W-CDMA Uplink Capacity and Interference Statistics of a Long Tunnel Cigar-Shaped Microcells

Bazil Taha-Ahmed, Miguel Calvo-Ramón, and Leandro de Haro-Ariet

Abstract: **The uplink capacity and the interference statistics of the sectors of the cigar-shaped W-CDMA microcells are studied. A model of 9 base station, assumed to be in a long tunnel, is used for the uplink analysis. The capacity and the interference statistics of the microcells are studied for different sector ranges, different propagation exponents, different antenna sidelobe levels, and different bend losses.**

Index Terms: **Shadowing, uplink capacity, W-CDMA.**

I. INTRODUCTION

It is well known that CDMA is characterized as being interference-limited, so reducing the interference results in increasing the capacity. Three factors are mainly used to reduce the interference: Power control (PC), which is essential in the uplink, voice activity monitoring, and sectorization. It is well known that urban microcell shapes may approximately follow the street pattern and can be modeled as cigar-shaped microcells [1]. This type of microcells also appears in tunnels.

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

- the number of the cigar-shaped sectors per base station is two and a directive antenna is used in each sector,
- the microcell has typically a range of about one kilometer,
- the user in the tunnel can reach a speed up to 120 km/h.

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

Min *et al.* studied the performance of the CDMA highway microcells [2] but the variance of the interference signal was not given. Hashem *et al.* studied the capacity and the interference statistics for hexagonal cells using a propagation exponent of 4.0 [3]. Ahmed *et al.* studied the capacity and interference statistics of highways cigar-shaped microcells using a standard two-slope propagation model [4]. In [5], the received signal within a large tunnels are measured at frequencies of 900 and 1800 MHz. It has been found that the received signal can be estimated using a two-slope propagation model with a lognormal shadowing factor. The received signal within a tunnel is also measured in [6] where it has been also found that the two-slope propagation model is applicable.

In this work, we introduce a model for cigar-shaped microcells in tunnel zones with general propagation exponent using a two-slope model with shadowing and bend loss and then investigate the sector capacity and the interference statistics of the uplink.

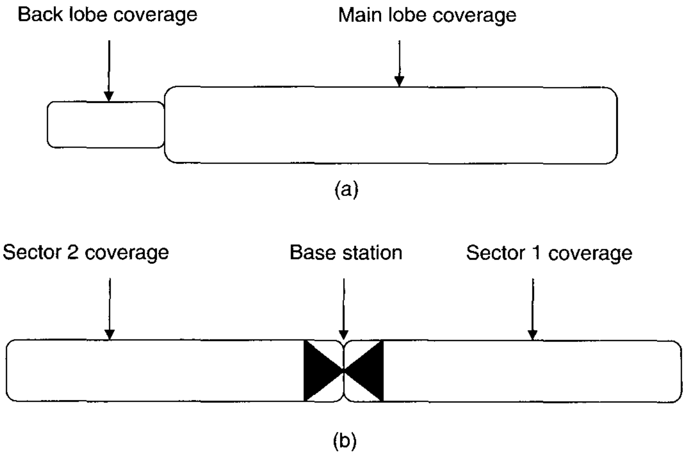

Fig. 1. The sector and microcell coverage: (a) The sector coverage, (b) the microcell coverage.

The paper has been organized as follows: In Section II, the propagation model is given. Section III explains the method to obtain the capacity and the interference statistics for the uplink. Numerical results are presented in Section IV. Finally, conclusions are drawn in Section V.

