WCDMA downlink capacity of cigar-shaped microcells using soft hand-over with SIR-based power control for over-ground train service

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Abstract

In this paper, the downlink sector capacity of a cigar-shaped microcells using wideband code-division multiple-access (WCDMA) with soft hand-over (SHO) mode is analyzed. The two-slope propagation loss with log-normal shadowing is used in the analysis where a model of eight cigar-shaped microcells is utilized to calculate the downlink sector capacity. The performance of the downlink is studied for different sector radii, standard deviations of the shadowing and propagation exponents. It is found that, for a sector range higher than 940 m, increasing the sector range will reduce the downlink sector capacity. Also it is found that increasing the value of the propagation parameters will reduce the downlink sector capacity. In many cases, the downlink sector capacity will be code limited since the theoretical downlink sector capacity is higher than the number of codes assigned to each sector. The high theoretical downlink sector capacity is due to the low value (0.06–0.1) of the WCDMA orthogonality factor of rural zone microcells.

1. Introduction

CDMA cellular systems including WCDMA for UMTS employs an elaborated hand-over method in which a mobile station is simultaneously connected to several base stations. This method of hand-over is called soft hand-over (SHO). CDMA techniques make possible to maintain an old connection while adding a new one (make before break); however, additional resources (codes) from several base stations are required   In downlink, this is achieved by multiple site transmission, which implies that several base stations transmit the same signal to a certain mobile station (MS).

The capacity in WCDMA systems is commonly limited by interference. In order to reduce the interference level in downlink, power control techniques are proposed. Using a power control algorithm that is based on signal to interference ratio (SIR) in downlink, the power that is transmitted to the MS is adjusted to achieve the energy-per-bit to noise power spectral density ratio (E_b/N_o) requirements Therefore, more capacity can be achieved by the system if SIR-based power control techniques are used since system interferences are reduced

Two issues must be taken into account in SHO performance evaluation, namely

- The active set where usual number of the involved base stations is 2–3.
- The SHO margin (M_{SH}) with a typical value of 3–6 dB.

The active set is the group of base stations to which a user terminal is connected. M_{SH} is the maximum allowed difference (measured in decibels) between the power that is received from the best server base stations and the power received from a candidate base station that is included in the active set of the user terminal

In   it has been shown that SHO used in the uplink of the Mobile Telecommunications System (UMTS), reduces

interference; therefore, SIR is increased. This effect is modelled as a SHO gain and can be used to offer higher quality services to users or to allocate a higher number of users in a cell (higher capacity). These analyses have demonstrated that capacity in uplink is always increased with M_{SH}. In Mehailescu et al. analyzed the downlink SHO performance in terms of E_b/N_o, assuming two candidate base stations in the active set. Connection probabilities were calculated to determine the connection situation of each mobile station location. SIR as a function of the distance to the interference base station has been given for different scenarios.

The effect of SHO on power-controlled downlink systems has been studied   Yang et al. studied the effect of cross-correlated shadowing on the SIR using hard hand-over and SHO algorithms. It has been demonstrated that the constant cross-correlation model overestimates the SIR in WCDMA systems. In   Zhang et al. obtained the downlink capacity gain for SHO CDMA systems by dividing a hexagonal layout in defined connection zones. In   the performance of hard and SHO algorithms in a downlink WCDMA system using a probabilistic method has been studied. The mean active set number (the average number of base stations in the active set) is calculated in a mobility scenario where the environment model is limited to the path between two base stations.

The uplink capacity of the cigar-shaped microcells in highways has been studied   the uplink capacity of WCDMA system used to service trains has been investigated. Downlink capacity has been studied for the case of street microcells assuming that omnidirectional antennas are used in the base stations without the use of the power control technique

We have to mention that, power control is efficient in increasing the downlink capacity if users are uniformly distributed within the cell. This means that power control is used to mitigate the near-far problem. Thus, for a cell with all users near to the cell border, power control is not efficient since all users are affected by quasi the same interference power.

It is well known that urban microcell shapes may approximately follow the street pattern and that it is possible to have cigar-shaped microcells. Cigar-shaped microcells are used to have coverage in tunnels, groove-ways, highways and streets.

