Co-Existence DCA: Dynamic Channel Allocations Allowing Underlaying Autonomous Microcells

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***Abstract*-To facilitate the coexistence of embedded autonomous indoor microcellular environments, a new form of Dynamic Channel Assignment (DCA) algorithms for outdoor macrocellular systems is proposed in this paper. The co-existence of two systems without excessive mutual interference is achieved through a novel mechanism, i.e., intelligent exclusion of predefined subsets of the universal channel set from the dynamic assignment in the outdoor cells. Such channel exclusion results in a guaranteed number of channels available to the autonomous indoor systems anywhere they are; while incuring minimal DCA performance degradation in the macrocells. The resulting DCA algorithms are termed the Co-Existence DCA (CE-DCA) algorithms. We formulate the problem of CE-DCA in a rigorous manner and discuss the parameters involved in achieving optimum combined capacity of macro and micro cellular systems. Using the Local Packing Dynamic Channel Assignment (LPDCA) algorithm [5, 6] as the base line DCA in the macrocellular system, we present both statistic and deterministic CE-DCA schemes, and compare their performances under various scenarios.**

1. INTRODUCTION

Existing and emerging indoor/microcellular systems, such as wireless PBX, private wireless networks on campus, in buildings or factories, often try to *autonomously* reuse the channels allocated to the outdoor/macrocellular systems. The prevention of mutual interference between them and the outdoor macrocells is easily achievable when the macrocells employ the Fixed Channel Assignment (FCA). Since each of the outdoor cells uses only a fixed subset of the total spectrum under FCA, indoor autonomous microcells can always scan [1,2] to find *stationarily* available channels, wherever they are located.

Dynamic Channel Assignment (DCA) is being adopted to enhance the spectral utilization and to ease the frequency planning in wireless networks. Conventional DCA algorithms [3-8], ranging from simple selection of a feasible channel, to maximal packing where a call request is rejected only when there is no feasible channel with all possible rearrangements, allow the use of any channel in the operational frequency range in every base station. Hence, at a given location in the macrocellular radio environment, microcells may experience interference over any part of the allocated frequency spectrum. The coordination required to avoid mutual interference becomes challenging.

We set out to design a new family of DCA algorithms ensuring the co-existence of macrocells and underlaid autonomous microcells. To avoid mutual interference between the two systems, these new DCA algorithms dictate that each of the cells in the outdoor system, while running a base line DCA, is excluded the use of a small part of the allocated spectrum. This channel exclusion must ensure, at a minimum, a certain number of channels available to the indoor autonomous systems, while minimizing the capacity degradation in the outdoor system. We name this class of DCA algorithms the *Co-Existence DCA (CE-DCA) algorithms*. CE-DCA algorithms can be baselined on any efficient DCA algorithm. In our simulation studies, LPDCA algorithm [5,6] is used as the basis of all the Co-Existence schemes presented.

We define the parameters governing the performance of CE-DCA algorithms and investigate their optimal ranges in section 2. A number of algorithms approaching the optimal performance, along with their credits and merits, are presented in section 3. Their relative performances are compared in section 4.

2. THE PROBLEM DEFINITION

The advantage of DCA lies in the fact that every cell is free to choose any channel from the *universal set* of channels available to the network, the only constraint is being imposed through the interference from the cells within the frequency reuse distance. This capability provides capacity gain in addition to alleviating radio frequency planning. However, it nearly prevents indoor autonomous wireless system from finding available channels in real time. To accommodate their coexistence, we propose the exclusion of a subset of channels in each macrocell from the universal set. Such exclusion should cause minimal performance degradation in macrocells compared to conventional DCAs (without exclusion).

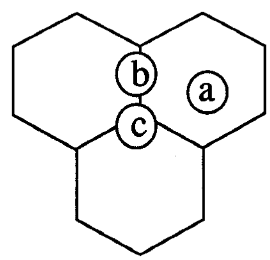

Figure 1 Three types of locations of microcellular environments within a hexagonal macrocellular layout.