II. THE PROPAGATION MODEL

The propagation model in the tunnels can be approximated by a model with two or more slopes as shown in [5] and [6]. The exponent of the propagation at a distance (dist) from the source is assumed to be s_1 till the break point (R_b) and then it converts to s_2. In our calculations, we improve the two-slope propagation model including a bend loss and a lognormal shadowing factors. The path losses are then given as

$$L_p(\mathrm{dB}) = K + L_b + 10 s_1 \log_{10}\left(\frac{r}{R_b}\right) + \xi_1, \text{if } r \leq R_b, \quad (1)$$

$$L_p(\mathrm{dB}) = K + L_b + 10 s_2 \log_{10}\left(\frac{r}{R_b}\right) + \xi_2, \text{if } r > R_b, \quad (2)$$

where

- K is a constant,
- L_b is the tunnel bend loss between the signal source and the point of observation if applicable,
- ξ_1 and ξ_2 are Gaussian random variables of zero-mean and a standard deviation of σ_1 and σ_2, respectively,
- r is the distance between the base station of the microcell C and the mobile,
- R_b is given in [6] by:

Manuscript received July 2, 2003; approved for publication by K. B. Lee, September 20, 2003.

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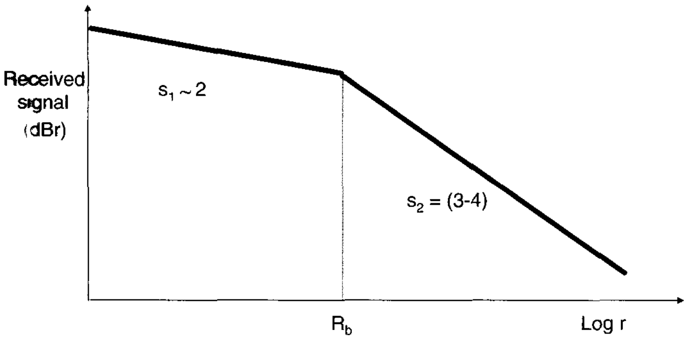

Fig. 2. The received signal power profile.

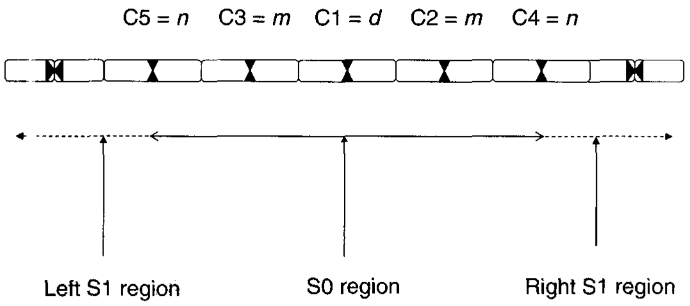

Fig. 3. The microcells model (7 out of 9 base stations are shown).

$$R_b \approx \min\left(\frac{a^2}{\lambda}, \frac{b^2}{\lambda}\right), \tag{3}$$

where a is the tunnel width, b is the tunnel height, and λ is the wavelength.

Typical values of s_1 and s_2 provided in [5] and [6] are $s_1 = 1.75 \sim 2.25$ and $s_2 < 2$ for a short tunnel or $s_2 = 3.0 \sim 4.0$ for a long tunnel.

Fig. 2 depicts the general shape of the propagation loss profile for a tunnel microcell.

III. UPLINK ANALYSIS

The configuration of the multi-cells model is shown in Fig. 3. In the uplink, each cell controls the transmitted power of its users. We assume that the power control is perfect. 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 base station of the reference cell d, as shown in Fig. 4, then the normalized interference signal $L(r_{id}, r_{im})$ due only to the distance and bends losses is given as

- If (r_{id} and $r_{im} \leq R_b$), then $L(r_{id}, r_{im})$ is

$$L(r_{id}, r_{im}) = (r_{im}^{s_1} L_{bim})/(r_{id}^{s_1} L_{bid}). \tag{4}$$

- If ($r_{id} > R_b$ and $r_{im} \leq R_b$), then $L(r_{id}, r_{im})$ is given as

$$L(r_{id}, r_{im}) = (r_{im}^{s_1} L_{bim})/(R_b^{(s_1 - s_2)} r_{id}^{s_2} L_{bid}). \tag{5}$$