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

• The number of directional sectors of the cigar-shaped microcell is two and a directional antenna is used in each sector.
• The microcell sector has typically a range of 1 km.
• User speed can reach 120 km/h.

The main contribution of this work is the calculation of the WCDMA downlink capacity of cigar-shaped microcells using soft hand-over with SIR-based power control when all users exist within a limited space of the microcell (only within train) a special case not studied before for which power control is not efficient.

The rest of the paper has been organized as follows. In Section 2, the propagation model is given. In Section 3, the downlink interference is analyzed. Numerical results are presented in Section 4. Finally, in Section 5 conclusions are drawn.

2. Propagation model

it has been found that the two-slope propagation model is the most appropriate model of propagation to be used in the analysis of the WCDMA capacity of microcells in rural zones. In the first slope region of the model, waves propagate in the quasi free space mode ($s_1 \approx 2$) while in the second slope region the propagation exponent s_2 is higher with value that can reach 5. Change of slope from s_1 to s_2 happens at the break point.

For the above mentioned reason, the two-slope propagation model with log-normal shadowing will be used in the analysis of the downlink. In this way the path loss is given by:

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

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

where L_g is the car's window penetration loss, r is the disance between the microcell base station and the mobile, L_b (propagation loss at the break point) is given as:

$$L_b \text{ (dB)} = 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10_{s_1}\log_{10}(R_b) \quad (3)$$

The break-point distance R_b is given by Tsai and Chang [12]:

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

where

• h_b is the base station antenna height,
• h_m is the mobile antenna height,
• λ is the wavelength and
• ξ_1 and ξ_2 are Gaussian random variables of zero-mean and a standard deviation of σ_1 and σ_2, respectively, representing the shadowing effect (path loss deviation from the average value).

Typical values of the above mentioned parameters are:

• $s_1 = 2.00–2.25$,
• $s_2 = 4.0–4.5$,
• $\sigma_1 = 2.0–3.0$ dB,
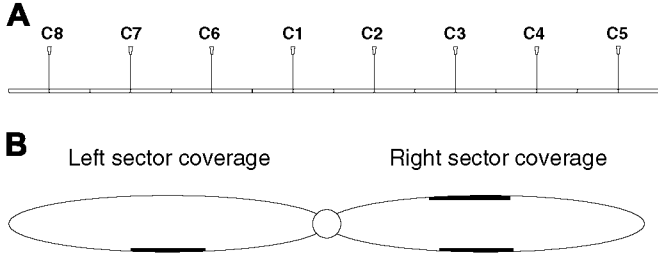• $\sigma_2 = 4.0–6.0$ dB,
• $R_b = 300$ m,
• $L_g = 3$ dB.

Fig. 1. The eight microcells model and the microcell coverage. (A) The eight microcells model. (B) The microcell coverage.

3. Downlink interference analysis

Fig. 1 shows the configuration of the eight microcells model and the coverage of each microcell. The microcells are assumed to be are regularly spaced every $2R$. Thus, the sector range is R. The downlink sector capacity will be studied considering the right sector of the microcell C1. If the user i is at a distance r_{io} from the microcell base station under study (C1) and at a distance r_{id} from the interfering microcell base station d as shown in Fig. 2, then the ratio of the interference signal ratio $L(r_{id}, r_{io})$ due to the distance only is given as:

* If (r_{id} and $r_{io} \leqslant R_b$) then $L(r_{id}, r_{io})$ is:

$$L(r_{id}, r_{io}) = (r_{io}/r_{id})^{s_1} \qquad (5)$$

* If $r_{id} > R_b$ and $r_{io} \leqslant R_b$ then $L(r_{id}, r_{io})$ is given as:

$$L(r_{id}, r_{io}) = r_{io}^{s_1}/\{R_b^{s_1}(r_{id}/R_b)^{s_2}\} \qquad (6)$$

* If (r_{id} and $r_{io} > R_b$) then $L(r_{id}, r_{io})$ is:

$$L(r_{id}, r_{io}) = (r_{io}, r_{id})^{s_2} \qquad (7)$$

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

$$L_{shd}(r_{id}, r_{io}) = 10^{(\xi_{id}-\xi_{io})/10}L(r_{id}, r_{io}) \qquad (8)$$

