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REVERSE LINK CDMA SYSTEM CAPACITY EVALUATION FOR STRATOSPHERIC PLATFORM MOBILE COMMUNICATIONS

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Abstract

We propose an analysis of reverse link CDMA multispot beam stratospheric platforms (SPF) in this paper. The SPF is currently proposed as a novel wireless technology for the development of the next generation fixed and mobile communications. The geometry of this technology is different from that of the terrestrial but rather similar to the satellite based cellular system. However, evaluation on the CDMA system capacity of this technology has not been much reported. This paper addresses all possible multiple access interference analyses including the effects of channel fading and shadowing in order to evaluate the system capacity. Single SPF and multiple SPF model are evaluated under perfect power control and imperfect power control. The results indicate that in SPF systems the reverse link CDMA capacity is significantly reduced because of the power control imperfections. Moreover, in multiple SPF model the interference caused by the users in overlapped region is not trivial. We found that because of this problem the capacity is reduced for both speech and real-time data applications compared with the single SPF model even though the assumption of perfect power control can be made. In order to improve the system capacity we proposed two methods, first is to increase the minimum elevation angle definition for each platform and the second is to employ an adaptive antenna.

Keywords: stratospheric platform, cellular communication, CDMA, power control, outage probability, adaptive antenna

1. Introduction

Stratospheric Platform (SPF) has been recently proposed as a novel technology for the development of wireless fixed and mobile communication systems [1-5]. It is based on aerial unmanned or manned vehicles, which are able to operate at stratospheric altitudes of approximately 17-30 km for a long endurance. This novel communication infrastructure has the advantages of higher line of sight capability and wider coverage area compared with the terrestrial systems, and a much shorter propagation distance which therefore give a significant advantage of link budget compared with the satellite systems. Cellular structure on the ground of this system will be implemented by using multispot beam antenna on board the platform for cells projection [6].

CDMA system capacity carried out by this system is an important matter that has to be investigated. It is well known in terrestrial cellular system that CDMA has a many-fold increase in capacity compared with TDMA/FDMA [7]. However, the same conclusion cannot be directly drawn for the SPF applications because of some fundamental differences between terrestrial and SPF links. In comparison with terrestrial mobile environment, the slightly larger propagation delay in SPF link may not allow an effective power control scheme to work properly. Therefore the power control imperfections in such a system must be considered in the capacity analysis. For a multispot beam CDMA SPF system, the users within a SPF's coverage are subject to the power control of the same platform even though they are located at different spot beams. This is because all spot beam antennas, which refer to all base station, are located at the same platform. As a result, the interference caused by these users is not attenuated by the distance between the users and the platform due to the influence of power control. For the interferers outside the platform coverage but still seen by the platform antenna, they are served by the adjacent nearest platform and the interference level will also decrease with a power low of the distance. However, the power falls off as distance squared, higher interference would be produced than that in the terrestrial case, where a fourth power law of the distance is usually assumed. Moreover, in a multispot beam SPF system the signal power of the interferers located outside the reference spot beam will be attenuated by the angular selectivity of the spot beam antenna radiation pattern. Therefore the interference level directly depends upon the antenna characteristics and the definition of the spot beam contour.

Although there are many literatures on terrestrial CDMA cellular system, CDMA capacity issues have not been much investigated for the case of SPF [8-11]. The downlink performance of such a system has been examined in [8], while the other cell interference factor and the reverse link capacity have been evaluated in [9]. However the analysis mentioned above did not consider the effects of imperfect power control and the interference from the users of adjacent platform. In [10] the extension analysis proposed in [9] is presented with considering the scenarios of multiple platform application, but the analysis was based on the condition of perfect power control. Both forward and reverse link CDMA capacity issues have also been investigated in [11] for a SPF rural macrocell integrated within a terrestrial UMTS network. However for pboth forward and reverse link, it has been modeled by using an oversimplified channel model for the capacity estimation. When considering CDMA system, the most serious problem we have to deal with is the user interference or known as multiple access interference (MAI), because all users are contending the same bandwidth at the same time. Power control must be used in such a system in order to overcome the near-far effect. However, it is rather impractical to assume that there is perfect power control. Therefore, in this contribution we address a comprehensive model to calculate all possible MAI for the reverse link SPF CDMA system for both single and multiple platform scenarios. The analysis is based on the condition of perfect power control and imperfect power control with considering channel fading and shadowing.

In addition, this paper has proposed the method of system capacity reduction problem, namely by increasing minimum elevation angle defined for each platform and the method of adaptive antenna. The former method resulting the capacity improvement, however, it has to be paid by the increasing of required platform to cover the global coverage. The latter method is a well-known rigorous technique to enhance the capacity and suppress multipath signal and interference. However, the number of elements of the array onboard the platform will be limited by the array size, which is only in a few meters.