- If ($r_{id} \leq R_b$ and $r_{im} > R_b$), then $L(r_{id}, r_{im})$ is given as

$$L(r_{id}, r_{im}) = (R_b^{(s_1 - s_2)} r_{im}^{s_2} L_{bim})/(r_{id}^{s_1} L_{bid}). \tag{6}$$

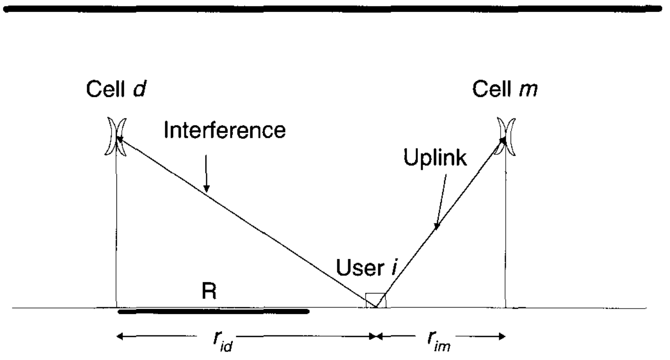

Fig. 4. Schematic diagram of base stations and mobiles for a tunnel microcells.

- Finally, if (r_{id} and $r_{im} > R_b$), then $L(r_{id}, r_{im})$ is given as

$$L(r_{id}, r_{im}) = (r_{im}^{s_2} L_{bim})/(r_{id}^{s_2} L_{bid}), \tag{7}$$

where L_{bij} is the tunnel bend losses between the user i and the base station j if applicable. Equation (4) is applied only in some possible situations, when the sector range R is less than R_b (impractical case), while (5), (6), and (7) are applied for the practical cases when $R \geq R_b$.

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

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

where ξ_{id} and ξ_{im} are given as

- In case of (r_{id} and $r_{im} \leq R_b$), then $\xi_{id} = \xi_1$ and $\xi_{im} = \xi_1$ (impractical case).
- If $r_{id} > R_b$ and $r_{im} \leq R_b$, then $\xi_{id} = \xi_2$ and $\xi_{im} = \xi_1$ (intercellular interference case highly probable).
- When $r_{id} \leq R_b$ and $r_{im} > R_b$, then $\xi_{id} = \xi_1$ and $\xi_{im} = \xi_2$ (intercellular interference case possible but with a very low probability).
- In case of (r_{id} and $r_{im} > R_b$), then $\xi_{id} = \xi_2$ and $\xi_{im} = \xi_2$.

We divide the total intercellular interference ($I_{inter,t}$) in the interference from users in the near interference region S0 (I_{S0}) and the interference from users in the far interference regions S1 (I_{S1}), where the regions are indicated in Fig. 3. For the 9 base stations model, the S0 region consists of 8 sectors while the S1 region consists of 10 sectors. We will find the interference at the right sector of the central base station C1 assuming it to be the reference microcell d. We will assume that users in the region S0 will communicate with the best of the two nearest microcells. In the S1 region, we will assume that the server base station is the closest one [3].

Let the desired signal level be S. Then, the interference from an active user communicating with the home cell will be also S. A user i in the S0 region will not communicate with the reference cell d but rather with base station m, if $\phi(\xi_{id} - \xi_{im}, r_{id}/r_{im}) = 1$, where

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

It is assumed that the number of users in each sector is N_u and that the activity factor is α. For a uniform distribution the density of users in each sector is $\rho = N_u/R$ users per unit length.