ξ_{id} and ξ_{im} are given as

* In case of (r_{id} and $r_{io} \leqslant R_b$) then $\xi_{id} = \xi_1$ and $\xi_{io} = \xi_1$.
* If $r_{id} > R_b$ and $r_{io} \leqslant R_b$ then $\xi_{id} = \xi_2$ and $\xi_{io} = \xi_1$.
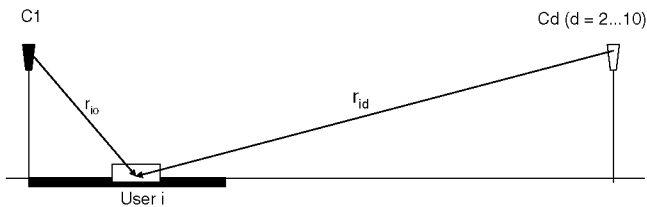* In case of (r_{id} and $r_{io} > R_b$) then $\xi_{id} = \xi_2$ and $\xi_{io} = \xi_2$.

Fig. 2. Schematic diagram of microcells base stations and mobiles for rural zones microcells.

To calculate the mean value of the downlink capacity it is necessary to calculate the expected value of the intracellular interference to the desired value ratio, the expected value of the intercellular interference to the desired value ratio and the expected value of the thermal noise to the desired value ratio.

For the user under study, the intercellular interference is due to the rest of the base stations that it is not connected with. The expected value of the intercellular interference power to the desired signal power $E\left[\frac{I_{inter}}{C}\right]$ when the signals emitted from C2 are interfering signals is given by Mehailescu

$$E\left[\frac{I_{inter}}{C}\right] = 0.5\frac{p_t}{p_{1,t}}e^{(\beta^2\sigma^2/2)}\sum_{d=2}^{8}L(r_{id}, r_{io})Q$$
$$\times \left[\beta\sigma + \frac{10\log_{10}\{L(r_{id}, r_{io})\} + M_{SH}}{\sigma}\right] \qquad (9)$$

where

* The factor 0.5 is due to the fact that half of the transmitted power will be transmitted in the direction of the user under study due to the utilization of two directive antennas in each base station.
* C is the desired signal power,
* p_t is the base station total transmitted power in two directions using two directive antennas at each base stations.
* $p_{1,i}$ is the power transmitted by the base station under study to the user at the location i.
* $\beta = (\ln 10)/10$,
* M_{SH} is the soft hand-over margin (dB) and
* σ is standard deviation of $(\xi_{id} - \xi_{im})$.
* Q is the Gaussian Q function given by:

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-y^2/2}\,dy \qquad (10)$$

Now the general value of σ^2 is given as:

* When (r_{id} and $r_{io} \leqslant R_b$) then $\sigma_{id} = \sigma_1$, also $\sigma_{io} = \sigma_1$ then

$$\sigma^2 = 2(1 - C_{do})\sigma_1^2 \qquad (11)$$

where C_{do} is the inter-sites correlation coefficient.

* If $r_{id} > R_b$ and $r_{id} \leqslant R_b$ then the value of σ^2 is given by

$$\sigma^2 = (\sigma_1 - \sigma_2)^2 + 2(1 - C_{do})\sigma_1\sigma_2 \qquad (12)$$

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

$$\sigma^2 = 2(1 - C_{do})\sigma_2^2 \qquad (13)$$

For the user under study, the intracellular interference is due to the sum of the received power of the rest of the users of the same microcell under study and the received power of the pilot signal taking into account the effect of the orthogonality factor. The expected value of the intracellu-

lar interference power to the desired signal power ratio due to base station 1 is given by:

$$E\left[\frac{I_{\text{intra}}}{C}\right] = 0.5\delta\left(\frac{p_t}{p_{1,i}} - 1\right) \tag{14}$$

where δ is the orthogonality factor of the order of 0.1.

