Uplink Capacity and Interference Statistics of W-CDMA Rural Highways Cigar-shaped Microcells with Non-uniform Spatial Traffic Distribution

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Abstract: - The capacity and the interference statistics of the sectors of the cigar-shaped W-CDMA macrocells are studied. A model of 5 microcells is used to analyse the uplink. The microcells are assumed to exist in rural zones. The capacity and the interference statistics of the microcells are studied for different non-uniform spatial traffic distributions. When the users density decreases moving away from the base station, the capacity of the sector increases due to the less total power transmitted by the interfering users.

Key-Words: - W-CDMA, Uplink capacity, Cross-shaped microcells.

1 Introduction

CDMA is characterized as being interference-limited and reducing the interference results in increasing the capacity. Three techniques are used to reduce the interference: power control (PC) essential for the uplink, voice activity monitoring and sectorization which can double or triple the capacity. It is well known that urban microcell shapes may approximately follow the street pattern and for that it is possible to have cross-shaped microcells [1].

The conditions that describe the rural highway cigar-shaped microcells under this study are

- the number of directive sectors of the cigar-shaped microcell is two and a directive antenna is used in each sector.
- a line-of-sight shaped microcell has typically a range of one kilometre.
- the user speed in rural areas can reach 120 km/h.

Fig. 1 depicts the coverage of the sector and the cigar-shaped microcell.

In the real world the uniform offered traffic spatial distribution inside microcells is very uncommon. Majority of the W-CDMA cellular networks capacity and coverage assume uniform spatial distribution which is unrealistic in practise.

Min *et al.* studied the performance of a cigar-shaped CDMA highway microcell [2]. Hashem *et al.* studied the capacity and the interference statistics for hexagonal cell for a propagation exponent of 4.0 [3].

In this work, we introduce a model for cigar-shaped microcells in rural highways zones with general propagation exponent using a two-slope model and then investigate the sector capacity and interference statistics of the uplink for different spatial distributions of users.

2 Propagation Model

A two-slope propagation model is used in the calculations. The exponent of the propagation is assumed to be s_1 till the break point (R_b) and then it converts to s_2. In this way the path loss is given by [4]:

$$L_p(dB) \approx L_b + 10 + 10 s_1 \log_{10}\left(\frac{r}{R_b}\right) + \xi_1 \quad \text{If } r \le R_b \quad (1)$$

$$L_p(dB) \approx L_b + 10 + 10 s_2 \log_{10}\left(\frac{r}{R_b}\right) + \xi_2 \quad \text{If } r > R_b \quad (2)$$

Where r is the distance between the base station of the microcell C and the mobile receiver, L_b (the propagation loss at a distance R_b) is given by:

$$L_b(dB) = \left| 10\log\left[\left(\frac{\lambda^2}{8\pi h_b h_m}\right)^2\right]\right| \quad (3)$$

$$R_b \approx \frac{4 h_b h_m}{\lambda} \quad (4)$$

where: h_b is the base station antenna height, h_m is the mobile antenna height and λ is the wavelength. ξ_1 and ξ_2 are Gaussian random variables of zero-mean and a standard deviation of σ_1 and σ_2 respectively. The variables ξ_1 and ξ_2 are assumed to have a correlation coefficient C_{12}. Typical values of s_1 , s_2, σ_1 and σ_2 are:

- s_1 = 1.75 to 2.25,
- s_2 = 3.5 to 4.5,
- σ_1 = 2 to 3 dB and
- σ_2 = 4 to 6 dB.

3 Uplink Analysis

Fig. 2 depicts the configuration of the 5 microcells model used in the analysis. Each microcell controls the transmitted power of its users. The sector range is assumed to be R.