2. Method

2.1. SPF System CDMA Model

In this paper we propose two CDMA system model for the reverse link capacity analysis. Those are a single SPF and a multiple SPF model. Each platform is equipped with a multispot beam phased array antenna to create the spot beams or cells on the ground. The spot beam antenna characteristic complies with the ITU recommendations given in the following expression and is shown graphically in Fig. 1 [12],

$$G(\theta) = \begin{cases} 34.8 - 3(\theta/1.57)^2, & for\ 0^0 \le \theta \le 4.53^0 \\ 9.8, & for\ 4.53^0 \le \theta \le 5.87^0 \\ 55.95 - 60\log(\theta), & for\ 5.87^0 \le \theta \le 37^0 \\ -38.2, & for\ 37^0 \le \theta \le 90^0 \end{cases} \quad (1)$$

where $G(\theta)$ is the antenna gain in (dBi) of the spot beam with boresight angle θ.

In the single SPF model, interference is originated from the users in a reference cell and the other cell within the coverage of the platform as depicted in Fig. 2. However, interference in multiple SPF model is produced from the users in a reference cell, the users in the other cell within the platform coverage and the users in an overlapped region. We introduce an overlapped region in multiple SPF model as a region outside the coverage but still seen by the reference SPF, as shown in Fig. 3. We will show the interference contribution from the users located in an overlapped region, in which they cannot be neglected in the analysis.

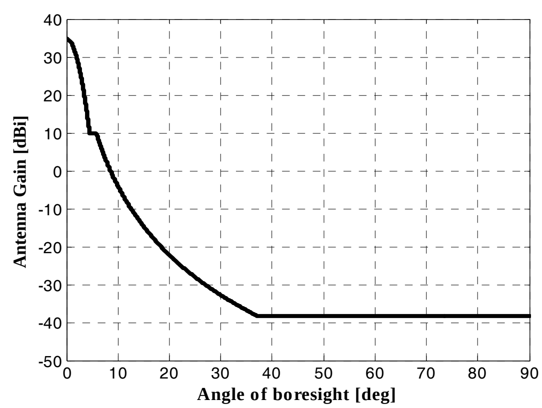

Figure 1. Antenna radiation diagram (ITU model)

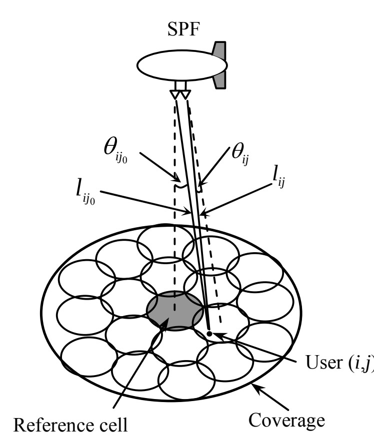

Figure 2. Single SPF model

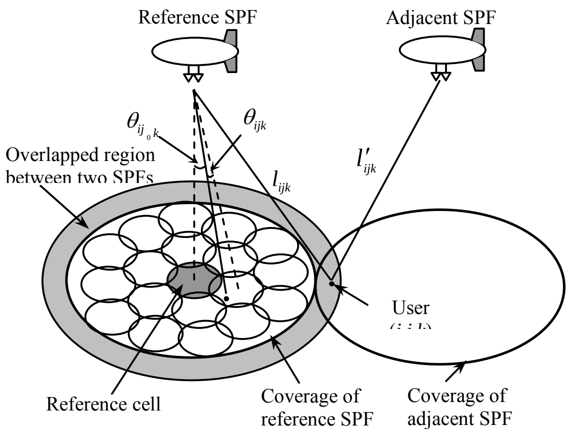

Figure 3. Multiple SPF model

We assume SPF located in the stratosphere at an altitude of 20 km and horizontal distance between each platform is 40 km. Therefore, the coverage area of each platform and the overlapped region are calculated directly using platform altitude and the setting of minimum elevation angle definition. The lower the minimum elevation angle is, the bigger the coverage area is and the larger of the overlapped region is. For analytical purposes we consider the minimum elevation angle to be of 10^0 and 20^0 for comparison.

The transmission quality for a digital CDMA system may be described in terms of the energy per bit over total noise power spectral density E_b/N_0,

$$\frac{E_b}{N_0} = \frac{W}{R}\frac{C}{I+\eta} \qquad (2)$$

where W is the channel bandwidth, R is the single user information bit rate, C is the received carrier power, I is the total co-channel interference power and η is the AWGN noise power.

