Research Article

Performance Analysis of CDMA WLL Systems with Imperfect Power Control and Imperfect Sectorization

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Wireless local loop (WLL) provides reliable, flexible, and economical access to the local telephone service using radio technology in the place of traditional wireline. In this paper, an analytical model is derived to evaluate the effect of both imperfect power control and imperfect sectorization on the performance of code division multiple access (CDMA) WLL systems. The results show that the capacity degradation, due to imperfect power control, is about 25.8% and 11.5% for single cell and multiple cell systems, respectively. Increasing the overlapping angle from 0° to 5° causes the capacity gain to decrease from 6 to 5.53, while the corresponding sectorization efficiency drops from 100% to 92.3%.

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1. Introduction

Wireless local loop (WLL) is a system that connects subscribers to the public switched telephone network (PSTN) using radio signals as a substitute for wireline for all or part of the connection between the subscribers and the switch. It is believed to be a fast and cost-effective mean to provide local phone service in rural areas and third world countries [1]. Since WLL is a fixed radio communication system; narrow-beam antennas can be employed at both the base station (BS) and subscriber's side so that the propagation between BS and subscriber's equipment is very close to free space propagation. This gives many inherent advantages to the WLL system over the traditional cellular systems, such as wider coverage area, reduced interference, higher capacity, no fast fading, and no handoff [2, 3].

CDMA technology has the potential to provide a significant improvement in the capacity of cellular radio systems compared with FDMA and TDMA systems [4]. However, this improvement is dependent upon the effectiveness of the power control system, especially on the reverse link. In the absence of power control, a BS would receive a much stronger signal from a subscriber unit that is geographically close to it than from a subscriber unit that is farther away. This is the so-called near-far problem [5, 6].

This paper presents a theoretical model to evaluate the reverse-link capacity of CDMA WLL systems in terms of outage probability, taking into account the power control error.

Sectorization in cellular CDMA systems increases the capacity in proportion to the number of sectors per cell. In practice, the antenna patterns do not fit the sector area perfectly, and there are overlapping between sectors, which causes additional interference on both the reverse and forward link [7]. The imperfect sectorization effect on the performance of CDMA WLL systems is also considered.

2. Effect of Imperfect Power Control in Single Cell CDMA WLL Systems

Consider a CDMA WLL single cell system consists of N subscriber units transmitting to a BS receiver on the reverse-link. A simplified CDMA transmitter is shown in Figure 1.

The signal transmitted from the i th user to its BS is given by [5]

$$S_i(t) = \sqrt{2A_i} b_i(t) c_i(t) \cos(w_1 t + \theta_i), \quad (1)$$

where A_i is the transmitted power of the i th user, $b_i(t)$ is the data sequence of the i th user, where each bit has an amplitude

FIGURE 1: A simplified CDMA transmitter diagram.

of ± 1 and a duration of T_b , $c_i(t)$ is the spreading code sequence of the i th user and each of the M chips per code has a duration T_c , w_i is the reverse link-carrier frequency, and θ_i is the random phase of the i th user carrier.

The received signal at the BS receiver $R_{up}(t)$ consists of the following: interference from other users in the cell which called intracell interference, the receiver noise $n(t)$, and the received signal from the desired user.

From Figure 2, $R_{up}(t)$ is given by

$$R_{up}(t) = \sum_{i=0}^{N-1} a_i S_i(t - \tau_i) + n(t), \quad (2)$$

where a_i represents the path loss of the i th user, τ_i is the random delay of the i th user signal at the receiver, and $n(t)$ is the additive white Gaussian noise (AWGN) of the receiver.

The signal at the output of the matched filter is given by

$$Z(T_b) = \frac{1}{T_b} \int_{\tau_0}^{T_b + \tau_0} R_{up}(t) 2\cos(w_1 t + \theta) c_i(t - \tau_i) dt, \quad (3)$$

where θ is the carrier phase angle in the receiver as shown in Figure 2.