Then the expected value of I_{S0} due to the users between base station 1 (Bs1) and base station 2 (Bs2) is given as

$$E[I_{\mathrm{Bs1,Bs2}}] = \alpha\rho \int_0^{2R} L(r_{id}, r_{im}) f\left(\frac{r_{id}}{r_{im}}\right) dr, \qquad (10)$$

where

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

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

being $\beta = \ln 10/10$. Now the general value of σ^2 is given as

- When $r_{id} \le R_b$ and $r_{im} \le R_b$, then $\sigma_{id} = \sigma_1$ and $\sigma_{im} = \sigma_1$ so

  $$\sigma^2 = 2(1 - C_{dm})\sigma^2, \qquad (13)$$

  where C_{dm} is the correlation coefficient between the random variables ξ_{id} and ξ_{im}.
- If $r_{id} \le R_b$ and $r_{im} > R_b$ or $r_{id} > R_b$ and $r_{im} \le R_b$, then the value of σ^2 is given by

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

- When $r_{id} > R_b$ and $r_{im} > R_b$, then $\sigma_{id} = \sigma_2$ and $\sigma_{im} = \sigma_2$, so

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

On the other hand, $Q(x)$ is given by

$$Q(x) = \int_x^{\infty} e^{-\nu^2/2} d\nu/\sqrt{2\pi}. \qquad (16)$$

The expected value of I_{S0} due to the users between Bs2 and Bs4 is given by

$$E[I_{\mathrm{Bs2,Bs4}}] = \alpha\rho \int_{2R}^{4R} \left[\left\{A(r_o, r_n) f\left(\frac{r_m}{r_o}\right)\right\} + \left\{A(r_o, r_m) f\left(\frac{r_n}{r_m}\right)\right\}\right] dr, \qquad (17)$$

where

$$A(r_o, r_n) = L(r_o, r_n) E[10^{(\xi_o-\xi_n)/10}] = e^{(\beta\sigma_{on})^2/2} L(r_o, r_n), \qquad (18)$$

and $r_o = r_{id}, r_m = r_{im}$, and $r_n = r_{in}$

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

$$E[I_{\mathrm{S1}}]_r \approx \alpha\rho \int_{\mathrm{S1}r} L(r_{id}, r_{im}) E\left[10^{(\xi_{id}-\xi_{im})/10}\right] dr. \qquad (19)$$

For the left part of S0, the expected value of I_{S0} due to the users between Bs1 and Bs3 is given by

$$E[I_{\mathrm{Bs1,Bs3}}] = \alpha\rho Sll \int_0^{2R} L(r_{id}, r_{im}) f\left(\frac{r_{id}}{r_{im}}\right) dr, \qquad (20)$$

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

The expected value of I_{S0} due to the users between Bs3 and Bs5 is given by

$$E[I_{\mathrm{Bs3,Bs5}}] = \alpha\rho Sll \int_{2R}^{4R} \left[\left\{A(r_o, r_n) f\left(\frac{r_m}{r_o}\right)\right\} + \left\{A(r_o, r_m) f\left(\frac{r_n}{r_m}\right)\right\}\right] dr. \qquad (21)$$

The expected value of I_{S1} due to the left part of S1 is given by

$$E[I_{\mathrm{S1}}]_l \approx \alpha\rho Sll \int_{\mathrm{S1}l} L(r_{id}, r_{im}) E\left[10^{(\xi_{id}-\xi_{im})/10}\right] dr. \qquad (22)$$

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

$$E[I]_{inter,t} = E[I_{\mathrm{S0}}] + E[I_{\mathrm{S1}}]. \qquad (23)$$

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

$$E[P]_{inter} = S \times E[I]_{inter,t}. \qquad (24)$$

The expected value of the intracellular interference power is given by

$$E[P]_{intra} = \alpha S N_u (1 + Sll). \qquad (25)$$

The total interference-to-signal ratio is given by

$$\frac{I_t}{S} = \frac{E[P]_{intra}}{S} + \frac{E[P]_{inter}}{S}. \qquad (26)$$

Finally, the uplink carrier-to-interference ratio $(C/I)_{up}$ is given as

$$(C/I)_{up} = \frac{S}{I_t}, \qquad (27)$$

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

$$(E_b/N_o)_{up} = (C/I)_{up} \times G_p. \qquad (28)$$

The expected number of users $\bar{N}_u$ is calculated from (24), (25), (27), and (28).