If the interfering user i is at a distance r_{im} from its base station and at a distance r_{id} from the home cell base station as shown in Fig.3, then the ratio of the interference signal $L(r_{id}, r_{im})$ due to the distance only is given as

• If (r_{id} and $r_{im} < R_b$) then $L(r_{id}, r_{im})$ is

$$L(r_{id}, r_{im}) = r_{im}^{s_1} / r_{id}^{s_1} \quad (5)$$

• If $r_{id} > R_b$ and $r_{im} < R_b$ then $L(r_{id}, r_{im})$ is given as

$$L(r_{id}, r_{im}) = R_b^{(s_2 - s_1)} r_{im}^{s_1} / r_{id}^{s_2} \quad \text{(6-a)}$$

• If $r_{id} < R_b$ and $r_{im} > R_b$ then $L(r_{id}, r_{im})$ is given as

$$L(r_{id}, r_{im}) = R_b^{(s_1 - s_2)} r_{im}^{s_2} / r_{id}^{s_1} \quad \text{(6-b)}$$

• If (r_{id} and $r_{im} > R_b$) then $L(r_{id}, r_{im})$ is

$$L(r_{id}, r_{im}) = r_{im}^{s_2} / r_{id}^{s_2} \quad (7)$$

Now the ratio of the interference signal $I(r_{id}, r_{im})$ due to the distance and shadowing is given by

$$I(r_{id}, r_{im}) = 10^{(\xi_{id} - \xi_{im})/10} L(r_{id}, r_{im}) \quad (8)$$

ξ_{id} and ξ_{im} are given as

• In case of (r_{id} and $r_{im} \le R_b$) then $\xi_{id} = \xi_1$ and $\xi_{im} = \xi_1$.

• If $r_{id} > R_b$ and $r_{im} \le R_b$ then $\xi_{id} = \xi_2$ and $\xi_{im} = \xi_1$.

• When $r_{id} \le R_b$ and $r_{im} > R_b$ then $\xi_{id} = \xi_1$ and $\xi_{im} = \xi_2$.

• In case of (r_{id} and $r_{im} > R_b$) then $\xi_{id} = \xi_2$ and $\xi_{im} = \xi_2$.

We will divide the total intercellular interference ($I_{inter,t}$) to interference from users in the S0 region (I_{S0}) and interference from users in the S1 region (I_{S1}), where these regions are shown in Fig. 2, and we will find the interference at the right sector (sector1) of the central base station C1 assuming it to be microcell d. Users in the region S0, will connect with the best of the two nearest microcell while users in S1 can not communicate with the central base station C1. In the S1 region we will will assume that users communicate with the nearest base station [3].

Let the desired signal level be S. The interference from an active user communicating with the home microcell will be also S. A user i in the S0 region will not communicate with the home base station d but rather with base station m, if

$\phi(\xi_{id} - \xi_{im}, r_{id}/r_{im}) = 1$, where

$$\phi(\xi_{id} - \xi_{im}, r_{id}/r_{im}) = \begin{cases} 1, & if \quad L(r_{id}, r_{im}) 10^{(\xi_{id} - \xi_{im})/10} \le 1 \\ 0, & otherwise. \end{cases} \quad (9)$$

Assume that the user are distributed within the sector with a distribution given as $f_s(r)$, the number of users in each sector is N_u and that the activity factor of the user is α, then for the right part of S0 the expected value of IS0 is given as

$$E[I_{S0}]_r = \alpha \frac{N_u}{R} \int_{S0} L(r_{id}, r_{im}) f_s(r) f(\frac{r_{id}}{r_{im}}) dr \quad (10)$$

where

$$f(\frac{r_{id}}{r_{im}}) = E\left[10^{(\xi_{id} - \xi_{im})/10} \phi(\xi_{id} - \xi_{im}, r_{id}/r_{im})\right] \quad (11)$$

$$= e^{(\beta\sigma)^2/2} Q\left[\sqrt{\sigma^2}\ \ln 10/10 - \frac{10}{\sqrt{\sigma^2}} \log_{10}\{1/L(r_{id}, r_{im})\}\right] \quad (12)$$

where β = ln10/10. Now the general value of σ^2 is given as:

• When (r_{id} and $r_{im} \le R_b$) then $\sigma_{id} = \sigma_1$, also $\sigma_{im} = \sigma_1$ then

$$\sigma^2 = 2(1 - C_{dm})\sigma_1^2 \quad (13)$$

where C_{dm} is the correlation coefficient between the random variable ξ_{id} and ξ_{im}.