As an autonomous underlay, an indoor wireless environment may be within a cell, or at a boundary common to two or more cells. With hexagonal cellular topology, we do not expect more than 3 mutually adjacent macrocells. (The extension to 4 overlapping macrocells is straightforward.) Hence the worst case situation we consider is a microcellular system located at an area labelled as 'c' as depicted in Figure 1. Let cell i in the outdoor wireless system be excluded the use of channel set, E_i, when executing DCA. To ensure a sufficient number of channels available for an autonomous system at any location within the macrocellular system, it is necessary that

$$\left|\bigcap_{i \in P} E_i\right| \geq N_{min} \qquad \text{(EQ 1)}$$

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where, N_{min} is the minimum number of channels required for an indoor mobile environment, and P is any set of mutually adjacent three cells.

It is possible to generate many different exclusion patterns to satisfy the codition as in (EQ 1). Such patterns would result in different *universal cluster sizes*. The universal cluster in this context, is defined as the "minimal set of clustered cells with no common exclusion channels". Let Ω be a set of cells belonging to a universal cluster. Then,

$$\bigcap_{i \in \Omega} E_i = \phi \qquad \text{(EQ 2)}$$

where, ϕ is the null set. Intuitively, the smaller $|\Omega|$ is, the better it is for DCA. Moreover, $|\Omega| > 3$ is required to guarantee channels available for microcells located at areas labeled as c in Figure 1. Thus, to minimize impacting the DCA performance, for a given N_{min}, CE-DCA should try to keep the sizes of *universal cluster*, $|\Omega|$, *exclusion set per cell*, $|E_i|$, and the common exclusion set per cluster C, $\left|\bigcap_{i \in C} E_i\right|$, for all $|C| < |\Omega|$, as small as possible.

There are trade-offs among the above requirements. At one extreme, if $|E_i| = N_{min}$, every cell has to be excluded the same set of channels of size N_{min} (*common exclusion*), which amounts to truncating the universal set of channel by N_{min}. The size of universal cluster in this case is ∞. On the other hand, we can design an exclusion pattern where every cluster of 3 cells has a common exclusion set of size N_{min}, while each group of four or more cells are able to utilize the universal set of channels. One of the CE-DCA to be presented, named 6-Min, has these desirable properties. The simulation results to be discussed later in this article, show that the common exclusion is worst of all while the 6-Min exclusion is **not** the best. It can be concluded that, for the optimal strategy, the size of exclusion set per cell lies in the range of $N_{min} < |E_i| < 6\,N_{min}$ and $|\Omega| > 4$. Neither the exact parameter values nor the optimum exclusion pattern are known yet.

3. EXCLUSION SCHEMES FOR CE-DCA

A number of exclusion schemes, namely *common, random, and 6-Min,* exclusion methods are presented in this section. We describe each algorithm along with the motivation for the design here. Their relative performance under different system parameters, such as the size of exclusion set per cell, $|E_i|$, and the ratio of microcell to macrocell radii, a, are presented in section 4.

A. Trivial solution: Common exclusion

The simplest idea would be to exclude a *unique set* with sufficient number of channels to serve the indoor systems from all the cells. With $|E_i| = N_{min}$, it ensures the co-existence of an indoor system at any location in the operational region. However, $|\Omega| = \infty$, thus it is not efficient with regard to spectral utilization and it's DCA performance of the outdoor system is simply the performance of the pure DCA algorithm with truncated universal channel set. The resulting capacity loss may not be acceptable by the outdoor service provider, especially if some of the indoor systems are operated by independent parties.

B. Random exclusion

We attempt to overcome the drawback of the above approache by choosing different *exclusion sets* for each of the cells. To preserve one of the advantages conventional DCAs offer, namely, no frequency planning in any form, we randomly pick an exclusion set of size $|E_i|$ for each of the cells.

C. 6-Min exclusion

We can design an exclusion pattern where every cluster of 3 cells has a common exclusion set of size N_{min}, while each group of four or more cells are able to utilize the universal set of channels. The size of exclusion set per cell, $|E_i|$ for this case is found to be $6\,N_{min}$ as shown in Figure 2. For every three mutually adjacent cells to have a common exclusion set c_i of size N_{min}, the three cells should be excluded the set c_i. For each four cells to have no common exclusion set, each corner of a hexagon has to be assigned a different common exclusion set c_i, i=1,...6, and the cell with those six corners has to be excluded all six sets. We name this strategy, "6-Min eExclusion".