The intracell interference at the output of the matched filter is given by

$$Z_{int}(t) = \sum_{i=1}^{N-1} Z_i(T_b). \quad (4)$$

2.1. Perfect Power Control

To reduce the near-far problem, as well as the interference from other users and hence to increase the capacity of CDMA WLL system, it is important to apply a power control on the reverse link so that the received power from each user at the BS is controlled to be the constant target power, S , [5] where

$$a_i^2 A_i = S \quad \text{for } i = 0, 1, \dots, N-1. \quad (5)$$

The total noise power is the sum of the intracell interference power and the AWGN power of the receiver.

The AWGN power at the output of the matched filter is given by [5, 7] as

$$\eta = N_o R_b = \left(\frac{N_o}{T_c} \right) T_c R_b = \frac{N_o W}{G_p}, \quad (6)$$

where $R_b = 1/T_b$ is the bitrate of the message sequence $b_i(t)$, $W = 1/T_c$ is the chiprate, and $N_o W$ is the noise power at the receiver input.

Thus, after despreading, the noise power η is the input noise power decreased by the processing gain $G_p = T_b/T_c$. The intracell interference power is given by [5]

$$I_{int} = \text{var}(Z_{int}(t)) = \frac{1}{G_p} \sum_{i=1}^{N-1} a_i^2 A_i, \quad (7)$$

where $\text{var}(Z_{int}(t))$ is the variance of intracell interference at the output of the matched filter.

By applying voice activity detection, users transmit only when speech signal is present. We introduce a voice activity variable (VAF) v_i which equals 1 with probability of μ , and equals 0 with probability of $1 - \mu$. By multiplying (7) by v_i and using (5) so,

$$\frac{I_{int}}{S} = \frac{1}{G_p} \sum_{i=1}^{N-1} \frac{v_i a_i^2 A_i}{S} = \frac{1}{G_p} \sum_{i=1}^{N-1} v_i, \quad (8)$$

the intracell interference to signal power ratio given by (8) is reduced by a factor of G_p after the process of matched filtering. Now, we define the ratio E_b/I_o , which is the energy per bit to interference density ratio, where $E_b = ST_b$, $I_o = I/R_b = IT_b$, and I is the total interference power (sum of I_{int} and η) so

$$\frac{E_b}{I_o} = \frac{S}{I} = \frac{1}{I_{int}/S + \eta/S}. \quad (9)$$

In (8), the summation of v_i over $(N - 1)$ users may be expressed as

$$\sum_{i=1}^{N-1} v_i = \mu(N - 1), \quad (10)$$

so that

$$\frac{E_b}{I_o} = \frac{1}{\mu(N - 1)/G_p + \eta/S}. \quad (11)$$

The bit error rate (BER) for the binary phase shift keying (BPSK) modulation can be expressed as

$$P_b = \frac{1}{2} \text{erfc} \left(\sqrt{\frac{E_b}{I_o}} \right), \quad (12)$$

where $\text{erfc}(\sigma)$ is the complementary error function [5]. For a required BER, a required E_b/I_o , $(E_b/I_o)_{req}$ can be determined from (12). Given $(E_b/I_o)_{req}$, the maximum number of active users, other than the i th user, that can be supported by the system is given by (11) as

$$m = \sum_{i=1}^{N-1} v_i = \left\lfloor \frac{G_p}{(E_b/I_o)_{req}} - \frac{G_p}{S/\eta} \right\rfloor, \quad (13)$$

where $\lfloor x \rfloor$ represent the largest integer that is smaller than or equal x . Provided that the number of active users does

FIGURE 2: Channel and BS receiver block diagram.

not exceed m . However, when the number of active users is larger than m , the BER will be greater than the required BER, and this situation is referred to as *system outage*. The outage probability of the single cell system is defined as

$$P_{\text{out}} = \Pr(\text{BER} > \text{BER}_{\text{req}}) = \Pr\left(\frac{E_b}{I_0} < \left(\frac{E_b}{I_0}\right)_{\text{req}}\right). \quad (14)$$

The outage probability is defined as the probability that the number of active users being greater than m , that is,

$$P_{\text{out}} = \Pr\left(\sum_{i=1}^{N-1} v_i > m\right) = \sum_{i=1}^{N-1} \binom{N-1}{i} \mu^i (1-\mu)^{N-1-i}. \quad (15)$$

