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PERFORMANCE ANALYSIS OF A CDMA WIRELESS LOCAL LOOP SYSTEMS

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ABSTRACT

In this paper, the capacity of the Code Division Multiple Access Wireless Local Loop (CDMA WLL) system is analytically derived, and the capacity gain achieved in a CDMA WLL over a cellular mobile environment is calculated. The results show that the CDMA WLL system can support up to 36 % more users than CDMA cellular mobile system. The paper also propose a new approach to increase the reverse link capacity of the CDMA WLL system, which synchronize the reverse link so that signals transmitted from different subscriber units within the same cell are time aligned at the base station (BS). A theoretical analysis of the potential capacity gain of reverse link synchronous CDMA WLL is presented.

1. Introduction

The wireless local loop (WLL) system is a local telephone system without wireline connection. It is believed to be a fast and cost-effective means to provide local phone service in rural areas and third world countries. WLL system deploy access technologies based either on the existing standards (such as TDMA, GSM, IS-95 CDMA, etc.) or proprietary radio link technologies to provide reliable, and cost effective local telephone service [1], [2]. Major differences between the WLL and the mobile cellular environment include a usual strong line-of-sight (LOS) component and a stationary subscriber unit with a directional antenna. LOS channels and stationary users result in Rician-rather than Rayleigh-type of fading. The fading reduction leads to a substantial decrease in the link requirements and consequently an increase in system capacity [3]. In this paper ideal multiple-tier hexagonal cells are used to derive the capacity of a CDMA WLL system and comparing it with the capacity of CDMA cellular mobile system.

The paper also propose a new approach to increase the reverse link capacity of the CDMA WLL system, where in CDMA WLL system, the ability to tolerate interference is used to allow other users to send their transmission on the same channel. Each of the other users also has a spreading code. It is important that each user has a different code and that the codes are orthogonal with each other. So whatever transmitted by the interferer and by the wanted user, the correlator produces the same result as if there were no interferer, more orthogonal interferers can be added without having any effect on the wanted signal. The only time this relationship does not hold is when the received signals are not synchronized [1], so that the transitions in the spreading sequences occur at different times. This would occur when the users were at different distances from the BS and so experiencing different propagation delays. This situation can be avoided through the use of timing advance commands from the BS to tell the user to change its internal clock by the propagation delay being experienced. This is one of the key differences between the use of CDMA for mobile and WLL purposes. In the mobile case, synchronization on the reverse link is almost difficult to achieve because of the movement of the mobile, resulting in variable propagation delays. Hence, the reverse link is designed to accept asynchronous input, resulting in a lower system capacity. But in WLL systems, there is no movement; hence, a synchronous system can be produced, so that signals transmitted from different users within the same cell are time aligned at the BS.

2. Reverse link capacity of a CDMA cellular mobile system

In this section the reverse link (MS to BS) capacity of a CDMA cellular mobile system is calculated, where in a multiple cell CDMA system,

an MS is power-controlled by the BS that sending the highest strength pilot signal to the MS. This BS is called the *home* BS of the given MS. The interference from subscribers within the same (*home*) cell is called intra-cell interference or self interference I_{self} and calculated as follows; since each user is power controlled by the same BS, it arrives with the same power S when active. Thus given N subscribers per cell, the total interference is never greater than $(N-1)S$ but on the average it is reduced by the voice activity factor, α. Subscribers in other cells, however are power controlled by other cell sites, so

$$I_{self} = \alpha(N-1)S. \tag{1}$$

Figure 1 shows an ideal hexagonal cellular structure. The path loss L between the MS and the BS is described as

$$L \propto r^{-\mu}\, 10^{\zeta/10} \tag{2}$$

where: r – distance from an MS to a BS; μ – path loss exponent; ζ – attenuation in dB due to shadowing, which is a Gaussian random variable with standard deviation σ of 8 dB and zero mean.