• If $r_{id} \le R_b$ and rim> R_b or $r_{id} > R_b$ and $r_{im} \le R_b$ then the value of σ^2 is given by

$$\sigma^2 = (\sigma_1 - \sigma_2)^2 + 2(1 - C_{dm})\sigma_1\sigma_2 \quad (14)$$

• When (r_{id} and $r_{im} > R_b$) then $\sigma_{id} = \sigma_2$, also $\sigma_{im} = \sigma_2$ then

$$\sigma^2 = 2(1 - C_{dm})\sigma_2^2 \quad (15)$$

Q(x) is given by

$$Q(x) = \int_x^\infty e^{-v^2/2} dv / \sqrt{2\pi} \quad (16)$$

The expected value of I_{S1} due to right part of the S1 region is given as

$$E[I_{S1}]_r \approx \alpha \frac{N_u}{R} \int_{S1} L(r_{id}, r_{im}) f_s(r) E\left[10^{(\xi_{id} - \xi_{im})/10}\right] dr \quad (17)$$

The expected value of the intercellular interference from the right side of the regions S0 and S1 is

$$E[I]_r = E[I_{S0}]_r + E[I_{S1}]_r \quad (18)$$

Thus the expected value of the total interference from the left and right sides is given as

$$E[I]_{inter,t} = E[I]_r * (1 + Sll) \quad (19)$$

where Sll is the side lobe level of the directive antenna used in each sector.

The expected value of the total intercellular interference power is given as

$$E[P]_{inter} = S * E[I]_{inter,t} \tag{20}$$

The intracellular interference power is given by

$$I_{intra} = \alpha S\, N_u (1 + Sll) \tag{21}$$

The total interference-to-signal ratio is given by

$$\frac{I_t}{S} = \frac{I_{intra}}{S} + \frac{E[P]_{inter}}{S} \tag{22}$$

The uplink carrier-to-interference ratio (C/I)up is given as

$$(C/I)_{up} = \frac{S}{I_t} \tag{23}$$

and $(E_b / N_o)_{up}$ is given as

$$(E_b / N_0)_{up} = (C/I)_{up} * G_p \tag{24}$$

For a user with bit rate of 9.6 kbit/sec and a velocity of 120 km/h, the relation (E_b/N_o)up has to be 7 dB or more while for a bit rate of 144kbit/sec, the relation $(E_b/N_o)_{up}$ has to be 3 dB or more [5]. The expected number of users $E(N_u)$ is calculated from (24).

The variance of I_{S0} due to right part of S0 is given as

$$\text{var}[I_{S0}]_r = \frac{N_u}{R} \int_{S0} [L(r_{id}, r_{im})]^2 [f_s(r)]^2 \left\{ \alpha g(\frac{r_d}{r_m}) - \alpha^2 f^2(\frac{r_d}{r_m}) \right\} dr \tag{25}$$

where

$$g(\frac{r_d}{r_m}) = E\left[10^{(\xi_{id}-\xi_{im})/10} \phi(\xi_{id} - \xi_{im}, r_{id}/r_{im})\right]^2 \tag{26}$$

$$= e^{2(\beta\sigma)^2} Q\left[\sqrt{\sigma^2}\ln 10/5 - \frac{10}{\sqrt{\sigma^2}} \log_{10}\{1/L(r_{id}, r_{im})\}\right] \tag{27}$$

The variance of I_{S1} due to right part of S1 is given as

$$\text{var}[I_{S1}]_r \approx \frac{N_u}{R} \int_{S1} [L(r_{id}, r_{im})]^2 [f_s(r)]^2 . \left\{ \alpha E\left[(10^{(\xi_{id}-\xi_{im})/10})^2\right] - \alpha^2 E^2\left[10^{(\xi_{id}-\xi_{im})/10}\right] \right\} dr \tag{28}$$

Thus the total intercellular variance due to the total region S0 and S1 is given by

$$\text{var}[I]_{inter,t} = \{\text{var}[I_{S0}]_r + \text{var}[I_{S1}]\} * (1 + Sll) \tag{29}$$