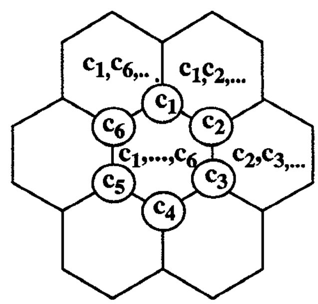

Figure 2 Exclusion with minimum reuse cluster size of $|\Omega|$=4.

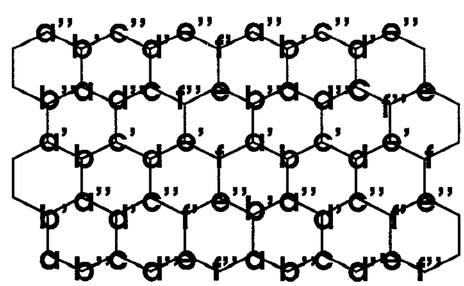

Figure 3 6-Min exclusion pattern: achieved with 18 mutually exclusive channel sets of size N_{min}.

In Figure 3, we illustrate the exclusion pattern that satisfies the condition in (EQ 1) while having a universal cluster size of 4. It is achieved by defining 18 mutually exclusive channel sets of size N_{min} within the universal set. Each corner of a hexagon is assigned an exclusion set choosen from $\{a,...,f,a',...,f',a'',...,f''\}$. Hence this 6-Min exclusion requires universal channel set, U, large enough to satisfy the condition, $|U| \geq 18\,N_{min}$.

4. PERFORMANCE

Two performance aspects of various CE-DCAs should be considered: one on indoor microcellular systems and the other on outdoor macrocellular systems. The former depends on the amount of spectrum made available to microcells by each scheme. The latter, on the other hand, is measured from the capacity reduction in macrocells due to exclusion. The overall performance is determined by the combination of both aspects.

4.1 Performance on Indoor Microcelluar systems

Let $N_s(=|E_i|)$, N_p, and N_t be the number of channels a microcell aquires when placed within a macrocell, at a boundary common to two cells, and a corner common to three cells, respectively. Given N_s, for random CE-DCA, N_p and N_t are random variables with distributions approximated by Bernoulli distributions, as given in the appendix; for common and 6-Min CE-DCAs, they are directly prportional to N_s. These parameters are shown in Table 1.

CE-DCA	N_p	N_t
Common	N_s	N_s
Random	N_s^2/M	N_s^3/M^2
6-Min	$1/3N_s$	$1/6N_s$

Table 1. The sizes of commonly excluded channel sets

An indoor microcellular system can scavenge different amount of spectrum depending on its position within the macrocellular environment. A reasonable measure of performance, therefore, is the expected amount of spectrum per microcell, given by $P_sN_s + P_pN_p + P_tN_t$, where P_s, P_p, and P_t are the probabilities of placing a microcellular system within a macrocell, at a boundary common to two cells, and a corner common to three cells respectively. These probabilities depend on the relative radii of micro v.s. macrocells, a, and are derived in the appendix.

Figure 4 shows the expected number of channels per indoor system against $|E_i|$ and a. It appears that the performance of the common, 6-Min and random CE-DCAs are in decreasing order if we consider microcells alone. In addition, the random exclusion is characterized by non-zero standard deviation as illustrated in Figure 5. This "uncertainity range" is a convex function of $|E_i|$ and a monotonically increasing function of a.

4.2 Performance on outdoor macrocellular systems

Due to the exclusion of channels, outdoor macrocellular system under CE-DCA algorithms suffer certain capacity degradation compared to pure DCA. Our exclusion schemes attempt to minimize the amount of capacity loss.

We evaluated the macrocell capacity of CE-DCAs via simulation. It was carried out on a 12 x 12 hexagonal cellular grid. To eliminate boundary effect, the cellular grid was wrapped around to form the surface of a torroid. Base station selection was based on the relative carrier reception levels. The propagation model are, distance dependent loss proportional to $1/d^{\gamma}$ where d is the distance and $\gamma = 4$, log normal shadow fading with a standard deviation of 6.0 dB, and additive white gaussian noise giving 30 dB signal-to-noise ratio at the farthest point of cell boundary in the absence of interference. Uniform traffic distribution was assumed. Frequency reuse was subject to a minimum of two cells buffering.

