking levels in all regions are approximately the same.

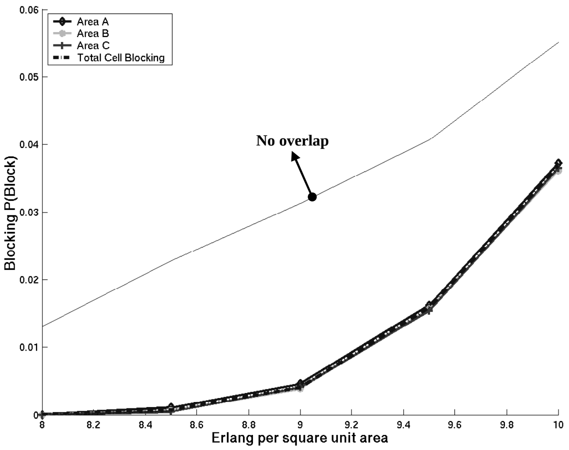

Figure 9: Uniform FCA Scheme (UFCA). The blocking probability has been reduced

In comparison with the other schemes, this model has improved the QoS by reducing the blocking probability in all areas, and has also achieved uniform blocking levels across the cell. The centre cell can now cope with approximately 10.5% more OT than in the standard case with no overlap. This improvement does not require any prior knowledge of the interference environment.

Up to now, we have assumed a cell radius of R=1.25. Figure 10 however shows that this technique is also applicable for other overlap radii.

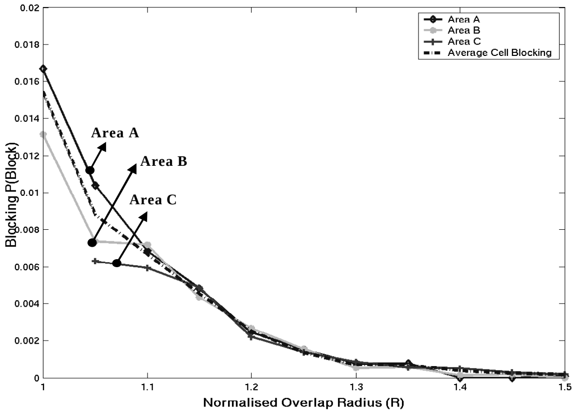

Figure 10: Uniform FCA Scheme (UFCA) Blocking Probability in Centre Cell for Different Degrees of Overlap Radius.

As the values of a and *ß* for areas B and C are optimised for R=1.25, the optimisation clearly does not work for lower overlap radius as the blocking probabilities in area A, B and C are significantly different; showing that the values of a and *ß* are functions of the amount of overlap. Although the blocking probability decreases as the cell overlap increases, a radius of greater than R=1.25 assumes that users can cope with the increased level of interference.

4. Conclusions

This paper has illustrated how channel assignment strategies can be configured for a high altitude platform architecture exploiting cell overlap. Results have shown that cell overlap can be exploited to improve the performance for a scheme that uses fixed channel allocation. The areas served by more than one cell (overlap areas), benefit from the multiplexing gain and as a result they have much lower blocking than the areas served by one cell. To improve uniformity and reduce the blocking probability within a cell, a simple technique has been developed where certain restrictions have been imposed in order to prevent a proportion of the channels from being allocated to the overlap areas; and as a result, these channels are more likely to remain available for areas with no overlap (area A). This technique enables us to control the number of channels being allocated to certain areas without partitioning the coverage area into smaller regions. It will therefore be of particular benefit in situations where there is non-uniform distribution of traffic.

REFERENCES

[1] HeliNet Project – June 2001, “*www.helinet.polito.it*” and Capanina Project - November 2003 “www.capanina.com”

[2] D. Grace, J. Thornton, T. Konefal, C. Spillard, and T.C. Tozer, "*Broadband Communications from High Altitude Platforms – The HeliNet Solution*", Wireless Personal Mobile Conference, Aalborg, Denmark, Vol.1, pp. 75-80, September 2001 (Invited Paper)

[3] D. Grace, C. Spillard, and T.C. Tozer, "*High Altitude Platform Resource Management Strategies with improved Connection Admission Control*", Wireless Personal Mobile Conference - Japan, September 2003

[4] I. Katzela and M. Naghshineh, "*Channel Assignement Schemes for Cellular Mobile Telecommunication Systems: A Comprehensive Survey, IEEE Personal Communications Magazine*", pp.10-31, June 1996

[5] D. Grace, C. Spillard, J. Thornton, T.C. Tozer, "*Channel Assignment Strategies for a High Altitude Platform Spot-Beam Architecture*", IEEE PIMRC 2002, Lisbon, September 2002

[6] J. Thornton, D. Grace, M. H. Capstick, T. C. Tozer, "*Optimising an Array of Antennas for Cellular Coverage from a High Altitude Platform*", IEEE Transactions on Wireless Communications, vol. 2, no. 3, May 2003

[7] J. Thornton and D. Grace, "*Effect of Lateral Displacement of a High Altitude Platform on Cellular Interference and Handover*", Submitted to IEEE Transactions on Wireless Communications, May 2003

[8] D. Everitt, "*Traffic Capacity of Cellular Mobile Communications Systems*", Comp. Networks ISDN Sys., vol. 20, 1990, pp. 447-454

[9] T. Fujii, "*Selective Handover for Traffic Balance in Mobile Communications*", Proc. IEEE / Supercomm / ICC’ 92, vol. 4 1992, pp. 212.3.1-212.3.7