The intracellular interference is calculated as

$$\text{var}[I]_{intra} = N_u\, \alpha\ (1-\alpha)(1 + Sll) \tag{30}$$

The total interference variance is given as

$$\text{var}[I]_t = \text{var}[I]_{inter,t} + \text{var}[I]_{intra} \tag{31}$$

Finally, the outage probability is calculated as

$$P_r = Q\left[\frac{E(I)_t\big|_{N_u=\bar{N}_u} - E(I)_t\big|_{N_u=N}}{\sqrt{\text{var}(I)_t\big|_{N_u=N}}}\right] \tag{32}$$

and the f factor is calculated as

$$f = \frac{Intercellular\ \ Interference}{Intracellular\ \ Interference} = \frac{E[P]_{inter}}{I_{intra}} \tag{33}$$

4 Numerical Results

In our estimation it has been assumed that the W-CDMA chip rate is 3.84 M chips/sec. For our calculations some reasonable figures are applied. The azimuth side lobe level is assumed to be –15 dB, the correlation coefficients C_{12} = 0.5, s_1=2, s_2 = 4, σ_1 =3 dB, σ_2 = 6 dB and R_b/R = 0.3. We assume that the accepted outage probability is 1% and that the capacity of the sectors is calculated at this probability.

Hereafter we study the case of voice users (9.6 k bits/sec). For the voice, the activity factor α is assumed to be 0.5.

First we assume the following spatial distribution of users.

- Case 1: $f_s(r) = 1$
- Case 2: $f_s(r) = 2*(1 - \frac{r}{R})$
- Case 3: $f_s(r) = 2*(\frac{r}{R})$

Fig. 4 shows the spatial distribution of the three above mentioned cases.

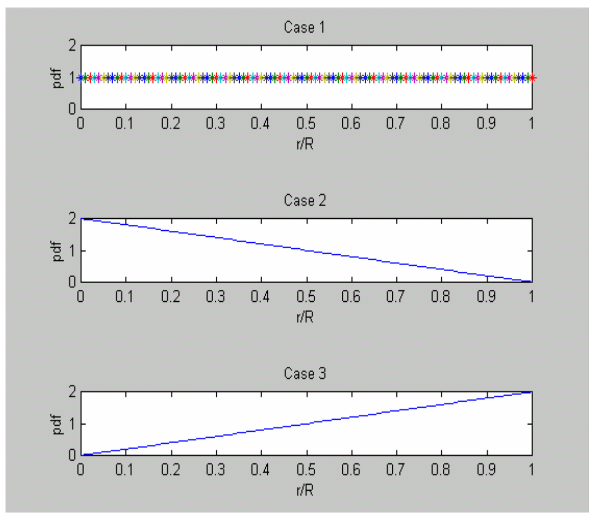

***Fig. 4*:** The pdf of the users for cases 1, 2 and 3.

Fig. 5 shows the outage probability of the sector for the up mentioned three distributions. For an outage probability of 1%, the capacity of the sector for the first, second and third case is 122 users, 133 users, 112 users respectively. Thus when the users density decreases moving away from the base station, the capacity of the sector increases due to the less total power transmitted by the interfering users.

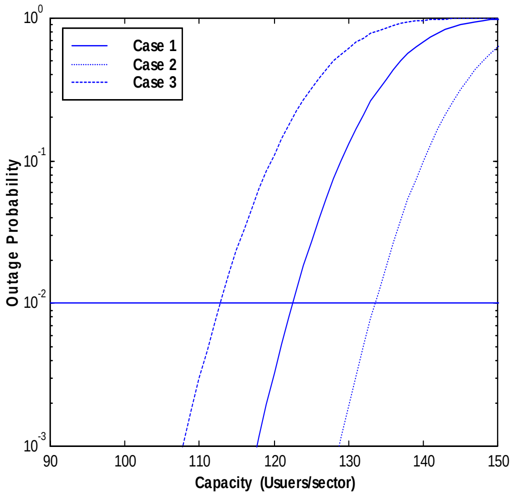

Fig. 5: The outage probability of the sector, case 1, 2 and 3 (voice users).

Next we consider the following distributions

- Case 4: $f_s(r) = \frac{4}{\pi} * \left[\frac{R^2 - r^2}{R^2}\right]^{0.5}$

- Case 5: $f_s(r) = \frac{4}{\pi} * \left(\left(\frac{2*r}{R}\right) - \left(\frac{r}{R}\right)^2\right)^{0.5}$

Fig. 6 shows the spatial distribution of the two above mentioned cases.