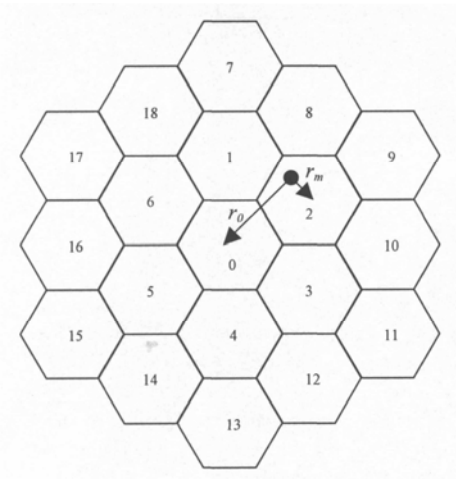

Fig. 1. A hexagonal cellular structure.

First, the reverse link interference from each tier to the center cell is calculated separately. Then, we can obtain the total other cell interference which is the interference produced by all users who are power-controlled by other BS's. If the interfering subscriber in another cell is located at a distance r_m from its BS and r_o from the BS of the desired user, the other user when active, produces an interference to the desired user's BS given by [4]

$$\frac{I(r_0, r_m)}{S} = \left(\frac{10^{(\zeta_0/10)}}{r_0^4}\right)\left(\frac{r_m^4}{10^{(\zeta_m/10)}}\right) = \left(\frac{r_m}{r_0}\right)^4 10^{(\zeta_0-\zeta_m)/10} \le 1. \tag{3}$$

Using a path loss exponent of 4, 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 interferer. For all values of the above parameters, the expression is less than unity, otherwise the subscriber would switch to the BS that makes it less than unity.

Assuming N users uniformly distributed in a circular cell of radius R, the user density is given by

$$\rho = \frac{N}{\pi R^2}. \tag{4}$$

To calculate the reverse link interference from each tier to the center cell, assuming a perfect power control so, the received power at the BS would be the same for each MS. Let S be the power of a CDMA mobile unit received at the BS of its own cell. Then, referring to Fig. 2 the total mobile power from a cell having N MSs uniformly distributed in it to a BS at distance $d = kR$ is given by [5]

$$P(d) = \int \alpha S \left(\frac{r_m}{r_o}\right)^4 \rho\, dA \tag{5}$$

where the integration is over one cell area, and r_0 is given by

$$r_0 = \sqrt{d^2 + r_m^2 + 2dr_m + \cos\theta}. \tag{6}$$

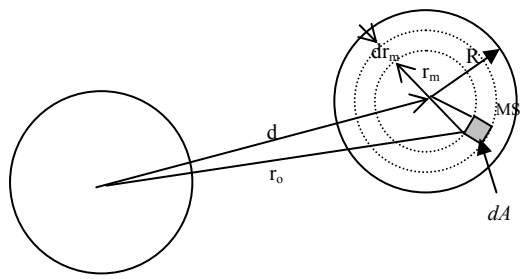

Fig. 2. CDMA interference calculation.

From Fig. 2 and using Eqs. (4) and (6), Eq. (5) becomes

$$P(d) = 2\int_0^{\pi}\int_0^{R} \alpha S \left(\frac{r_m}{r_0}\right)^4 \rho r_m\, dr_m\, d\theta$$

or

$$P(d) = 2\alpha\rho S \int_0^{R} r_m^5 dr_m \int_0^{\pi} \frac{d\theta}{\left(d^2 + r_m^2 + 2dr_m \cos\theta\right)^2}. \tag{7}$$

This integration can be evaluated analytically as follows.