2.2. Imperfect Power Control

In a practical system, the power control is not perfect. So, the received signal power from the i th user at its BS will differ from the target power level S by δ_i dB. This power error δ_i is a random variable with a standard deviation σ_e . There are several reasons for δ_i being nonzero, such as the power measurement error at the BS and the inability to adjust the subscriber unit transmitted power sufficiently fast to force δ_i to zero [5, 8]. The signal power at the output of the matched filter for the i th user can be expressed as

$$S' = 10^{\delta_0/10} \cdot S, \quad (16)$$

and the intracell interference power is

$$I'_{\text{int}} = \frac{1}{G_p} \sum_{i=1}^{N-1} v_i 10^{\delta_i/10} \cdot S. \quad (17)$$

The intracell interference to signal power ratio at the output of matched filter becomes

$$\frac{I'_{\text{int}}}{S'} = \frac{1}{G_p} \sum_{i=1}^{N-1} v_i 10^{(\delta_i - \delta_0)/10}, \quad (18)$$

where δ_0 and δ_i are two mutually independent random variables of power control errors of the signal and the intracell interferers, respectively. By setting $\varepsilon = \delta_i - \delta_0$ (18) becomes

$$\frac{I'_{\text{int}}}{S'} = \frac{1}{G_p} \sum_{i=1}^{N-1} v_i 10^{\varepsilon/10} = \frac{I_{\text{int}}}{S} 10^{\varepsilon/10}, \quad (19)$$

where ε is a random variable with zero mean and a standard deviation $\sigma_\varepsilon = \sqrt{2}\sigma_e$. Following the same procedure as in the perfect power control case, the ratio E_b/I_0 can be written as

$$\left(\frac{E_b}{I_0}\right)_{\text{imp}} = \frac{1}{I'_{\text{int}}/S' + \eta/S'} = \frac{1}{(I_{\text{int}}/S) 10^{\varepsilon/10} + \eta/S'}. \quad (20)$$

In order to evaluate the system performance, we introduce the outage probability that is defined as the probability of a system's BER being greater than 10^{-3} , that is,

$$P_{\text{out}} = \Pr(\text{BER} > 10^{-3}) \\ = \Pr\left(\left(\frac{E_b}{I_0}\right)_{\text{imp}} = \frac{S'}{I'_{\text{int}} + \eta} < \gamma_{\text{req}}\right) \quad (21)$$

$$= \Pr\left(\frac{I'_{\text{int}} + \eta}{S'} > \frac{1}{\gamma_{\text{req}}}\right) \\ = \Pr\left\{10^{\varepsilon/10} \sum_{i=0}^{N-1} v_i > G_p \left(\frac{1}{\gamma_{\text{req}}} - \frac{\eta}{S'}\right)\right\}, \quad (22)$$

where γ_{req} is the required E_b/I_0 to ensure that the BER is less than 10^{-3} . If the number of active users inside the cell is k , then (22) can be rewritten as

$$P_{\text{out}} = \Pr\left\{\left(k 10^{\varepsilon/10} > G_p \left(\frac{1}{\gamma_{\text{req}}} - \frac{\eta}{S'}\right)\right) \middle| \left(\sum_{i=0}^{N-1} v_i = k\right)\right\} \\ \times \Pr\left(\sum_{i=0}^{N-1} v_i = k\right) = P_1 P_2. \quad (23)$$

The probability P_1 in (23) is given by [5]

$$P_1 = Q\left(\frac{G_p(1/\gamma_{\text{req}} - \eta/S') - kE(10^{\epsilon/10})}{\sqrt{k \text{var}(10^{\epsilon/10})}}\right), \quad (24)$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{(-y^2/2)} dy. \quad (25)$$