Fig. 7 shows the outage probability of the sector for the up mentioned two distributions. For an outage probability of 1%, the capacity of the sector for the fourth, and fifth case is 128 users, 117 users respectively. Thus also when the users density decreases moving away from the base station, the capacity of the sector increases due to the less total power transmitted by the interfering users.

Table 1 gives $E[I]_{inter,t}$, $\mathrm{var}[I]_{inter,t}$ and f for the three cases 1, 2 and 3 while Table 2 gives $E[I]_{inter,t}$, $\mathrm{var}[I]_{inter,t}$ and f for the two cases (4 and 5).

Table 1 $E[I]_{inter,t}$, $\mathrm{var}[I]_{inter,t}$ and f for the three cases 1,2 and 3.

Case	$E[I]_{inter,t}$	$\mathrm{var}[I]_{inter,t}$	f
1	0.0675 N_u	0.0261 N_u	0.1308
2	0.0239 N_u	0.0035 N_u	0.0406
3	0.1110 N_u	0.0768 N_u	0.2153

Table 2 $E[I]_{inter,t}$, $\mathrm{var}[I]_{inter,t}$ and f for the three cases 4 and 5.

Case	$E[I]_{inter,t}$	$\mathrm{var}[I]_{inter,t}$	f
4	0.0444 N_u	0.0111 N_u	0.0861
5	0.0837 N_u	0.0408 N_u	0.1623

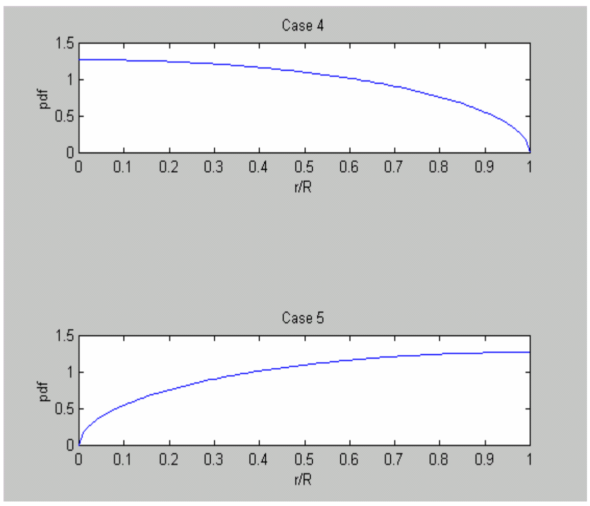

Fig. 6: The pdf of the users for cases 4 and 5.

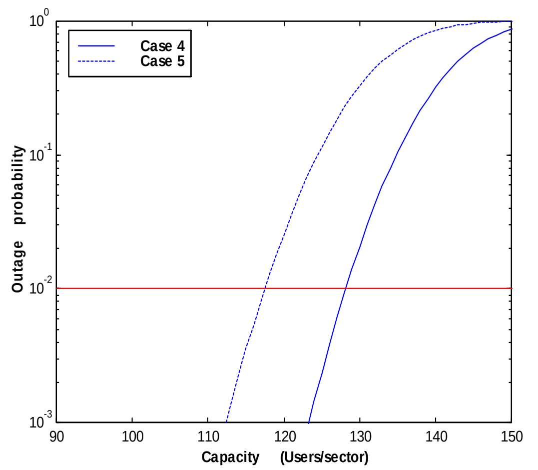

Fig. 7: The outage probability of the sector, case 4 and 5 (voice users).

Next we study the case of data users only with a bit rate of 144 kbit/sec.

Fig. 8 shows the outage probability of the sector for the first three distributions. For an outage probability of 1%, the capacity of the sector for the first, second and third case is 10 users, 12 users and 8 data users respectively.