Let

$$B(r_m) = \int_0^{\pi} \frac{d\theta}{\left(d^2 + r_m^2 + 2dr_m \cos\theta\right)^2} = \pi \frac{d^2 + r_m^2}{\left(d^2 - r_m^2\right)^3} \tag{8}$$

and

$$A = \int_0^{R} r_m^5 dr_m \quad B(r_m). \tag{9}$$

Thus,

$$A = \pi \int_0^{R} \frac{d^2 r_m^5 + r_m^7}{\left(d^2 - r_m^2\right)^3} dr_m \tag{10}$$

when $d = kR$, this integration becomes

$$A = \pi R^2 \left[2k^2 \ln\left(\frac{k^2}{k^2-1} \right) - \frac{4k^4 - 6k^2 + 1}{2(k^2-1)^2} \right]. \tag{11}$$

Finally,

$$P(d) = 2\alpha NS \left[2k^2 \ln\left(\frac{k^2}{k^2-1} \right) - \frac{4k^4 - 6k^2 + 1}{2(k^2-1)^2} \right] \tag{12}$$

which is the total interference received at the *home* cell from an interfering cell i.

Now consider the case when all CDMA cells are loaded with N active mobile units, the total interference power received at *home* BS from all mobiles in other cells is the sum of the interfering power from 6 ring-1 cells, 12 ring-2 cells and so on.

Figure 3 shows that the distance between the BS of a ring-n cell and that of the cell under consideration is

$$d_{n,i} - 2R\sqrt{n^2 + i^2 - ni}. \tag{13}$$

The number of cells at the tier n facing one side of the reference cell is n. Thus the total number of cells in ring-n is $6n$. Substituting from Eq. (13) into Eq. (12), the total other cell interference in the case of cellular mobile system, I_{occ}, for N tiers is given as follows

$$I_{occ} = \sum_{n=1}^{N} \sum_{i=1}^{n} 6P(d_{n,i}) =$$

$$= 12\alpha NS \sum_{n=1}^{N} \sum_{i=1}^{n} \left[2M \ln\left(\frac{M}{M-1} \right) - \frac{4M^2 - 6M + 1}{2(M-1)^2} \right] \tag{14}$$

where:

$$M = 4(n^2 + i^2 - ni) \tag{15}$$

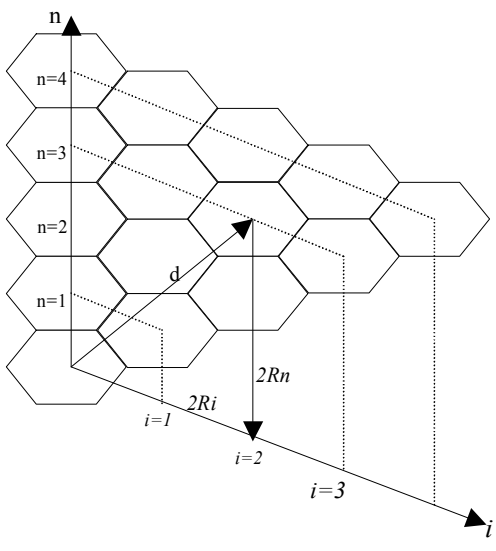

Fig. 3. Co-ordinates for inter-base station distance calculation.

For this system the reverse link capacity can be calculated by using [4]

$$P_r(BER > 10^{-3}) = \sum_{k=0}^{N-1} \binom{N-1}{k} \alpha^k (1-\alpha)^{N-1-k} \times$$

$$\times Q\left(\frac{\delta - k - E(I_{occ}/S)}{\sqrt{Var(I_{occ}/S)}} \right) \tag{16}$$

where:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{(-y^2/2)} dy \quad \text{and} \quad \delta = \frac{W/R_b}{E_b/N_o} - \frac{\eta}{S} \tag{17}$$

and W is the frequency band assigned, R_b is the bit rate, W/R_b is the processing gain, E_b/N_o is the energy per bit to interference density ratio, η is the back ground noise, and $E(I_{occ}/S)$ and $Var(I_{occ}/S)$ are the mean and variance of I_{occ}/S respectively. The reverse link capacity N_c is defined as the maximum integer N satisfying $P_r(BER > 10^{-3}) < 0.01$, and can be easily calculated using Eq. (16) when $E(I_{occ}/S) = 0.247xN$ and $Var(I_{occ}/S) = 0.078xN$, as given in [4]. This expression is plotted for $E_b/N_o = 7$ dB, $W = 1.25$ MHz, $R_b = 8$ Kbps, $\alpha = 3/8$, and $\eta/S = -1$dB as shown in Fig. 4. This figure indicates that, the reverse link can support over 36 users/cell with 10^{-3} *BER*. This number becomes 45 users/cell if the neighbouring cells are kept to half of this loading .The rightmost curve applies to a single cell without other cell interference ($I_{occ} = 0$).