2.1.1 Single SPF Model

First we evaluate a single SPF model. In this model, platform coverage area is divided into J cells with N simultaneously active users per cell. Each cell has the same area with the maximum main lobe gain of the spot beam is 34.8 dBi and intersection between adjacent cells is assumed at –3 dB contour, refer to 9.6^0 boresight angle according to the spot beam antenna characteristic presented in (1). The ith user in the jth cell is identified by a unique set of indices (i, j), where $1 \le i \le N$, $1 \le j \le J$. Let V denotes the set of interfering users who can be seen by the platform for the user-of-interest. For this model, if the user-of-interest is denoted by (i_0, j_0) then we can express received carrier-to-total interference plus noise power ratio in (2) as,

$$\frac{C}{I+\eta} = \frac{\alpha_{i_0j_0} EIRP_{i_0j_0} G_{j_0}(\theta_{i_0j_0})}{\sum_{(i,j)\in V} \alpha_{ij} EIRP_{ij} G_{j_0}(\theta_{ij}) + \eta} \qquad (3)$$

where α_{ij}^{-1} is the attenuation in the link from user (i,j) to the reference platform, including path loss and channel fading. $EIRP_{ij}$ is the effective isotropic radiated power of the user, and $G_{j_0}(\theta_{ij})$ is the antenna gain of the spot beam covering the user-of-interest with boresight angle θ_{ij}.

2.1.2 Multiple SPF Model

In a multiple SPF model, we assume each platform service area of an M-platform constellation is divided into J cells with N simultaneously active users per cell. For simplicity, the same size of coverage area for each platform under consideration is assumed in this paper. The cell structure is assumed to be similar with that of the cell structure for the single SPF model. This means each cell has the same area and intersection between adjacent cells is also assumed at –3 dB contour. In this model, the ith user in the jth cell of the kth platform is identified by a unique set of indices (i, j, k), where $1 \le i \le N$, $1 \le j \le J$, $1 \le k \le M$. Similar to the single SPF model, now let V denotes as the set of interfering users who can be seen by the serving platform for the user-of-interest, referred to as the reference platform including the users from overlapped region. We set the indices (i_0, j_0, k_0) to denote the user-of-interest in this model. The received carrier to total interference plus noise power ratio in (2) is then expressed as,

$$\frac{C}{I+\eta} = \frac{\alpha_{i_0j_0k_0} EIRP_{i_0j_0k_0} G_{j_0}(\theta_{i_0j_0k_0})}{\sum_{(i,j,k)\in V} \alpha_{ijk} EIRP_{ijk} G_{j_0}(\theta_{ijk}) + \eta} \qquad (4)$$

where all parameters definition is similar to (3) unless subscript k in (4) is added to denote an adjacent platform.

For both cases (single and multiple SPF model), a threshold value of E_b/N_0 for a certain performance requirement $(E_b/N_0)_{req}$, can be specified depending on channel characteristics, modulation method, and coding scheme. We define the outage probability, P_{out}, as the probability of failing to achieve the required $(E_b/N_0)_{req}$ and can be expressed by,

$$P_{out} = \Pr\left\{\frac{E_b}{N_0} \le \left(\frac{E_b}{N_0}\right)_{req}\right\} \qquad (5)$$

The SPF CDMA system capacity, referred to as the average number of users per cell N, is then linked to the outage probability, i.e. $N = f(P_{out})$, and can be determined by a certain requirement on the outage probability.

2.2. Reverse Link Interference Analysis

We notice the most important difference between the multispot beam SPF and cellular terrestrial scenarios lies in the interference mechanism. For a multispot beam SPF CDMA system, the users will be under power control of their respective spot beam, i.e. their respective base station. However, in SPF system all base stations are located on the location within a distance of few meters corresponds to the aperture of the phased array antenna onboard the platform. Thus, the user signal within the coverage of their respective spot beam will traverse the same path towards all base stations and experience approximately the same shadowing. Such a situation is not applicable for the users within the overlapped region, for example in multiple platforms scenario. Users in overlapped region are considered belong to adjacent SPF so that they will be under power control of their respective spot beam in their respective platform. These users will experience different shadowing with the users in the reference SPF and therefore they can contribute to produce interference to the user at the reference platform.