Let us now calculate the second order statistics. The variance of I_{S0} due to the users between Bs1 and Bs2 is given as

$$\mathrm{var}[I_{\mathrm{Bs1}}, I_{\mathrm{Bs2}}] = \rho \int_0^{2R} [L(r_{id}, r_{im})]^2 \times \left\{\alpha g\left(\frac{r_d}{r_m}\right) - \alpha^2 f^2\left(\frac{r_d}{r_m}\right)\right\} dr, \qquad (29)$$

where

$$g\left(\frac{r_d}{r_m}\right) = E\left[10^{(\xi_{id}-\xi_{im})/10}\phi(\xi_{id}-\xi_{im}, r_{id}/r_{im})\right]^2 \qquad (30)$$

$$= e^{2(\beta\sigma)^2} Q\left[\sqrt{\sigma^2}\frac{\ln 10}{5} - \frac{10}{\sqrt{\sigma^2}}\log_{10} 1/L(r_{id}, r_{im})\right]. \qquad (31)$$

The variance of I_{S0} due to the users between Bs2 and Bs4 is given as

$$\begin{aligned}\mathrm{var}[I_{\mathrm{Bs2}}, I_{\mathrm{Bs4}}] &= \rho \int_{2R}^{4R} [B(r_o, r_n)]^2 \left\{\alpha g\left(\frac{r_m}{r_n}\right) - \alpha^2 f^2\left(\frac{r_m}{r_n}\right)\right\} dr \\ &+ \rho \int_{2R}^{4R} [B(r_o, r_m)]^2 \left\{\alpha g\left(\frac{r_n}{r_m}\right) - \alpha^2 f^2\left(\frac{r_n}{r_m}\right)\right\} dr, \quad (32)\end{aligned}$$

where

$$\begin{aligned}B(r_o, r_n) &= E\left[10^{(\xi_o - \xi_n)/10}\right]^2 [L(r_o, r_n)]^2 \\ &= e^{2(\beta\sigma_{on})^2}[L(r_o, r_n)]^2. \quad (33)\end{aligned}$$

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

$$\begin{aligned}\mathrm{var}[I_{S1}]_r &\approx \rho \int_{S1r} [L(r_{id}, r_{im})]^2 \\ &\times \left\{\alpha E\left[(10^{(\xi_{id} - \xi_{im})/10})^2\right] - \alpha^2 E^2\left[10^{(\xi_{id} - \xi_{im})/10}\right]\right\} dr. \quad (34)\end{aligned}$$

The variance of I_{S0} due to the users between Bs1 and Bs3

$$\begin{aligned}\mathrm{var}[I_{\mathrm{Bs1}}, I_{\mathrm{Bs3}}] &= \rho Sll \int_0^{2R} [L(r_{id}, r_{im})]^2 \\ &\times \left\{\alpha g\left(\frac{r_d}{r_m}\right) - \alpha^2 f^2\left(\frac{r_d}{r_m}\right)\right\} dr. \quad (35)\end{aligned}$$

The variance of I_{S0} due to the users between Bs3 and Bs5 is given as

$$\begin{aligned}\mathrm{var}[I_{\mathrm{Bs3}}, I_{\mathrm{Bs5}}] &= \rho Sll \int_{2R}^{4R} [B(r_o, r_n)]^2 \left\{\alpha g\left(\frac{r_m}{r_n}\right) - \alpha^2 f^2\left(\frac{r_m}{r_n}\right)\right\} dr \\ &- \rho Sll \int_{2R}^{4R} [B(r_o, r_m)]^2 \left\{\alpha g\left(\frac{r_n}{r_m}\right) - \alpha^2 f^2\left(\frac{r_n}{r_m}\right)\right\} dr. \quad (36)\end{aligned}$$