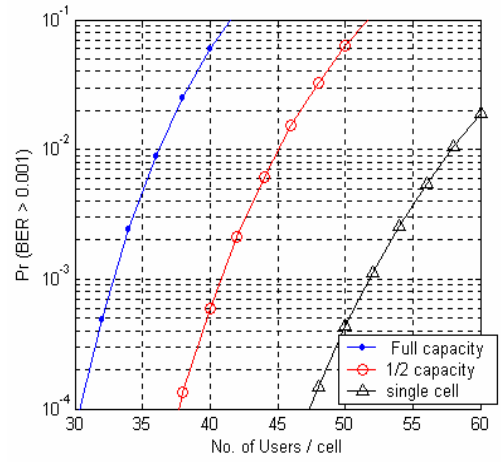

Fig. 4. Reverse link capacity/cell.

3. The reverse link capacity of a CDMA WLL system

WLL is a fixed communication system, narrow beam antennas can be employed at both the base station and subscriber's side so that the propagation between base station and house is very close to free space propagation (20 dB/dec) [2], [9].

Applying the same model used in section 2, taking into account the major difference between the WLL and the mobile cellular environment which include

a usual *LOS* component and a stationary subscriber unit with a directional antenna, result in Rician type of fading. That leads to a substantial decrease in the link requirements and consequently an increase in system capacity.

We will now present the derivation of an analytical formula for determining reverse link interference for a CDMA WLL system. Assuming N houses uniformly distributed in a circular cell of radius R so that the houses density as in Eq. (4). The transmitted power of the house with power control is directly proportional to r^2, where r is the distance from the house to the BS.

3.1. Interference from a single cell

It is noticed that, not every house from another cell causes interference to the center cell. Only those whose transmitting antennas cover the center cell BS are interferers.

Suppose the gain of a perfect house antenna with beam width w is given by, [2]

$$G(\theta)=\begin{cases}1, & -w/2<\theta<w/2\\ 0, & \text{otherwise}\end{cases}. \tag{18}$$

The area with interfering houses is shown as a shadowed area in Fig. 5. If $w \ll 1$ or $R \ll D$, the interference area can be simplified as a perfect pie shape with angle span of

$$W=w\left(1+\frac{R}{D}\right). \tag{19}$$

Figure 5 shows the reference cell C_o, and the interfering cell C_i. Hence the interference received at the reference cell from a house in the interfering cell is

$$\alpha S\left(\frac{r_1}{r_o}\right)^2. \tag{20}$$

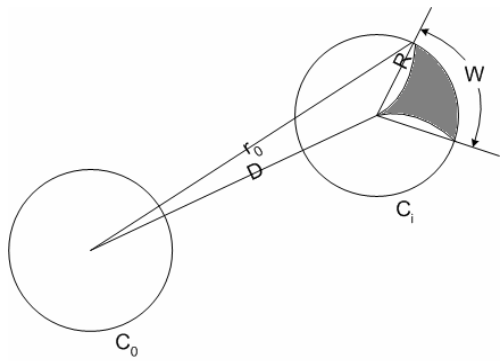

Fig. 5. Interference from a single cell.