It has been experimentally investigated in our previous work that the SPF channel characteristic strongly depends on the elevation angle [13]. In such a situation, the channel for shadowed user (mostly in low elevation angle) is represented as a Rayleigh fading channel. While for unshadowed users, which are mostly in high elevation angle, the channel is modeled as Ricean with *K* (Rice factor) varies between 0.9 to 18.6 dB. By taking these into account, even an unshadowed user may experience a nontrivial degree of power control error (PCE) for a multispot beam SPF CDMA system. The power control error, γ, can be modeled as a lognormal distribution, i.e., $\gamma = e^{\delta}$, where δ is a zero-mean Gaussian random variable with standard deviation σ_δ. In the case of perfect power control the logarithmic standard deviation is 0 dB. After averaging over the fast fading, E_b/N_0 can be expressed as,

$$\frac{E_b}{N_0} = \frac{W}{R}\frac{P_0\, e^{\delta_{i_0 j_0 k_0}}}{I_{intra} + I_{inter} + \eta} \quad (6)$$

where P_0 is the nominal received power with ideal power control. I_{intra} is the interference originated from users within the reference cell and I_{inter} is the interference originated from users within the other cell. For both model we consider a reference cell is located at the nadir of the platform, served by the reference base station. The interference analysis for each type of interference will be described in the following sub-section.

2.2.1 Intracell Interference

When we consider perfect power control, the total interference power from the users inside the reference cell can be given as,

$$I_{intra} = \upsilon (N-1) P_0 \quad (7)$$

where υ is the voice activity factor, which is 1 with probability ψ and 0 with probability 1-ψ. In practical situation, the average received power at the spot beam antenna onboard the platform may not be the same for each user signal. Therefore, the total interference from users located within the reference cell under imperfect power control condition can be expressed by,

$$I_{intra} = \sum_{i=1}^{N-1} \upsilon P_0\, e^{\delta_i} \quad (8)$$

where δ_i is the Gaussian random variable of the received signal of the *i*th user.

2.2.2 Intercell Interference

The total interference power from other cell includes the interference power from other cell within the coverage of the reference platform and from the other cell within the overlapped region. This interference power is given as,

$$I_{inter} = \sum_{k=2}^{M} \sum_{j=1}^{J}\sum_{i=1}^{N} \upsilon P_0\, e^{\delta_{ij}}\, \beta_{ijk}^2 + \sum_{k=2}^{M} \sum_{j=1}^{J}\sum_{i=1}^{N} \upsilon P_0\, e^{\delta_{ijk}}\, \beta_{ijk}^2\, \varepsilon_{ijk}^2 \quad (9)$$

where β_{ijk}^2 is the power discrimination due to spot beam antenna radiation pattern and ε_{ijk}^2 is the power control factor for users in the overlapped region. Note the second term of (9) is neglected for the single SPF model analysis, which means there is no overlapped region.

According to the spot beam antenna radiation diagram that we consider in this paper, the distribution of spot beam antenna gain over a cell region is not uniform. The users in each cell must have additional power gain which is proportional to $1/G_j(\theta_{ijk})$, where $G_j(\theta)$ is the *j*th spot beam antenna gain to equalize the received power at their own spot beam antenna. However, the reference spot beam will suffer from this power gain. The power discrimination factor β_{ijk}^2 due to reference spot beam antenna gain is then given by,

$$\beta_{ijk}^2 = \frac{G_{j_0}(\theta_{ij_0k})}{G_j(\theta_{ijk})} \quad (10)$$

where θ_{ij_0k} is the off-boresight angle relative to the reference spot beam as depicted in Fig. 3.

Now let we consider the power control factor ε_{ijk}^2 to account for the interference brought by the users in the overlapped region, which are served and power controlled by an adjacent platform. Here we cannot ignore the distance, shadowing, and channel fading of the user relative to their respective platform. With considering the distances from the users and the shadowing state for such a user to both the reference platform and their own

platform, we can express the power control factor as,

$$\varepsilon_{ijk}^2 = \left(\frac{l'_{ijk}}{l_{ij_0k}}\right)^{\mu} 10^{\frac{\xi'_{ijk} - \xi_{ijk}}{10}} \quad (11)$$

where l'_{ijk} and l_{ijk} denote the distance from the users to their own serving platform and reference platform, respectively. ξ'_{ijk} and ξ_{ijk} is random variable modeling the shadowing effect corresponding to these two paths. The shadowing is modeled to follow Gaussian distribution with mean μ_ξ and standard deviation σ_ξ in dB. μ is the path loss exponent, in which μ = 2 is considered in our work. If we consider the shadowing to be taken as different values for the users at different elevation angles, the analysis will become too complicated. Thus we assume the shadowing varies only with the region in which the user is. This means the value of shadowing for the users within the reference cell (at the nadir) is smaller than that within the other cell inside the coverage of the reference platform. And shadowing of the users within the coverage of the reference platform is smaller than that within the overlapped region.