To calculate the desired signal power to the noise ratio, it is necessary to calculate the expected value of the received signal power using the appropriate model of propagation. The expected value of the desired signal power to the noise ratio is given by:

$$E\left[\frac{N_o}{C}\right] = \frac{N_o}{p_{1,i}10^{-(L_{1,i}(\text{dB})-G_{\text{TX}}(\text{dB})-G_{\text{RX}}(\text{dB}))/10}} \tag{15}$$

where $L_{1,i}$ is the path loss between the base station 1 and the location i measured in dB, G_{TX} is the base station antenna gain measured in dB and G_{RX} is the mobile antenna gain assumed to be 0 dB. In $L_{1,i}$ the effects of the distance and shadowing are included assuming ξ_2 to be $2.33\sigma_2$.

When the power control is inhibited, the power assigned to each user is the user's total transmitted power divided uniformly between all of them taking into account the effect of the user activity factor α. Thus, the power transmitted from the base station to the desired user at location i is given by:

$$p_{1,i} \approx \frac{0.5p_t p_{\text{ch}}}{N_u \alpha} \tag{16}$$

where

- p_{ch} is the ratio of the power assigned to all of the users ≈ 0.8 of the base station total transmitted power (0.2 of the base station total transmitted power is assigned to the pilot and common channel),
- N_u is the number of the users uniformly distributed within the microcell sector and
- α is the source activity factor (0.66 for voice and it is 1 for data).

Calculating the expected value of the intracellular interference to the desired value ratio, the expected value of the intercellular interference to the desired value ratio and the expected value of the thermal noise to the desired value ratio it is possible to calculate the signal to interference ratio. The ratio C/I of the user under consideration is given by:

$$C/I = \frac{1}{E\left[\frac{I_{\text{intra}}}{C}\right] + E\left[\frac{I_{\text{inter}}}{C}\right] + E\left[\frac{N_o}{C}\right]} \tag{17}$$

In WCDMA the energy-per-bit to the noise power (E_b/N_o) ratio is given by:

$$E_b/N_o = G_p(C/I) \tag{18}$$

where G_p is the WCDMA processing gain.

Finally, the maximum number of users (N_{ui}) that can be supported at the location i can be found using Eq. (18)

increasing the number of the users within the sector and calculating E_b/N_o. The process will be stopped when the value of E_b/N_o is little bit greater than the required E_b/N_o.

When perfect power control is used, then, the downlink capacity of the sector is average value of the capacity in all point where users exists. Thus, the downlink capacity is given by:

$$N_{\text{pc}} \approx \text{avg}(N_{\text{ui}})|i = i_o \rightarrow i_o + L \tag{19}$$

where L is the train length.

4. Numerical results

For our calculations some reasonable figures are applied. The inter-sites correlation coefficients $C_{\text{do}} = 0.5$, $\delta = 0.1$, $s_1 = 2$, $s_2 = 4$, $\sigma_1 = 3$ dB, $\sigma_2 = 6$ dB, $R_b = 300$ m, $R = 1000$ m and $L = 80$ m unless other values are mentioned. Also we assume that the base station total transmitted power is 1 W, mobile receiver thermal noise power of -100 dBm, directive antenna gain of 10 dB and a frequency of operation of 2.14 GHz.

Since users exist only within the train, then, the calculation of the interference and capacity is done only for the zone where the train exist, i.e., not in all the points of the sector under study. For this reason we will get two extreme cases. The first one which is the worst case will happen when the trains are at the middle of the distance between the base stations. In this case the interference is the highest possible and for that the downlink capacity is the minimum. The second case which is the best case will happen when the trains are very near to the base stations. In this case the total interference is the lowest possible. Thus, the downlink capacity is the maximum possible.