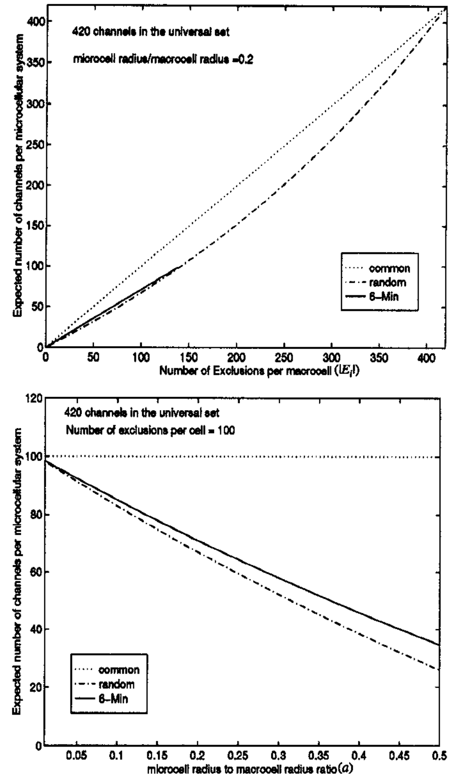

Figure 4 Expected number of channels per microcellular system versus $|E_i|$ and a, under various CD-DCA.

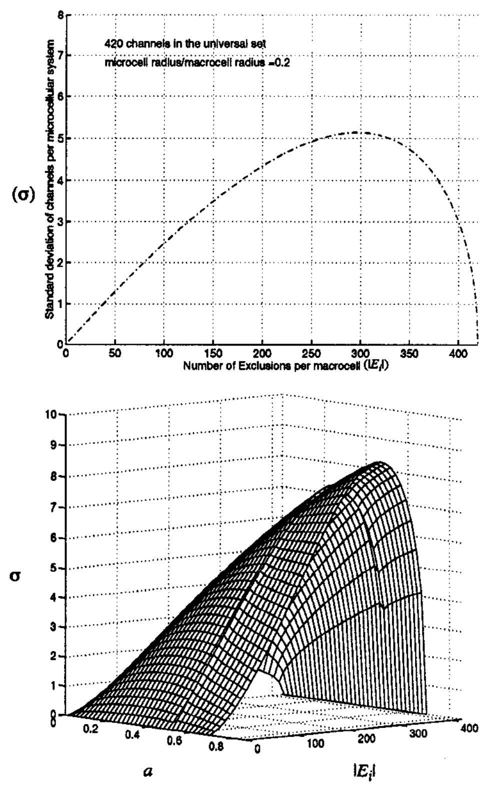

Figure 5 Standard deviation of the number of channels per microcellular system versus $|E_i|$ and a, under random exclusion.

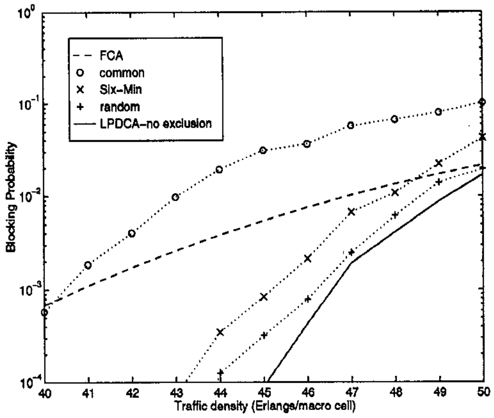

Figure 6 Blocking Performance of CE-DCAs in macrocellular system with $|U| = 420$ and $|E_i| = 50$.

Typical simulation results are shown in Figure 6. Interestingly, we observe that the performance of the three CE-DCAs in macrocells follows the reverse order of that in microcells. Moreover, common exclusion is worse than even FCA, as expected; while 6-Min and random exclusions still outperform FCA, and random CE-DCA suffers very little capacity loss relative to pure DCA.

4.3 Overall performance

The overall performance of CE-DCA algorithms is represented by the joint measure of nominal carried traffic for the macrocells, at blocking of 1%, and the expected number of available channels per microcellular system. Derived from the results in 4.1 and 4.2 with various $|E_i|$, Figure 7 illustrates the relative performances of CE-DCAs with representative ratios of micro-to-macro cells radii. Since the spectum available to the microcellular system under random exclusion is a random variable, we include its $\pm 3\sigma$ bars in the plots to indicate the uncertainty ranges.