It is reasonable that the total MAI component can be approximated as a Gaussian random variable when the number of users in each cell (N) is become large. Therefore, the mean of total MAI (I) component normalized to P_0 (I/P_0) can be expressed as,

$$\mu_I = \psi\left[c_1\left(N-1+\sum_{(i,j,k)}\beta_{ijk}^2\right) + c_2\sum_{(i,j,k)}(l'_{ijk}/l_{ijk})^2\,\beta_{ijk}^2\right] \quad (12)$$

where

$$c_1 = E[e^{\delta}] = Ae^{\alpha^2\sigma_s^2} + (1-A)e^{\alpha^2\sigma_{\mu s}^2} \quad (13)$$

is the expectation value to account power control imperfection of both shadowed users and unshadowed users with standard deviation σ_s and σ_{us}, respectively.

$$c_2 = E[\varepsilon_{ijk}^2]/\left(l'_{ijk}/l_{ijk}\right)^2 = A^2e^{\alpha^2\sigma_\xi^2} + A(1-A)\frac{e^{\alpha\mu_\xi+\alpha^2\sigma_\xi^2/2}}{1+K} + A(1-A)e^{-\alpha\mu_\xi+\alpha^2\sigma_\xi^2/2}(1+K) + (1-A)^2 \quad (14)$$

is the parameter to account power control factor imperfection for the users within the overlapped region, where α= (ln 10)/10 and the parameter of A is the shadowing probability.

Similarly, we can derive the variance of normalized MAI (I/P_0) and is given by the following expression

$$\sigma_I^2 = \psi\left[(d_1 - \psi c_1^2)\left(N-1+\sum_{(i,j)}\beta_{ijk}^2\right) + (d_2 - \psi c_2^2)\sum_{(i,j,k)}(l'_{ijk}/l_{ijk})^4\,\beta_{ijk}^4\right] \quad (15)$$

where

$$d_1 = E[(e^{\delta})^2] = Ae^{2\alpha^2\sigma_s^2} + (1-A)e^{2\alpha^2\sigma_{\mu s}^2} \quad (16)$$

and

$$d_2 = E[\varepsilon_{ijk}^2]/\left(l'_{ijk}/l_{ijk}\right)^2 = A^2e^{4\alpha^2\sigma_\xi^2} + A(1-A)\frac{e2^{\alpha\mu_\xi+2\alpha^2\sigma_\xi^2/2}}{1+K} + A(1-A)e^{-2\alpha\mu_\xi+2\alpha^2\sigma_\xi^2/2}(1+K)^2 + (1-A)^2 \quad (17)$$

both d_1 and d_2 are the second moment to account power control imperfection for the users within the coverage of the reference platform and within the overlapped region, respectively.

Based on the definition in (5), we can express the outage probability for the reverse link SPF CDMA as,

$$P_{out} = \Pr\left\{\frac{W}{R}\frac{e^{\delta_{i_0j_0k_0}}}{I_{intra}/P_0 + I_{inter}/P_0 + \eta/P_0} \le \left(\frac{E_b}{N_0}\right)_{req}\right\}$$

$$= \Pr\{I_{intra}/P_0 + I_{inter}/P_0 \ge \varsigma\} \quad (18)$$

where

$$\varsigma = \frac{W}{R}\left[\frac{e^{\delta_{i_0j_0k_0}}}{(E_b/N_0)_{req}} - \frac{1}{E_b/\eta_0}\right] \quad (19)$$

where E_b/η_0 is the bit energy-to-AWGN spectral density ratio. Since the Gaussian distribution of $(I_{intra} + I_{inter})/P_0$ with mean μ_I and variance σ_I^2, we can obtain the outage probability conditioned on the power control error of the user-of-interest, $e^{\delta_{i_0j_0k_0}}$, as expressed by,

$$P_{out}|\delta = \frac{1}{2}erfc\left(\frac{\varsigma - \mu_I}{\sqrt{2\sigma_I^2}}\right) \quad (20)$$

where $erfc(\lambda)$ is the error function given by,

$$erfc(\lambda) = 1 - \int_0^{\lambda}\frac{2}{\sqrt{\pi}}\exp\left(-x^2\right)dx \quad (21)$$

3. Results and Discussion

The CDMA capacity is determined by evaluating (20) numerically for different parameters. We evaluate the system capacity in the reverse link for two different classes in 3G mobile services as presented in Table 1.

We assume all the numerical results obtained in this contribution refer to a voice activity factor of 3/8. We also set the total bandwidth W = 5 MHz and the bit energy-to-AWGN spectral density ratio E_b/η_0 = 20 dB. We choose the probability of shadowing (A) is 0.3 and the PCE standard deviation for unshadowed users (σ_{us}) is 1 dB.