First we study the case of voice service assuming that $\alpha = 0.66$, $G_p = 256$ and $(E_b/N_o)_{\text{req}} = 7$ dB. In this case, the maximum number of codes assigned for the sector is
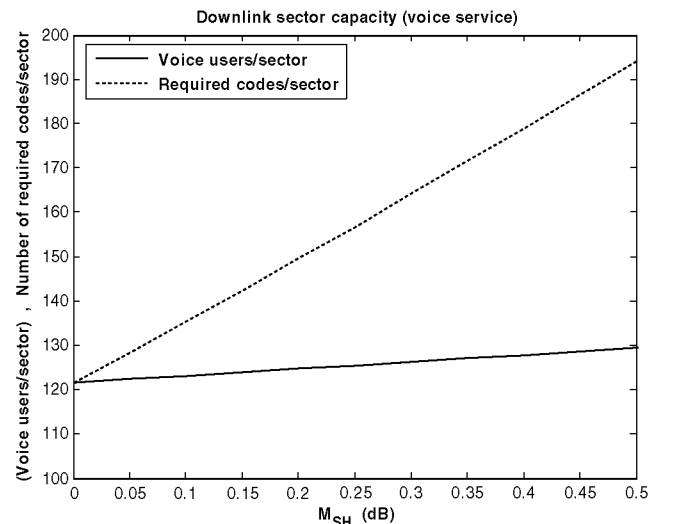

Fig. 3. Worst case sector downlink capacity and the required codes/sector as a function of M_{SH} for the standard parameters.
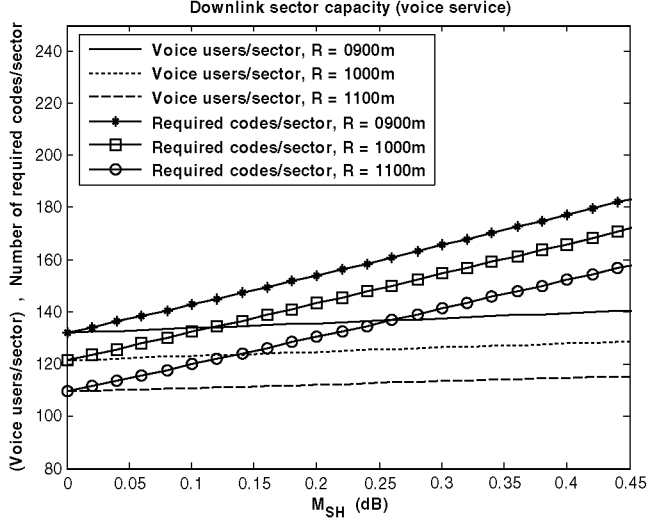
Fig. 4. Worst case sector downlink capacity and the required codes/sector as a function of M_{SH} for different sector range R.

128 ($G_p/2$) codes. Fig. 3 shows the worst case sector downlink capacity as a function of M_{SH}. It can be noticed that at M_{SH} of 0.047 dB, the sector capacity is 122 voice users and that the required number of codes is 128 codes. In this case six extra codes are used for the soft hand-over algorithm. To calculate the sector downlink capacity we have to define the M_{SH} such that the required codes are $G_p/2$. The sector downlink capacity is the number of users at the previously defined M_{SH}.

Fig. 4 depicts the worst case sector downlink capacity as a function of M_{SH} for three values of the sector range R. The sector downlink capacity is (+128, 122 and 111) voice users for a sector range of (900, 1000 and 1100) m, respectively. To get the maximum possible sector downlink capacity, the sector range should be up to 940 m. The practical sector range could be 1 km.
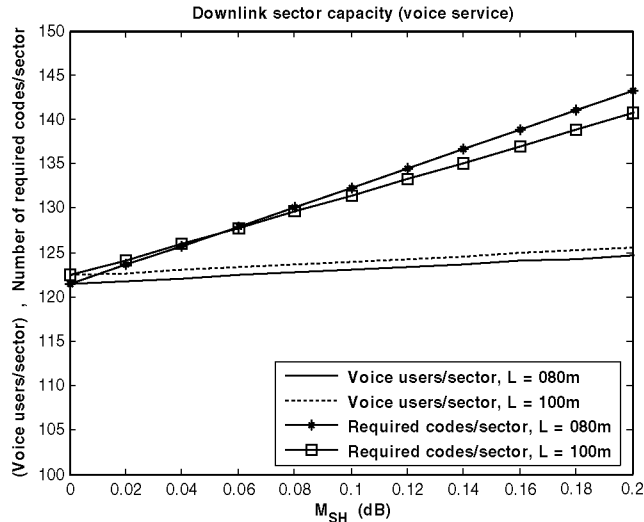
Fig. 5 portrays the worst case sector downlink capacity as a function of M_{SH} for two values of the train length L. The sector downlink capacity is (122 and 123) voice users for train length of (80 and 100) m, respectively. Thus, it can be noticed that the effect of the train length is very little.