The value of a in practice are in the range of [0.1 - 0.3]. Within this range of a and for smaller values, common exclusion performs considerably worse compared to other CE-DCAs. Random exclusion is found to render the best performace. Note that Random CE-DCA is also the simplest in complexity, apart from ''common exclusion''. The randomness nature bodes well with no frequency planning.

As the size of microcellular systems increseas, the requirement in (EQ 1) becomes more difficult to meet with random exclusion, 6-Min is an attractive solution if microcells require only a small number of channels. However, a new form of "planning" is needed in this case. In the extreme case where microcellular systems are of comparable size with macrocells, common exclusion may outperform others. Nonetheless, we expect random CE-DCA to be the winner in most of cases of interest.

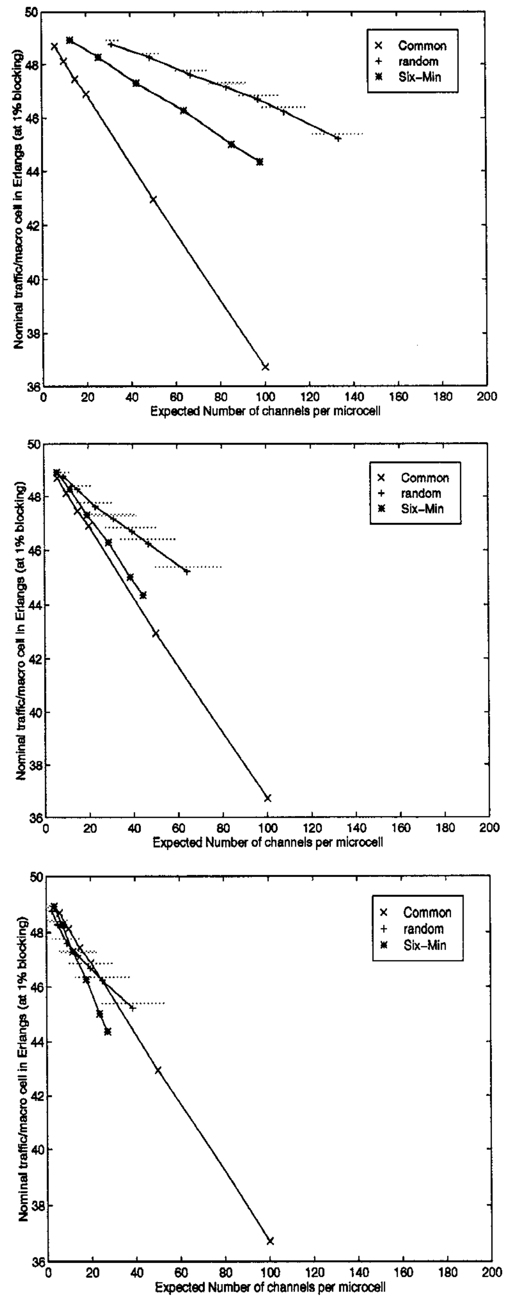

Figure 7 Nominal traffic carried in macrocell, at 1% blocking probability, versus expected number of channels per microcell with $|U|$=420. From top to bottom the curves are for a=0.2 ,0.55, and 0.7 respectively. The horizontal bars indicate $\pm 3\sigma$ range.

5. CONCLUSION

Many microcellular systems, mostly indoor, operate within the same spectrum of outdoor macrocellular network *autonomously*. Their operations are based on the assumption that there are relatively stationary channel sets never used by the local macrocells. This assumption holds true when the macrocellular system operates under FCA. However, with the realization of the DCA advantages such as its capacity gain and ease of frequency planning, the outdoor/macrocellular systems are turning away from FCA to DCA, and the stationarily available channel sets at the locality of autonomous indoor systems will no longer exist.

To satisfy the conflicting needs of both systems, we proposed the Co-Existence DCA (CE-DCA) algorithms, a new class of DCA algorithms for the outdoor/macrocellular wireless systems to permit the coexistence of the autonomous indoor/microcellular systems. A formal formulation of the problem was presented. A number of novel solutions were proposed and their performance for outdoor and indoor systems jointly were investigated.