The mean of the term $10^{\epsilon/10}$ in (24) can be derived as following:

$$\begin{aligned} E(10^{\epsilon/10}) &= \int_{-\infty}^{\infty} \exp\left[\frac{\epsilon \ln(10)}{10}\right] \frac{\exp(-\epsilon^2/4\sigma_e^2)}{\sqrt{4\pi\sigma_e^2}} d\epsilon \\ &= \exp\left(\sigma_e \frac{\ln(10)}{10}\right)^2, \end{aligned} \quad (26)$$

and the variance of the $10^{\epsilon/10}$ is given by

$$\begin{aligned} \text{var}(10^{\epsilon/10}) &= E(10^{\epsilon/10})^2 - \{E(10^{\epsilon/10})\}^2 \\ &= \exp\left(\sigma_e \frac{\ln(10)}{5}\right)^2 - \left(\exp\left(\sigma_e \frac{\ln(10)}{10}\right)^2\right)^2. \end{aligned} \quad (27)$$

Now, consider the probability that there are k active intracell users, P_2 , which is given by [5]

$$P_2 = \Pr\left(\sum_{i=0}^{N-1} v_i = k\right) = \sum_{k=0}^{N-1} \binom{N-1}{k} \mu^k (1-\mu)^{N-1-k}. \quad (28)$$

The performance of the reverse link in a single cell CDMA WLL system, shown in Figure 3, is evaluated for 20 dB/dec, where WLL has a fixed-to-fixed link so propagation exponent of 2 is used [2], $E_b/I_o = 5$ dB [9], $W = 1.25$ MHz, $R_b = 8$ Kbps, $\text{VAF} = 3/8$, a signal-to-AWGN ratio of 20 dB at the output of the matched filter and a BER outage threshold of 10^{-3} were used in the calculations.

For perfect power control and an outage probability of 2%, the single cell system can support up to 89 users/cell as shown in Figure 3. The outage probability of the imperfect power-controlled system having different standard deviations of power control error is also shown in the figure. For an outage probability of 2% and a standard deviation of power control errors of 2 dB, the system can support 66 users per cell. The capacity degradation, due to imperfect power control, is about 25%.

Table 1 shows the number of users per cell for different values of the standard deviation (STD) of power control errors and the percentage decrease in users due to imperfect power control, for an outage of 2%.

3. Effect of Imperfect Power Control in Multiple Cell CDMA WLL Systems

In addition to the intracell interference, there is now interference from neighboring cells, which called intercell

FIGURE 3: Outage probability of a single cell CDMA WLL system.

TABLE 1: Number of users per cell for different values of σ_e , and $P_{\text{out}} = 2\%$.

STD	Users/cell	% decrease
0 dB	89	0%
1.5 dB	69	22.4%
2 dB	66	25.8%
2.5 dB	62	30.3%

interference. The received signal at the BS includes: the desired signal, intracell interference, the AWGN at the receiver input, and intercell interference. Figure 4 shows the reverse-link communication system, where the arrangement for the transmitter and BS receiver is the same as those shown in Figures 1 and 2, respectively.

The received signal at the BS is given by [5]

$$R_{\text{up}}(t) = \sum_{i=0}^{N-1} a_i S_i(t - \tau_i) + \sum_{j=1}^{J-1} \sum_{i=0}^{N-1} a_{ij} S_{ij}(t - \tau_{ij}) + n(t), \quad (29)$$

where the intercell interference from the $J - 1$ surrounding cells is

$$\sum_{j=1}^{J-1} \sum_{i=0}^{N-1} a_{ij} S_{ij}(t - \tau_{ij}), \quad (30)$$

where a_{ij} represents the effects of path loss, τ_{ij} is the random time delay of the i th user in the j th cell, and $S_{ij}(t)$ is the signal transmitted by the i th user in the j th cell.