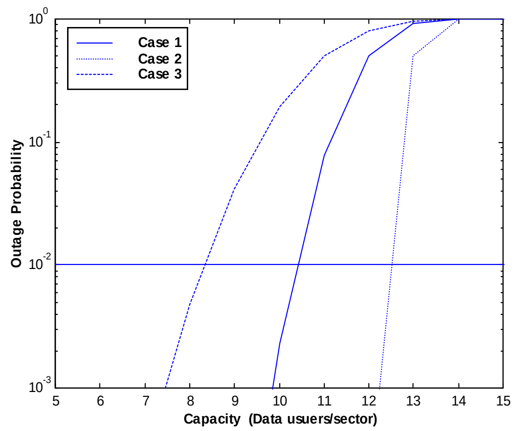

***Fig. 8*:** The outage probability of the sector, case 1, 2 and 3 (data users).

Fig. 9 shows the outage probability of the sector for the distributions. For an outage probability of 1%, the capacity of the sector for the fourth, and fifth case is 10 users and 8 data users respectively.

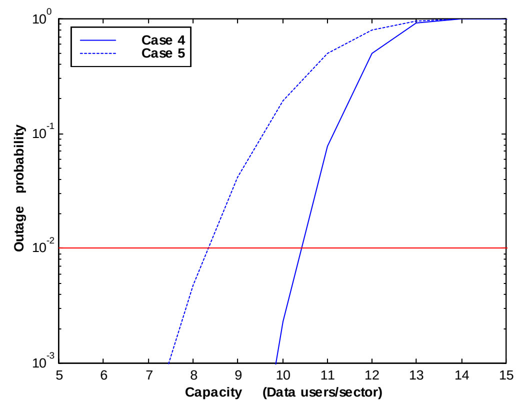

***Fig. 9*:** The outage probability of the sector, case 4 and 5 (data users).

5 Conclusion

We have presented a model that give the capacity and interference statistics of a W-CDMA rural highway cigar-shaped microcells. The capacity of the sector is studied for a general two-slope propagation model with lognormal shadowing for different spatial distribution of users. When the users density decreases moving away from the base station, the capacity of the sector increases due to the less total power transmitted by the interfering users.

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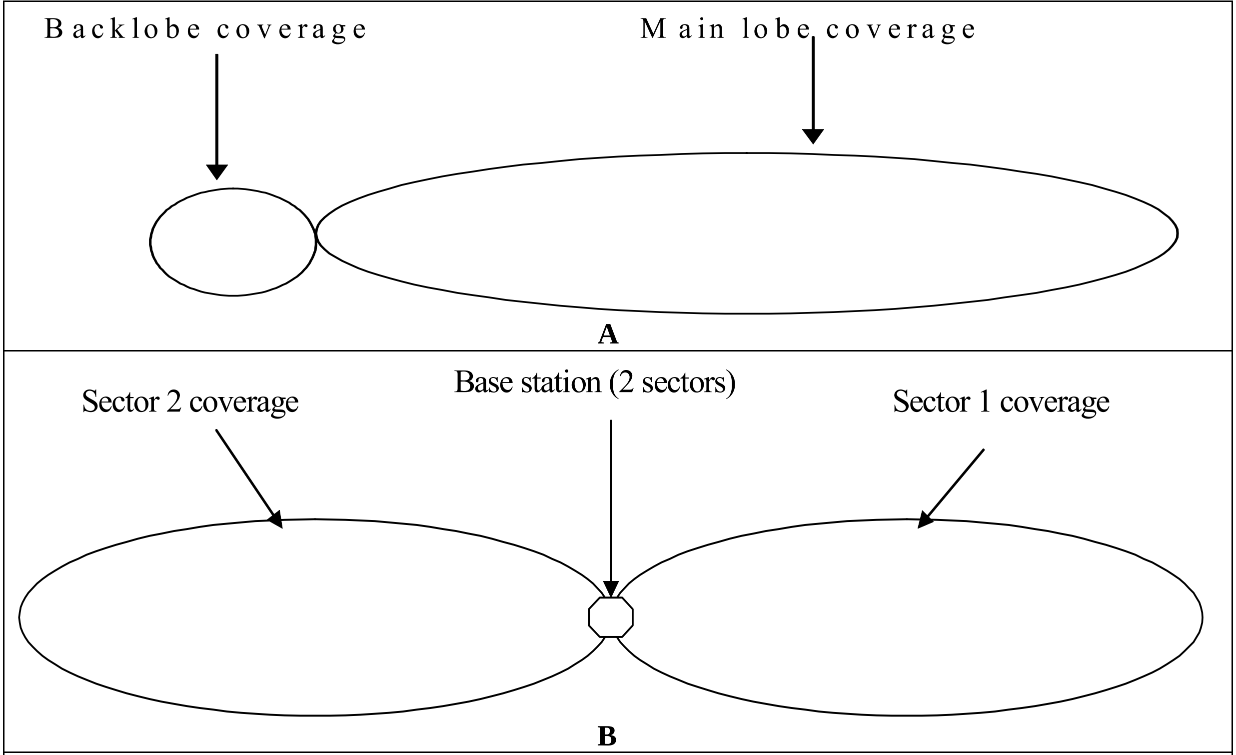