Key factors governing the relative performance of CE-DCA algorithms in outdoor/macrocellular systems are: the size of the exclusion set per macrocell and the size of the universal cluster. The former is largely dictated by the minimally required number of available channels in the microcells. The latter, on the other hand, varies with the type of the exclusion algorithms. The quantity of spectrum aquired by a microcell is dectated by the type of algorithm as well as the relative position of the microcellular system within the macrocellular environment. We quantified the performance of CE-DCAs in microcells by the expected number of channels available to a typical microcellular system.

The performance of the CE-DCAs we proposed have been evaluated in terms of the joint macro/micro cells capacity. Among the algorithms presented in this paper, the simplicity of a CE-DCA with common exclusion is overshadowed by its poor performanc, except when the microcells needs only a very small number of channels. CE-DCA with 6-Min exclusion provides the smallest universal cluster size and pretty good performace, with the caveat that its universal set size must be at least 18 times of the number of channels the microcells need. If the microcellular systems are reasonably small in radius in comparison with the macrocells, as would be true in most of the cases of interest, we recommend the CE-DCA with random exclusion. Random CE-DCA also preserves the advantage of not requiring global frequency planning.

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APPENDIX

i) Common exclusion sets under Random Exclusion

Macrocell i is excluded a set of channels, E_i, of size m, which is chosen randomly from the universal set of channels, U. The probabilitis of having k ($\leq m$) channels in common among two, and three such exclusion sets are [7]:

$$Pr\left(\left|\bigcap_{i=1}^{2} E_i\right| = k\right) = \frac{\binom{m}{k}\binom{M-m}{m-k}}{\binom{M}{m}} \qquad \text{(EQ 3)}$$

$$Pr\left(\left|\bigcap_{i=1}^{3} E_i\right| = k\right) = \sum_{l=k}^{m} \frac{\binom{l}{k}\binom{m}{l}\binom{M-m}{m-l}\binom{M-l}{m-k}}{\binom{M}{m}^2} \qquad \text{(EQ 4)}$$

In general, the probability for k of m channels in E_n to be in E_i:i=1,...,n-1 is approximated by Bernoulli distribution with probability of success $(m/M)^{n-1}$. Its expectation and variance are:

$\mu = \frac{m^n}{M^{n-1}}$ and $\sigma^2 = \frac{m^n}{M^{n-1}}\left(1-\left(\frac{m}{M}\right)^{(n-1)}\right)$ respectively.

ii) Probability Distribution of Microcellular systems Location

For simplicity, we approximate macrocells by hexagons and microcells by circles. The probabilities of a microcellular system overlapping with one, two or three macrocells correspond to the fractional areas shown in Figure 8. Let the radii of macrocell and microcell be R and aR, where $0 \leq a \leq 0.7$. If the center of a microcell is in the inner hexagon with radius $(1\text{-}b)R$, it is enclosed within the single macrocell. A microcell with its center placed within ABCDEF will overlap with three macrocells. The remaining area correponds to microcells overlapping with two mutually adjacent macrocells. Thus, it can be shown that,

$P_s = \frac{1}{3}(\sqrt{3}-2a)^2$, $P_p = \frac{2}{3\sqrt{3}}(6-(4\sqrt{3}+\pi)a)a + \frac{8}{\sqrt{3}}U[a-0.5]A$,

and $P_t = \frac{2}{3\sqrt{3}}(2\sqrt{3}+\pi)a^2 - \frac{8}{\sqrt{3}}U[a-0.5]A$, where $U[a]$ denotes unit step funtion, and $A = \frac{1}{2}a^2\operatorname{acos}\left(\frac{1}{2a}\right) - \frac{1}{4}\sqrt{a^2-0.5^2}$.

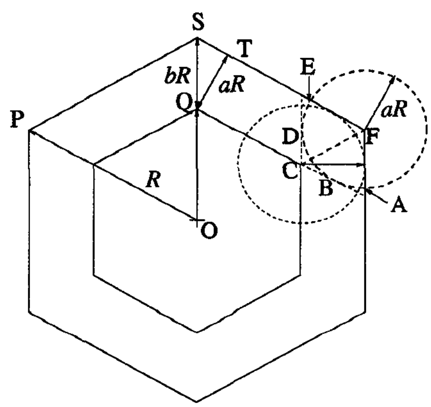

Figure 8 Corresponding areas in a macrocell centered by a microcell that overlapps with one, two and three macrocells.