3.1 Capacity for Single SPF Model

We evaluate the effect of multiple access interference in a single SPF model by at first calculating other-cell interference factor. The other cell interference factor is defined as the interference power produced by the users belonging to the other cells divided by that produced by the users within the reference cell. Table 2 demonstrates simulation result of the mean value of the other cell interference for different power control error standard deviation (σ_s). It can be observed that the other cell interference factor is increased as the power control error become large.

Table 1. QoS parameters for 3G multimedia services that we used in the analysis

R [kbps]	Typical Application	Min. Required $(E_b/N_0)_{req}$ [dB]
12.2	Speech	5
144	Real-time data	1.5

Table 2. Mean value of the other cell interference factor for single SPF model

PCE standard deviation (σ_s)	R = 12.2 kbps	R = 144 kbps
0 dB	0.24	0.26
1 dB	0.32	0.35
2 dB	0.39	0.43
3 dB	0.48	0.52

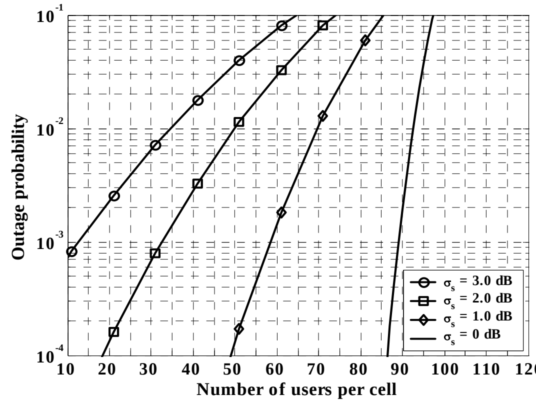

Figure 4. Effect of PCE standard deviation on the outage probability for a single SPF CDMA model (R = 12.2 kbps, E_b/N_0 = 5.0 dB)

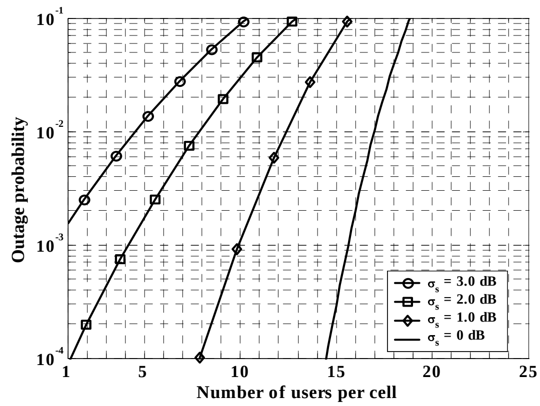

Figure 5. Effect of PCE standard deviation on the outage probability for a single SPF CDMA model (R = 144 kbps, E_b/N_0 = 1.5 dB)

In Fig. 4 and 5 the outage probability is plotted for the situation of perfect power control and imperfect power control with the information bit rate of 12.2 kbps (speech) and 144 kbps (real-time data), respectively. It is clear that the system capacity heavily depends on the accuracy of power control scheme. If the perfect power control could be achieved, the number of users per cell supported at P_{out} = 10^{-2} would be 93 users for speech and 17 users for real-time data. If the assumption of perfect power control is not held, the values of N will decrease dramatically. The system capacity drops by at

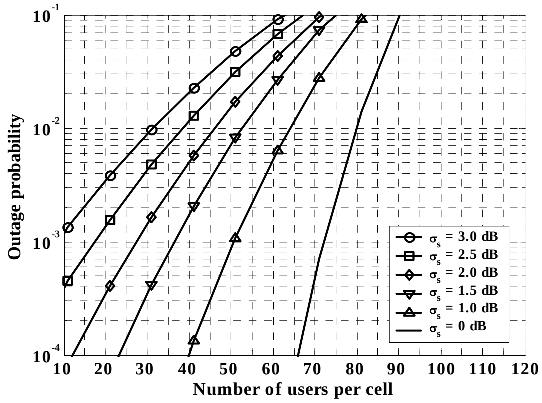

Figure 6. Effect of PCE standard deviation on the outage probability for a multiple SPF CDMA model (*R* = 12.2 kbps, E_b/N_0 = 5.0 dB, minimum elevation angle 10^0)

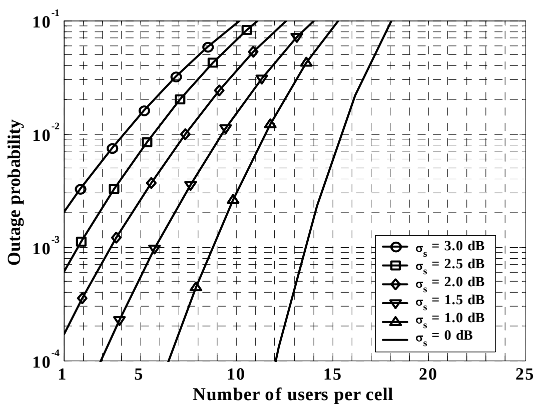

Figure 7. Effect of PCE standard deviation on the outage probability for a multiple SPF CDMA model (*R* = 144 kbps, E_b/N_0 = 1.5 dB, minimum elevation angle 10^0)

least 17% and 20% every 1 dBincrease in PCE standard deviation for speech and real-time data services, respectively.