For a particular user, say the zeroth one, the signal at the output of the matched filter is given by

$$Z(T_b) = a_0 \sqrt{2A_0 b_0} \cos \phi_0 + Z_{\text{int}}(T_b) + Z_{\text{ext}}(T_b) + Z_n(T_b), \quad (31)$$

FIGURE 4: Block diagram of the multicell CDMA reverse-link system.

where φ_0 is the carrier phase difference. The first term is the desired signal, the second term is the intracell interference component, the third term is the intercell interference component, while the last term is the AWGN component. The intercell interference at the output of the matched filter is given by

$$Z_{\text{ext}}(t) = \frac{1}{T_b} \int_0^{T_b} \sum_{j=1}^{J-1} \sum_{i=0}^{N-1} a_{ij} \sqrt{2A_{ij}} b_{ij}(t - \tau_{ij}) c_{ij}(t - \tau_{ij}). \quad (32)$$

3.1. Perfect Power Control

Similar to the approach in deriving the intracell interference power, the intercell interference power at the output of the matched filter, I_{ext} , can be shown to be

$$I_{\text{ext}} = E((Z_{\text{ext}}(T_b))^2) = \frac{1}{G_p} \sum_{j=1}^{J-1} \sum_{i=0}^{N-1} a_{ij}^2 A_{ij}. \quad (33)$$

The intercell interference to signal ratio is given by

$$\frac{I_{\text{ext}}}{S} = \frac{1}{G_p} \sum_{j=1}^{J-1} \sum_{i=0}^{N-1} v_{ij} \frac{a_{ij}^2 A_{ij}}{S} = \frac{1}{G_p} \sum_{j=1}^{J-1} \frac{I_j}{S}, \quad (34)$$

where I_j/S is the interference to signal power ratio from the j th cell.

Let us consider one of the interfering cells, say cell _{j} , where its BS is at a distance d from BS₀ as shown in Figure 5. The interference term I_j in (34) is the interference power from all the users in cell _{j} to the BS₀, [5, 10].

If the interfering user in cell _{j} is located at a distance r from its BS and r_0 from the BS₀, the interfering user, when active, produces an interference to the BS₀ given by [11]

$$\frac{I(r_0, r)}{S} = \left(\frac{10^{(\zeta_0/10)}}{r_0^\alpha} \right) \left(\frac{r^\alpha}{10^{(\zeta_m/10)}} \right) = \left(\frac{r}{r_0} \right)^\alpha 10^{\zeta/10} \leq 1, \quad (35)$$

where the first term is, due to the attenuation, caused by distance and blockage to the given BS, while the second term is the effect of power control to compensate for the corresponding attenuation to the BS of the out-of-cell

FIGURE 5: CDMA interference calculation.

interferer, ζ , ζ_0 , and ζ_m all are random variables with zero mean and standard deviation σ , ($\zeta = \zeta_0 - \zeta_m$), and r_0 is given by

$$r_0 = \sqrt{d^2 + r^2 + 2dr\cos\theta}. \quad (36)$$

Replace the summation in (34) by an integration over the area of the cell _{j} , so I_j/S will be

$$\frac{I_j}{S} = \int_0^{2\pi} \int_0^R v_{ij} \frac{I(r_0, r)}{S} \cdot \varphi\left(\xi, \frac{r}{r_0}\right) \rho da, \quad (37)$$

where ρ is the user density, assuming N users are uniformly distributed in a circular cell of radius R , $\rho = N/\pi R^2$, $da = r dr d\theta$ is the unit area in Figure 5, $\Phi(\zeta_0 - \zeta_m, r/r_0)$ is the constraint function for the interfering users in the cell _{j} , which can be defined as [5, 11]

$$\varphi\left(\xi, \frac{r}{r_0}\right) = \begin{cases} 1, & \text{if } \left(\frac{r}{r_0}\right)^\alpha 10^{\xi/10} \leq 1, \\ 0, & \text{otherwise.} \end{cases} \quad (38)$$

It is necessary to calculate the mean and variance of the intercell interference power in order to calculate the outage probability. From (35) into (37) and by taking the mean, we obtain [11]

$$E\left(\frac{I_j}{S}\right) = \rho \mu \int_0^{2\pi} \int_0^R \left(\frac{r}{r_0}\right)^\alpha E\left(10^{\xi/10} \cdot \varphi\left(\xi, \frac{r}{r_0}\right)\right) r dr d\theta, \quad (39)$$

where $E(v_{ij}) = \mu$. The variance of I_j/S can be given by [11]

$$\begin{aligned} \text{var}\left(\frac{I_j}{S}\right) &= \int_0^{2\pi} \int_0^R E\left[v_{ij}\left(\frac{r}{r_0}\right)^\alpha 10^{\xi/10} \cdot \varphi\left(\xi, \frac{r}{r_0}\right)\right]^2 \\ &\quad - \left\{E\left[v_{ij}\left(\frac{r}{r_0}\right)^\alpha 10^{\xi/10} \cdot \varphi\left(\xi, \frac{r}{r_0}\right)\right]\right\}^2 \rho r dr d\theta. \end{aligned} \quad (40)$$