The total interference received at the reference cell from an interfering cell C_i is calculated by integrating the total interference power over the interference region in C_i, using (6) and (20).

$$I_i \alpha\rho S\int_0^R\int_{-W/2}^{W/2}\frac{r^2}{d_i^2+r^2+2d_i r\cos\theta}d\theta\cdot rdr. \tag{21}$$

However, for narrow beam antennas, $W \ll 1$ (in radian), the above integral can be approximated to,

$$I_i=\alpha\rho S\int_0^R\int_{-W/2}^{W/2}\frac{r^2}{d_i^2+r^2+2d_i r}d\theta\cdot rdr=$$

$$=\alpha\rho SW_i d_i^2\left\{\frac{1}{2}\left(\frac{R}{d_i}\right)^2-\frac{2R}{d_i}+3\ln\left(1+\frac{R}{d_i}\right)-\frac{\frac{R}{d_i}}{1+\frac{R}{d_i}}\right\} \tag{22}$$

where d_i given in (13).

3.2. Total interference received from all cells

The number of cells at the tier n facing one side of the reference cell is n. Thus the total number of cells in ring-n is $6n$. Hence, the total interference received from all cells at tier n is

$$I_n=6\sum_{i=1}^{n}I_i,\quad i=1,2,\ldots,n. \tag{23}$$

Thus I_{ocw} (total other cell interference in the case of CDMA WLL system) for N tiers will be

$$I_{ocw}=6\sum_{n=1}^{N}\sum_{i=1}^{n}I_i. \tag{24}$$

The capacity of this system can be calculated by using (16), when $E(I_{ocw}/S)$ and $Var(I_{ocw}/S)$ are given. Define the relative interference from all cells at tier n as

$$I_{nr}=I_n/I_{self}. \tag{25}$$

Table 1 shows the results for relative interference from first 4 tiers.

Table 1. Relative interference

n (tier umber)	I_{nr} (relative interference)
1	0.10883
2	0.05890
3	0.03916
4	0.02922

The values of $E(I_{ocw}/S)$ and $Var(I_{ocw}/S)$ can be numerically obtained as, $E(I_{ocw}/S) \approx 0.23611\text{x}N$, and $Var(I_{ocw}/S) \approx 0.03293\text{x}N$.

Figure 6 shows the reverse link capacity of CDMA WLL system for E_b/N_o = 6 dB [6], the other parameters as in Fig. 4. According to this figure, the reverse link can support up to 49 users/cell with 10^{-3} *BER*. This number becomes 60 users/cell when the neighboring cells kept to half of this loading. The rightmost curve applies to a single cell without other cell interference (I_{ocw} = 0).

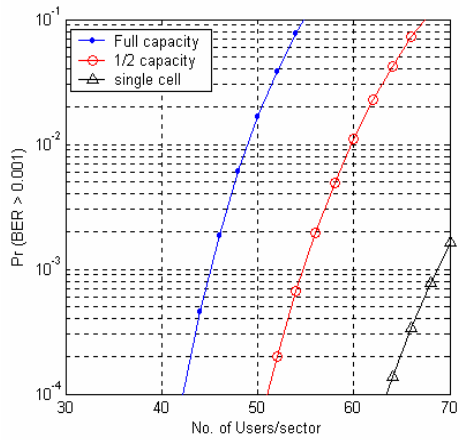

Fig. 6. Reverse link capacity/cell for CDMA WLL system.

Figure 7 represents a comparison between the obtained results and that from CDMA cellular mobile system. The figure shows that the CDMA WLL system can accommodate approximately 36% more users than CDMA cellular mobile system (when the surrounding cells are full).

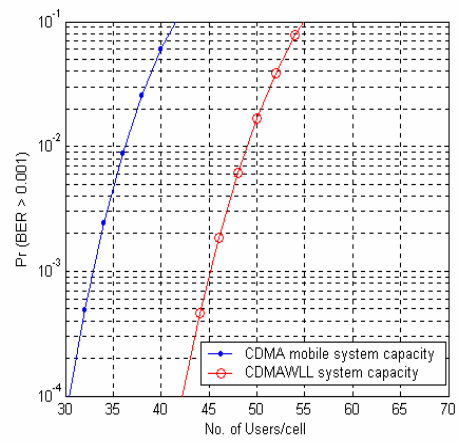

Fig. 7. Reverse link capacity/cell for CDMA & CDMAWLL system.