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

$$\begin{aligned}\mathrm{var}[I_{S1}]_l &\approx \rho Sll \int_{S1l} [L(r_{id}, r_{im})]^2 \\ &\times \left\{\alpha E\left[(10^{(\xi_{id} - \xi_{im})/10})^2\right] - \alpha^2 E^2\left[10^{(\xi_{id} - \xi_{im})/10}\right]\right\} dr. \quad (37)\end{aligned}$$

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

$$\mathrm{var}[I]_t = \mathrm{var}(I_{S0}) + \mathrm{var}(I_{S1}). \quad (38)$$

Finally, from the obtained first and second order statistics, the outage probability for a given number of users N is calculated as

$$P_r = Q\left[\frac{E(I)_t|_{N_u = \bar{N}_u} - E(I)_t|_{N_u = N}}{\sqrt{\mathrm{var}(I)_t|_{N_u = N}}}\right]. \quad (39)$$

From the equation the user capacity for a given outage probability P_r is obtained.

We can also obtain the F factor as

$$F = \frac{Intercellular\ Interference}{Intracellular\ Interference} = \frac{E[P]_{inter}}{E[P]_{intra}}. \quad (40)$$

Table 1. Values of $E[I]_{inter,t}$, $\mathrm{var}[I]_t$, and the F factor for different conditions.

Conditions	$E[I]_{inter,t}$	$\mathrm{var}[I]_t$	F
$s_1 = 2$, $s_2 = 4.0$, $\sigma_1 = 1$ dB, $\sigma_2 = 2$ dB	0.0676 N_u	0.0216 N_u	0.1310
$s_1 = 2$, $s_2 = 3.0$, $\sigma_1 = 1$ dB, $\sigma_2 = 2$ dB	0.1029 N_u	0.0289 N_u	0.1995
$s_1 = 2$, $s_2 = 3.5$, $\sigma_1 = 2$ dB, $\sigma_2 = 2$ dB	0.0812 N_u	0.0247 N_u	0.1575

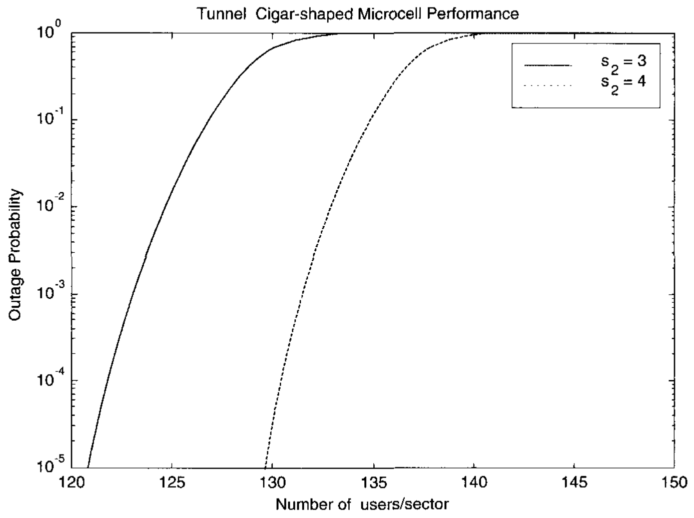

Fig. 5. The outage probability of the sector (voice users).

IV. NUMERICAL RESULTS

The 9 microcells model is used and some reasonable figures are applied in our calculations. We assume the W-CDMA chip rate of 3.84 Mchip/sec, an antenna azimuth sidelobe level of -15 dB, correlation coefficient is $C_{dm} = 0.5$ and the other parameters are $s_1 = 2$, $s_2 = 4$, $\sigma_1 = 1$ dB, $\sigma_2 = 2$ dB, $R_b = 300$ m, and $R = 1000$ m unless other values are mentioned. We assume that the accepted outage probability is 1% and that the capacity of the sectors is calculated at this probability.

Table 1 gives the value of $E[I]_{inter,t}$, $\mathrm{var}[I]_t$, and the F factor for different conditions assuming $\alpha = 0.5$.