The total interference-power-to-signal-power ratio for all the surrounding cells, I_{ext}/S , in (34) has a mean and variance of the following:

$$\begin{aligned} E\left[\frac{I_{\text{ext}}}{S}\right] &= \frac{1}{G_p} \sum_{j=1}^{J-1} E\left[\frac{I_j}{S}\right], \\ \text{var}\left[\frac{I_{\text{ext}}}{S}\right] &= \left(\frac{1}{G_p}\right)^2 \sum_{j=1}^{J-1} \text{var}\left[\frac{I_j}{S}\right]. \end{aligned} \quad (41)$$

The ratio E_b/I_o at the output of the matched filter can be written as

$$\frac{E_b}{I_o} = \frac{1}{I_{\text{int}}/S + I_{\text{ext}}/S + \eta/S}. \quad (42)$$

The system performance in terms of the outage probability that has a BER greater than 10^{-3} is

$$\begin{aligned} P_{\text{out}} &= \sum_{k=0}^{N-1} \binom{N-1}{k} \mu^k (1-\mu)^{N-1-k} \\ &\quad \times Q\left(\frac{1/\gamma_{\text{req}} - \eta/S - k/G_p - E(I_{\text{ext}}/S)}{\sqrt{\text{var}(I_{\text{ext}}/S)}}\right). \end{aligned} \quad (43)$$

3.2. Imperfect Power Control

The received signal power S' from a user at its BS will differ from the target power level S by δ_0 dB. This error power is a random variable with standard deviation σ_e . Using (16) and (35), the interfering power to received signal power ratio will be

$$\frac{I'(r_o, r)}{S'} = \left(\frac{r}{r_0}\right)^\alpha 10^{\xi/10} 10^{\delta_{ij} - \delta_0} = \left(\frac{r}{r_0}\right)^\alpha 10^{\xi/10} 10^{\epsilon/10}, \quad (44)$$

where δ_{ij} is the power error for the i th user in cell j . The total intercell interference-to-signal ratio is

$$\frac{I'_{\text{ext}}}{S'} = \frac{I_{\text{ext}}}{S} 10^{\epsilon/10}. \quad (45)$$

The ratio E_b/I_o can be written as

$$\begin{aligned} \left(\frac{E_b}{I_o}\right)_{\text{imp}} &= \frac{1}{I'_{\text{int}}/S' + I'_{\text{ext}}/S' + \eta/S'} \\ &\quad + \frac{1}{(I_{\text{int}}/S) 10^{\epsilon/10} + (I_{\text{ext}}/S) 10^{\epsilon/10} + \eta/S'}. \end{aligned} \quad (46)$$

FIGURE 6: Outage probability of the multiple cell CDMA WLL system.

Following the same procedure as employed in the perfect power control case, P_{out} is found as

$$\begin{aligned} P_{\text{out}} &= \sum_{k=0}^{N-1} \binom{N-1}{k} \mu^k (1-\mu)^{N-1-k} \\ &\quad \times Q\left(\frac{1/\gamma_{\text{req}} - \eta/S' - k/G_p - E(I'_{\text{int}}/S') - E(I'_{\text{ext}}/S')}{\sqrt{\text{var}(I'_{\text{int}}/S') + \text{var}(I'_{\text{ext}}/S')}}\right), \end{aligned} \quad (47)$$

where I'_{int}/S' and I'_{ext}/S' are two independent Gaussian distributed random variables, whose mean and variance may be expressed as

$$\begin{aligned} E\left[\frac{I'_{\text{int}}}{S'} + \frac{I'_{\text{ext}}}{S'}\right] &= E\left[\frac{I_{\text{int}}}{S} 10^{\epsilon/10}\right] + E\left[\frac{I_{\text{ext}}}{S} 10^{\epsilon/10}\right], \\ \text{var}\left[\frac{I'_{\text{int}}}{S'} + \frac{I'_{\text{ext}}}{S'}\right] &= \text{var}\left[\frac{I_{\text{int}}}{S} 10^{\epsilon/10}\right] + \text{var}\left[\frac{I_{\text{ext}}}{S} 10^{\epsilon/10}\right]. \end{aligned} \quad (48)$$