3.2 Capacity for Multiple SPF Model

Now let we evaluate the system capacity for a model of multiple SPF. For the SPF constellation we considered, when the minimum elevation angle is 10^0, the mean values of the other cell interference factor for the overlapped region is 0.11. This value must be taken into account with the interference from the other cell within the coverage of the reference platform. In this model, PCE standard deviation (σ_s) is considered to vary every 0.5 dB so as to represent small variation of the power control imperfection. As a result, in Fig. 6 and 7 the outage probability is plotted for different class of services considered in this paper. Compared with the result obtained for single SPF model, if

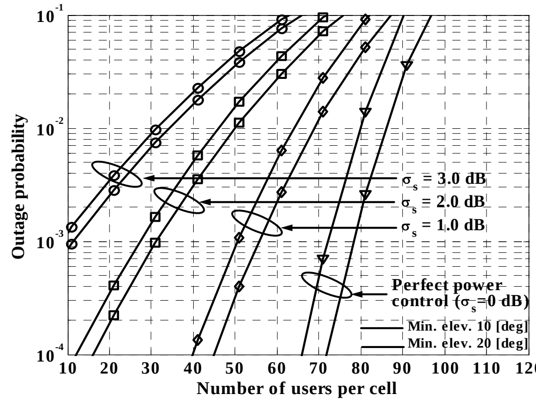

Figure 8. Effect of PCE standard deviation on the outage probability for a multiple SPF CDMA model with different minimum elevation angle (*R* = 12.2 kbps, E_b/N_0 = 5.0 dB, minimum elevation angle 10^0 and 20^0)

perfect power control can be achieved, the number of users supported at $P_{out} = 10^{-2}$ would reduce by at least 14% for speech services and 12% for real-time data. This capacity reduction in multiple SPF model is because of the interference from the users within the overlapped region belonging to the nearest adjacent platform. This amount of capacity reduction is not trivial in the particular system when the bandwidth is very critical.

One approach to solve this problem is to increase the minimum elevation angle of the platform's coverage. This scheme is able to reduce the size of the overlapped region so that additional interference from this region can be decreased. In Fig. 8 we demonstrate that the system capacity, i.e. for speech services, can be improved by increasing the minimum elevation angle defined for each platform. The system capacity can be increased so as become close to the capacity of single SPF model if the minimum elevation angle changes from 10^0 to 20^0. However, such scheme would increase the number of platforms in the constellation that are required in order to provide global coverage.

The specification of $(E_b/N_0)_{req}$ is another parameter that affecting the system capacity. The influence of $(E_b/N_0)_{req}$ on the system capacity is illustrated in Fig. 9. From the figure, we observe that the system capacity is increased significantly by decreasing the required threshold of E_b/N_0. In a multiple SPF model with the minimum elevation angle 10^0, the system capacity will increase by at least 30% at $P_{out} = 10^{-2}$ for every 1 dB decrease in $(E_b/N_0)_{req}$. When the minimum elevation angle increases to 20^0, a proportional increasing in capacity can also be obtained by decreasing the value of $(E_b/N_0)_{req}$.

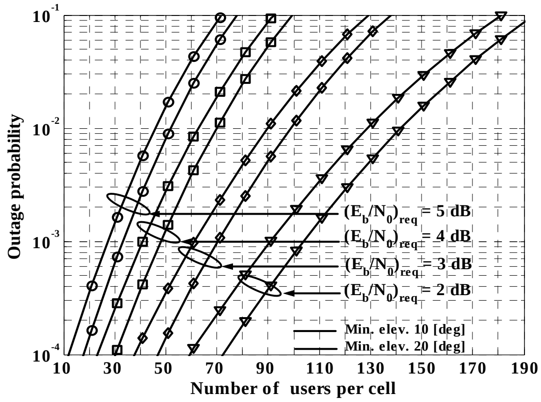

Figure 9. Effect of E_b/N_0 on the outage probability for a multiple SPF CDMA model with different minimum elevation angle (R = 12.2 kbps, σ_s = 2 dB, minimum elevation angle 10^0 and 20^0)