We study first the case of voice users only (9.6 kbits/sec) assuming that the activity factor α is 0.5. For a user with a bit rate of 9.6 kbit/sec and a chip rate of 3.84 Mchip/sec ($G_p = 400$), the $(E_b/N_o)_{up}$ ratio has to be 7 dB or more [7].

Fig. 5 shows the outage probability of the sector for different values of s_2. As it can be noticed, the sector capacity is of 124 voice users for $s_2 = 3$ and of 133 voice users for $s_2 = 4$.

Fig. 6 shows the effect of the sector range for two values of s_2. We can notice that the capacity of the sector is constant for ranges R higher than 450 m. In reality, the sector capacity for a medium length tunnel is the capacity shown by the curve corresponding to $s_2 = 3$, while for a large tunnel the sector capacity is given by the curve corresponding to $s_2 = 4$.

Fig. 7 shows the effect of the sidelobe level on the sector capacity. Reducing the sidelobe level will increase the capacity of the sector. An antenna with a sidelobe level of -15 dB or lower

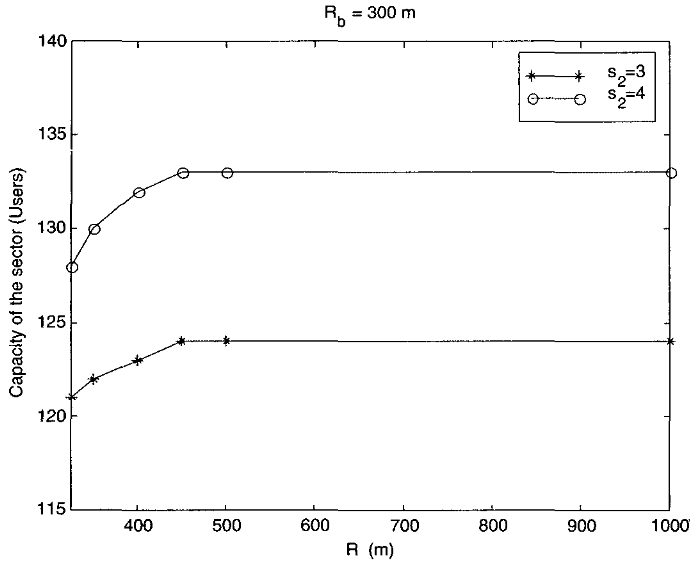

Fig. 6. Sector performance for different sector range (R).

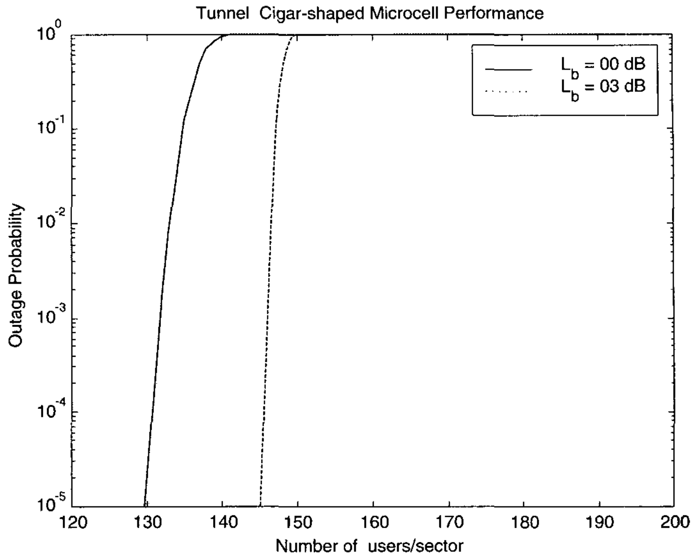

Fig. 8. Effect of the tunnel bends loss.