The performance of the reverse-link CDMA WLL system is shown in Figure 6. For an outage probability of 2%, the perfect power-controlled system can support 52 users/cell for a VAF of 3/8. The number of users per cell for different values of the standard deviation of power control errors and the percentage decrease in users, due to imperfect power control, are displayed in Table 2 for an outage of 2%.

4. Effect of Imperfect Sectorization in CDMA WLL Systems

In the case of perfect directional antennas, there is a sharp separation between the sectors. Due to overlap and sidelobe

TABLE 2: Number of users per cell for different values of σ_e , and $P_{\text{out}} = 2\%$.

STD	Users/cell	% decrease
0 dB	52	0%
1.5 dB	47	9.6%
2 dB	46	11.5%
2.5 dB	44	15.4%

FIGURE 7: Imperfect sectorization: (a) three sector; (b) six sector per cell.

of practical antenna, the BS still receives some interference from users in other sectors [11, 12].

Figure 7 shows a sectorized cell arrangement having N_s overlapping sectors, each with an angle of $(2\pi/N_s) + \theta_0$, where θ_0 is the overlapping angle. If there is no overlapping, that is, $\theta_0 = 0$, then $1/N_s$ of the total interference is received, and the capacity gain, due to sectorization, is N_s times that of an unsectorized cell.

In a sectorized cell, only $(2\pi/N_s) + \theta_0/2\pi$ of the total interference from the surrounding is received. For this condition, the capacity gain, due to sectorization, is $2\pi/(2\pi/N_s) + \theta_0$ times that of the unsectorized cell.

We define the efficiency of sectorization e_s as the ratio of the capacity gain with the sector antennae pattern having an overlapping angle θ_0 to the nonoverlapping antennae pattern of $2\pi/N_s$, so

$$e_s = \frac{2\pi/(2\pi/N_s + \theta_0)}{2\pi/(2\pi/N_s)} = \frac{2\pi/N_s}{2\pi/N_s + \theta_0}. \quad (49)$$

So, the imperfect sectorization capacity gain G_{imp} will be

$$G_{\text{imp}} = N_s e_s. \quad (50)$$

In WLL system, due to fixed-to-fixed link, six sectors per cell arrangement can be used, the capacity gain due to sectorization and its corresponding sectorization efficiency for different values of overlapping angle θ_0 in degrees is shown in Figure 8. From the figure, the interference on the reverse link increases as the overlapping angle θ_0 is increased, which causes the capacity gain and sectorization efficiency to decrease proportionally. Increasing θ_0 from 0° to 5° causes the capacity gain to decrease from 6 to 5.53, while the corresponding sectorization efficiency drops from 100% to 92.3%.

FIGURE 8: Reverse-link sectorization gain and efficiency as a function of the overlapping angle.

5. Conclusion

CDMA technology has the potential to provide a significant improvement in the capacity of WLL systems compared with FDMA and TDMA systems. However, this improvement is dependent upon the effectiveness of the power control system, especially on the reverse link. In this paper, a theoretical model to evaluate the reverse-link capacity of CDMA WLL systems in terms of outage probability, taking into account the power control error, is obtained. The results show that the capacity degradation, due to imperfect power control, is about 25.8%, and 11.5% for single cell and multiple cell systems, respectively. The effect of imperfect sectorization on the performance of CDMA WLL systems is also considered. The interference on the reverse link increases as the overlapping angle is increased, which causes the capacity gain and sectorization efficiency to decrease proportionally as shown in Figure 8.

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