Fig. 6 represents the worst case sector downlink capacity as a function of M_{SH} for two values of s_1. The sector downlink capacity is (122 and 75) voice users for s_1 of 2.00 and 2.25, respectively. Thus, it can be noticed that for higher s_1, the sector downlink capacity will be lower.

Fig. 7 shows the worst case sector downlink capacity as a function of M_{SH} for two values of s_2. The sector downlink capacity is (122 and 110) voice users for s_2 of 4.0
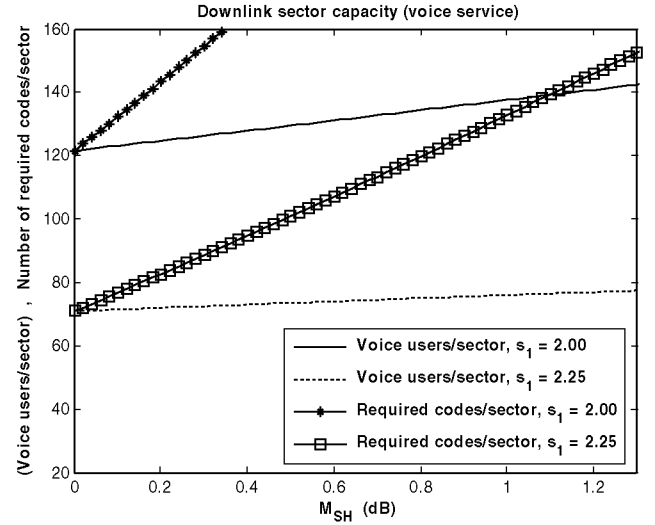

Fig. 6. Worst case sector downlink capacity and the required codes/sector as a function of M_{SH} for different values of s_1.
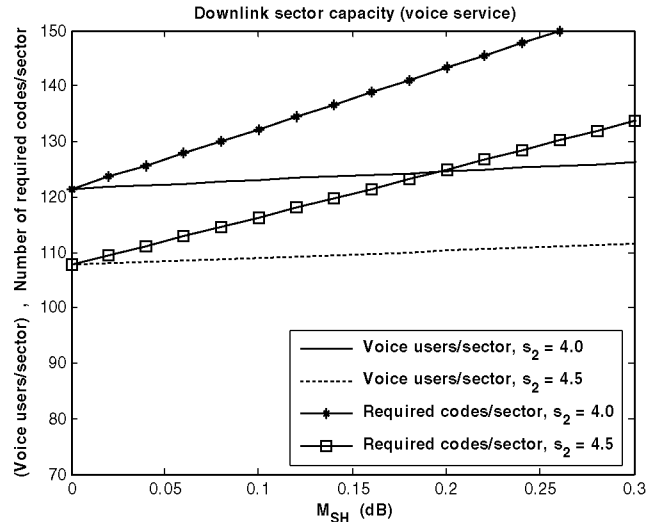

Fig. 5. Worst case sector downlink capacity and the required codes/sector as a function of M_{SH} for different train length L.

Fig. 7. Worst case sector downlink capacity and the required codes/sector as a function of M_{SH} for different values of s_2.

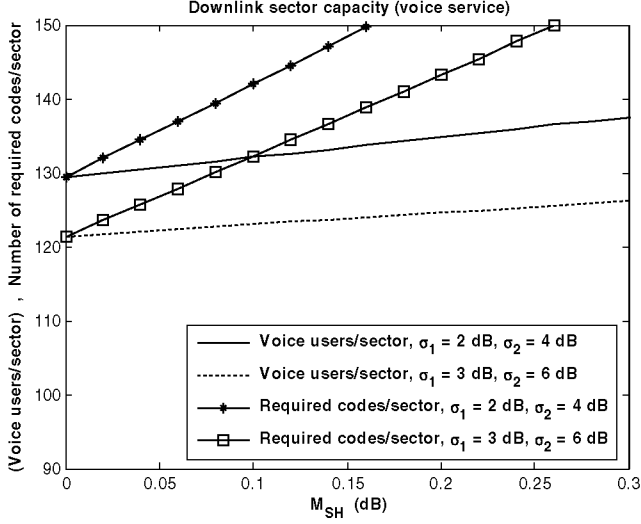Fig. 8. Worst case sector downlink capacity and the required codes/sector as a function of M_{SH} for different values of σ_1 and σ_2.