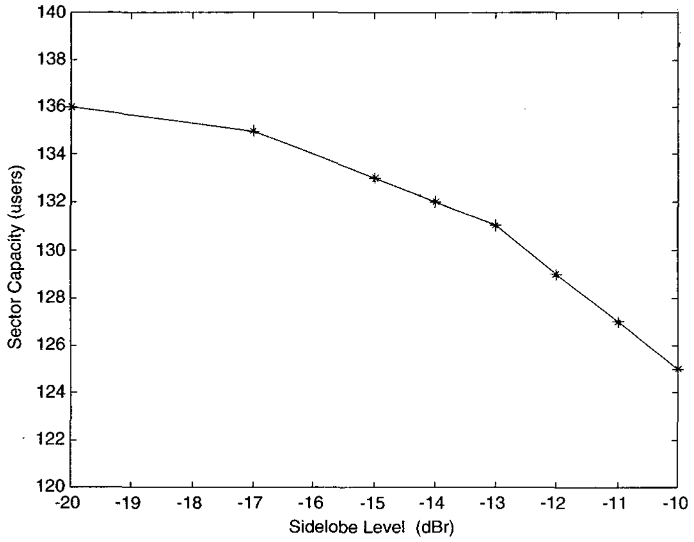

Fig. 7. Effect of the antenna side lobe level on the sector capacity.

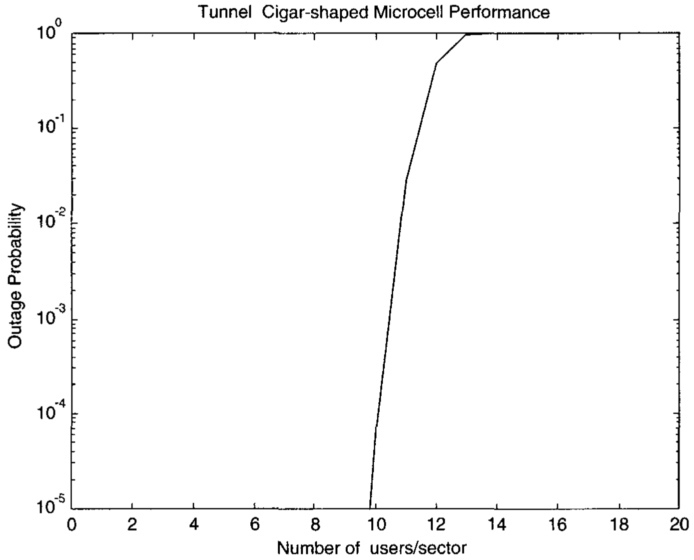

Fig. 9. The outage probability of the sector (data users).

is a good choice.

To study the effect of the tunnel bend loss, we assume that there is a bend between microcells C1–C2. From Fig. 8 we can notice that the sector capacity is higher for higher bend losses.

Next we study the case of data users only (144 kbits/sec) assuming that $G_p = 26.6$, $\alpha = 1$, and $(E_b/N_o)_{req} = 2.75$ dB [7]. Fig. 9 shows the microcell performance. It can be noticed that in this case the sector capacity in this case is of 10 data users.

V. CONCLUSIONS

We have presented a model that gives the interference statistics and capacity of W-CDMA tunnel cigar-shaped microcells. The effect of the sector range and the side lobe level of the directive antenna has been studied. The capacity of the sector has been found for a general two-slope propagation model with lognormal shadowing and bends losses.

It has been noticed that

- For $R_b = 300$ m, the sector capacity is constant when the microcell range $R \geq 450$ m.
- With an antenna sidelobe level of -15 dB, the capacity is quasi the maximum possible.
- Increasing s_1 and s_2 will increase the sector capacity.
- The sector capacity increases with the bend losses.
- Increasing σ_1 and σ_2 will reduce the sector capacity.

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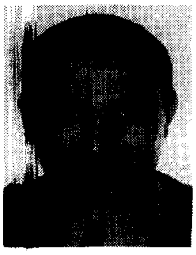

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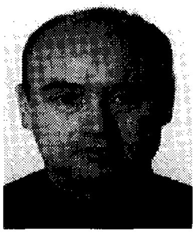

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