***Fig. 1*:** The sector and cell coverage**.**
A- The sector coverage. B- The cell coverage.

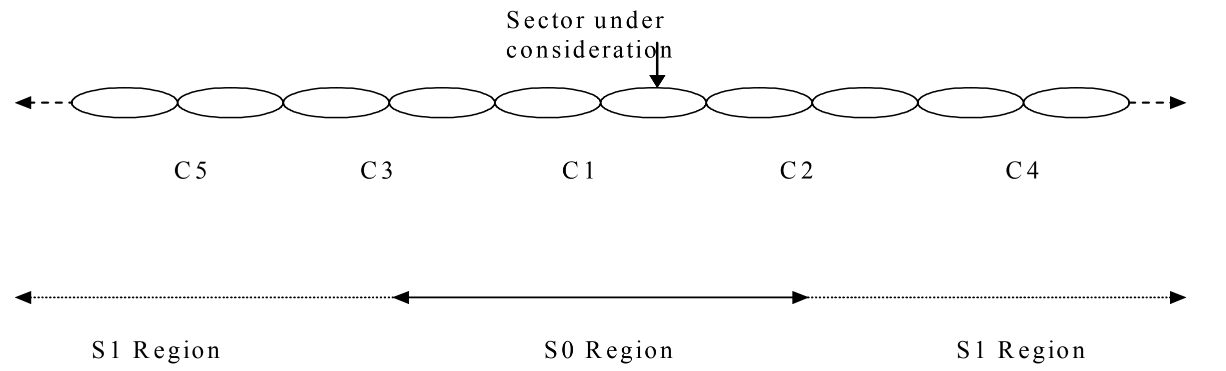

Fig. 2: The 5 microcells model.

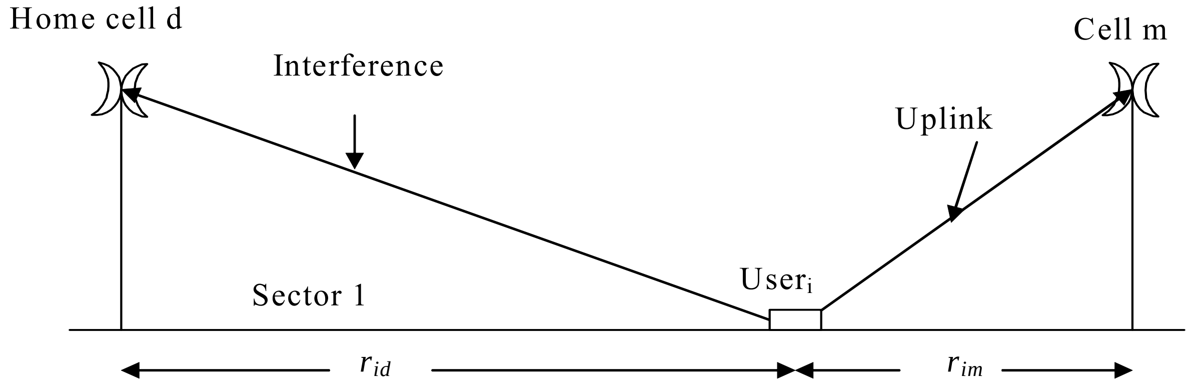

Fig. 3: Schematic diagram of base stations and mobiles for highway microcells.