Fig. 10. Worst case sector downlink capacity and the required codes/sector as a function of M_{SH} for the standard parameters considering the data service.

and 4.5, respectively. Thus, it can be noticed that for higher s_2, the sector downlink capacity will be lower.

Fig. 8 depicts the worst case sector downlink capacity as a function of M_{SH} for different values of value of σ_1 and σ_2. The sector downlink capacity is (+128 and 122) voice users for ($\sigma_1 = 2$ dB, $\sigma_2 = 4$ dB) and ($\sigma_1 = 3$ dB, $\sigma_2 = 6$ dB), respectively. Thus, it can be noticed that for higher σ_1 and σ_2, the sector downlink capacity will be lower.

Fig. 9 represents the worst case sector downlink capacity as a function of M_{SH} for two different values of the orthogonality factor δ. The sector downlink capacity is (+128 and 122) voice users for an orthogonality factor δ with a value of (0.06 and 0.10), respectively. Thus, it can be noticed that for higher δ, the sector downlink capacity will be lower. This is due to fact that, higher δ give a rise to higher intracellular interference.

Finally, the case of data users will be studied assuming $\alpha = 1$, $G_p = 32$ and $(E_b/N_o)_{req} = 5.5$ dB. Fig. 10 portrays the sector downlink capacity as a function of M_{SH}. It can be noticed that for M_{SH} of 0.038, the sector downlink capacity is **15.4** data users and that the required number of codes is 16 codes.

The assigned power for the data users should be ≈ 5.26 times the power assigned to the voice users. Fig. 11 represents the worst case sector downlink capacity for mixed services (voice and data).

For the worst case, the number of the users that can be supported within the train is the double of the sector downlink capacity.

We have to mention that, the best case downlink theoretical capacity of the sector is 618 voice users or 72 data
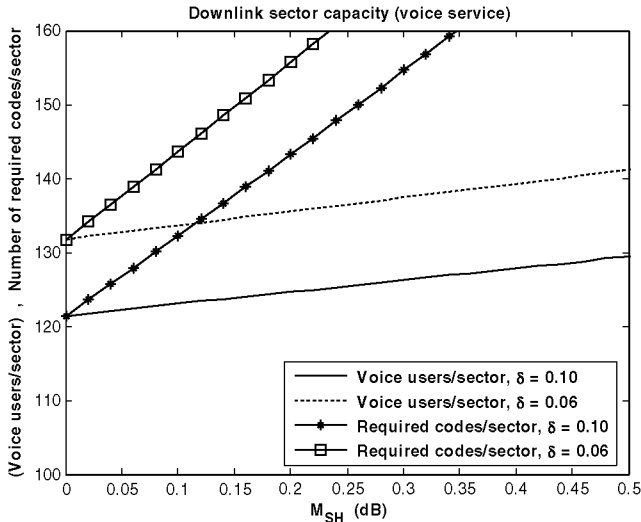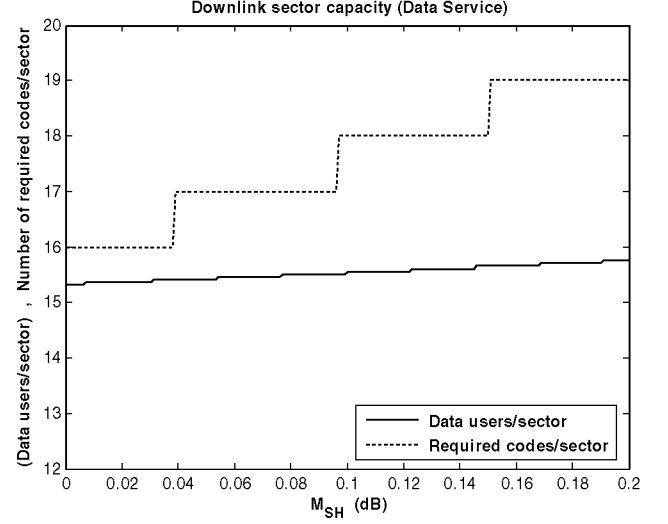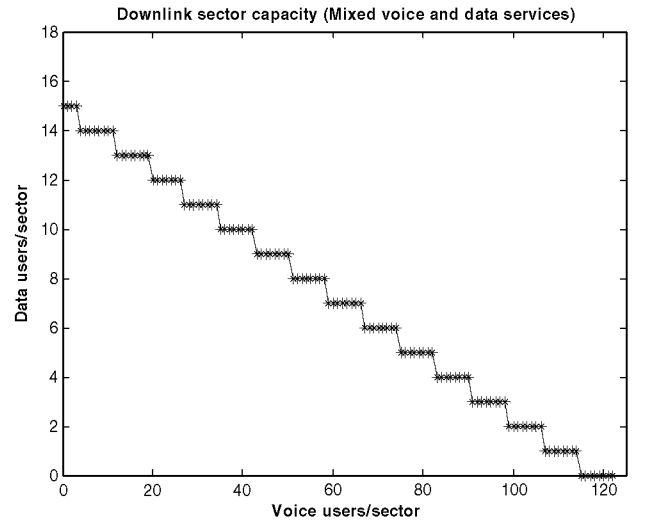