4. Capacity gain of synchronous CDMA WLL system

In a conventional reverse link asynchronous direct-sequence CDMA system, each user is allocated a unique pseudonoise (PN) sequence; we will refer to the PN sequences as scrambling codes. In reverse link synchronized CDMA WLL, subscriber units within the same cell share the same scrambling code (the scrambling code is cell specific), while using different orthogonal channelization codes derived from the set of Walsh codes. The channelization codes are utilized to separate physical channels from subscriber units. Hence, the narrow-band signal from a subscriber unit is both multiplied by a channelization code (Walsh code) and a scrambling code (PN).

The number of available channelization codes sets an upper limit of the maximum number of subscriber units per cell. However, this limitation can be lifted by introducing several scrambling code groups within a cell. This implies that a certain set of subscriber units are transmitted under one scrambling code while another set of subscriber units is transmitted under different scrambling codes [7]. The introduction of multiple scrambling codes within a cell eliminates the constraint on the maximum number of subscriber units due to channelization code shortage. However, this is obtained at the expense of an increased multiple-access interference (MAI), since signals transmitted under different scrambling codes are nonorthogonal. So the need to introduce an upper limit of the maximum number of scrambling code groups within a cell.

The maximum cell capacity defined as the number of subscriber units that can be supported at a given noise rise (*NR*) at the BS. The *NR* at the BS is known to be a robust measure of the reverse link load of a CDMA system. The *NR* is defined as

$$NR = \frac{P_{total}}{P_{noise}} \tag{26}$$

where P_{total} is total average received power at the BS and P_{noise} is the power of the thermal noise at the BS. The reverse link load factor is defined as [8]

$$\eta = \frac{N}{N_{\max}} \tag{27}$$

where N is the number of subscriber units within the cell and N_{max} is called the pole point and represent a theoretical maximum capacity that cannot be reached but serves as a useful reference point.

The *NR* is related to the reverse link load factor as [7]

$$\eta = \frac{NR-1}{NR}. \tag{28}$$

Hence, the *NR* can be used to control how close the system is operated to the pole capacity. To derive an expression for the *NR*, assuming that there are N_{async} subscriber units in the cell of interest, which are transmitting asynchronously. In addition, there are N^{j}_{sync} subscriber units in synchronous mode transmitting under scrambling code number j. Let us furthermore assume that the required E_b/N_o is identical for all subscriber units. Under these assumptions, we can approximate the E_b/N_o for the subscriber units operating in asynchronous mode as,

$$\rho = G\frac{P_{async}}{P_{total}} \tag{29}$$

where G is the effective processing gain (ratio between the chip rate and the bit rate), P_{async} is the received power level at the BS from a subscriber unit in asynchronous mode, and P_{total} is the total received power. Similarly, we can express the E_b/N_o for synchronous subscriber units under scrambling code number as

$$\rho = G\frac{P_{sync}^{j}}{P_{total} - N_{sync}^{j}P_{sync}^{j}\psi} \tag{30}$$

where P^{j}_{sync} is the received power level at the BS from a synchronous subscriber unit under scrambling code number j and ψ expresses the degree of orthogonality (orthogonality factor) between the signals received under the same scrambling code and its value is between zero and one. From (29) and (30), the following expressions are obtained

$$P_{async} = \frac{\rho P_{total}}{G}, \tag{31}$$

$$P_{sync}^{j} = \frac{\rho P_{total}}{G + \rho N_{sync}^{j}\psi}. \tag{32}$$

The total received power at the BS can be expressed as

$$P_{total} = P_{own} + P_{other} + P_{noise} = P_{own}\,(1+i) + P_{noise} \tag{33}$$

where P_{own} is the own-cell power, P_{other} is the other-cell power, P_{noise} is the noise level, and $i = P_{other}/P_{own}$ is the other-to-own-cell interference ratio. The own-cell power equals

$$P_{own} = N_{async}P_{async} + \sum_{j=1}^{J} N_{sync}^{j}P_{sync}^{j} \tag{34}$$

where J is the number of enabled scrambling code groups within the cell of interest. Combining (31), (32), and (34) yields

$$P_{own} = P_{total}\rho\left(\frac{N_{async}}{G} + \sum_{j=1}^{J}\frac{N_{sync}^{j}}{G + \rho N_{sync}^{j}\psi}\right). \tag{35}$$