Fig. 9. Worst case sector downlink capacity and the required codes/sector as a function of M_{SH} for two different values of the orthogonality factor δ.

Fig. 11. Worst case sector downlink capacity (mixed voice and data services).
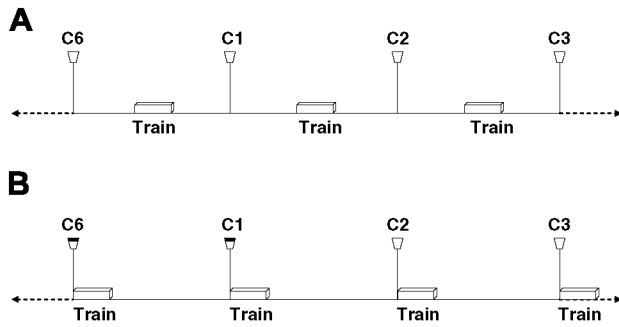
A

B

Fig. 12. Base stations and trains locations for the worst case and the best one. (A) The worst case. (B) The best case.

users. Also we have to mention that, the perfect power control can increase the sector capacity little bit and that the capacity increment factor for the worst case has an upper limit of $f_c = \left(1 + \frac{L}{4R}\right)^{s_2}$. For the practical imperfect power control the capacity increment will be very small or even it can be negative (lower capacity using the practical imperfect power control in comparison with case when the power control is not used. For the best case, the capacity increment factor due to the perfect power control is quasi one $(1 + \Delta)$ where $\Delta \ll 1$.

Fig. 12 depicts the base stations and trains locations for the worst case and the best one.

5. Conclusions

In this paper, the downlink performance of a cigar-shaped microcells using wideband code-division multiple-access (WCDMA) with soft hand-over (SHO) mode has been analyzed where microcells are deployed to give UMTS service to an over-ground train users. The two-slope propagation loss with log-normal shadowing has been used in the analysis where a model of eight cigar-shaped microcells has been utilized to calculate the downlink sector capacity. The downlink sector capacity has been studied for different sector radius R, standard deviation of the shadowing (σ_1 and σ_2) and propagation exponents s_1 and s_2. It has been found that, for a sector range higher than 940 m, increasing the sector range will reduce the downlink sector capacity. Also it has been found that increasing the value of the propagation parameters (s_1, s_2, σ_1 and σ_2) will reduce the downlink sector capacity. It has been found that, in many cases, the downlink sector capacity will be code limited since the theoretical downlink sector capacity is higher than the number of codes assigned to each sector. The high theoretical downlink sector capacity is due to the low value (0.06–0.1) of the orthogonality factor in the highways microcells environment.

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