An expression for the *NR* at the BS is subsequently obtained by combining (33) and (35), i.e.,

$$NR = \frac{P_{total}}{P_{noise}} = \left[1 - (1+i)\rho\left(\frac{\alpha N_{async}}{G} + \sum_{j=1}^{J}\frac{\alpha N_{sync}^{J}}{G + \alpha\rho N_{sync}^{J}\psi}\right)\right] \tag{36}$$

The expression for the *NR* is plotted in Fig. 8 versus the number of subscriber units, conditioned on $\psi = 0.9$, $G = 314$, $\rho = 6$ dB, $\alpha = 0.5$, and $i = 0.6$ [7].

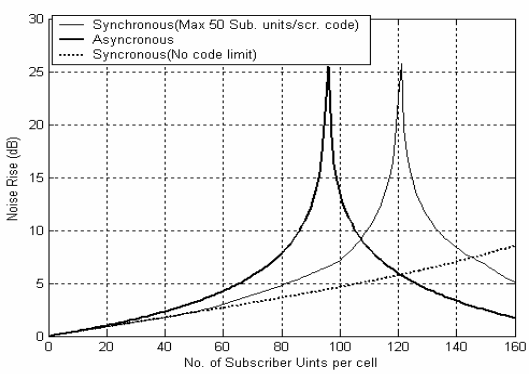

Fig. 8. *NR* as a function of the number of subscriber units.

Results are presented for the cases where all subscriber units are either in asynchronous or synchronous mode.

The curve labeled *no code limit* refers to the case where $J = 1$, independent of the number of synchronous subscriber units, i.e., corresponding to an infinite number of channelization codes under a single scrambling code. The other curve for subscriber units in synchronous mode assumes maximum of 50 subscriber units under each scrambling code, subscriber units are first allocated under scrambling code number one. Once the number of subscriber units exceeds the maximum number of channelization codes, the second scrambling code is enabled, and so forth.

According to this figure the capacity gain of synchronous CDMA WLL for a *NR* target of 4dB is 19 % greater than asynchronous mode. From (27) the reverse link load factor η can not be greater than one, and so from (28) the *NR* can not be negative. Using Fig. 8, we can set an upper limit of the maximum number of scrambling code groups within a cell, from the curve labeled synchronous (*Max 50* sub. units*/scr. Code*) the maximum number of users that can be supported in a cell 120 users/cell i.e., maximum of 3 scrambling code groups within a cell, after this number the *NR* will be negative and this will achieve an up link load factor η greater than one. This is obtained at the expense of an increased multiple-access interference (MAI), since signals transmitted under different scrambling codes are nonorthogonal.

4. Conclusion

The capacity of the CDMA WLL system is analytically obtained, and the capacity gain in a WLL over a cellular mobile system is calculated. The results show that the system capacity of both systems are largely affected by the other cell interference (i.e. number of active users in the surrounding cells) as shown in Figs. 4 and 6. It is also shown that the same capacity expression characterizes both mobile cellular and WLL CDMA networks. However, directional subscriber antennas deployed at a WLL network reduce the other-cell interference, or equivalently increase the system capacity where the CDMA WLL system can support about 36 % more users than CDMA cellular mobile system. The paper also discusses the performance of reverse link-synchronous CDMA WLL in terms of the capacity gain relative to an asynchronous system. The capacity gain is evaluated theoretically. The results show that the potential capacity gain of the reverse link synchronous CDMA WLL system with a noise rise target of 4 dB is 19 % greater than the asynchronous mode.

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