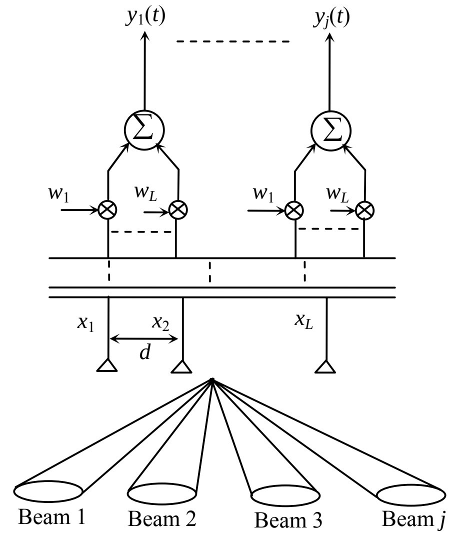

Figure 10. System model for SPF adaptive antenna

4. Capacity Performance with Adaptive Antenna Arrays

We have considered CDMA capacity in SPF system, which is equipped with multi-beam phased array antenna whose radiation pattern characteristics follow the reference model specified in [12]. The array antenna that we used has a static beam and the results have indicated that the interference from users outside the reference cell is attenuated by the spot beam antenna characteristics.

Interference level is found not trivial because the desired spot beam antenna suffers from the power gain of the users outside the reference cell. In this condition the users in each cell outside the reference cell must have an additional in power to equalize the received power at their own spot beam antenna due to the distribution of the antenna gain over a cell region is not uniform. If user (i,j,k) has an off-boresight angle $\theta_{ijk}^{(j)}$ relative to his own spot beam, the additional power gain is then proportional to $1/G_j(\theta_{ijk}^{(j)})$, where $G_j(\theta)$ is the j-th spot beam antenna gain.

It is possible to implement flexible beam steering that is intended for each of the user terminals by means of adaptive array antennas onboard the platform [8]. It represents the special cases of cellular communication in the sense of that all base stations are co-located in one platform and operated in a free space environment. The latter case is associated with that there is no scatterers present, and where the wave arriving at the array can be represented by simple plane waves with constant amplitude. Therefore the propagation channel between users and base stations antenna depends only on the direction of the wave arrival. In such a case the propagation channel is given by a steering vector whose components are the relative phases and amplitudes of a single wave at each of the antenna elements. This following sub-section aims at evaluating the SPF CDMA capacity under the condition of employing adaptive antenna.

4.1 Adaptive Antenna Model for the SPF

When adaptive antenna arrays are employed at the base station, directional beams can be formed to the desired user to reduce the interference level by allowing users to transmit lower power. Fig. 10 shows a model of linear adaptive array antenna onboard the platform. The array is having L elements with a spacing of d and generates j receiving beams. The arrays response in any direction is found by calculating the magnitude of the array output y

when the channel is set to the array vector for that direction as expressed by,

$$y = \vec{w}_{opt}^{H} \bullet \vec{x} \tag{22}$$

where $\vec{x}$ is the array response vector which is a function of direction of arrival (θ) of each element. $\vec{w}_{opt}^{H}$ represents the transpose complex conjugate of an optimum value of adaptive weight vector, which is associated with each user (i,j,k). For an array of L elements at the base station, the array response vector $\vec{x} = \vec{a}(\theta)$ is an L x 1 vector expressed as,

$$\vec{x} = \vec{a}(\theta) = \left[a_1, a_2, a_3, ..., a_L\right]^T, \tag{23}$$

where for m^{th} element the array response is

$$a_m = \exp\left(-i\frac{2\pi}{\lambda}m\,d\sin\theta\right) = \exp(-ikmd\sin\theta) \quad (24)$$

It is then possible to direct the maximum gain of the array factor in the desired direction by adjusting the weight vector. We used well-known correlation matrices of the received signal to compute the direction-of-arrival [14] rather than the sub-space algorithms of direction finding, such as MUSIC or ESPRIT. This is because the number of users, in SPF CDMA system, usually exceeds the number of antenna array elements due to the space limitation onboard the platform for the array size. After getting the weight vector for the user-of-interest, $w_{i_0 j_0 k_0}$, then the power discrimination factor β^2_{ijk} in (10) has to be modified and is given by,

$$\beta^2_{ijk} = \left| w^H_{i_0 j_0 k_0}\, a(\theta^{j_0}_{ijk}) \right|^2 \quad (25)$$

4.2 Numerical Results

In order to estimate CDMA capacity by employing adaptive antennas, we use the same specification of parameters as used in section 4. In this sub-section, however, we assume that a directional beam in the direction of desired user is formed by adaptive algorithms, which also cover the reference cell. Sidelobes level is assumed to exist with a certain level much lower than the main lobe. For comparison purposes, fixed multi-beam antenna radiation pattern adopted by ITU [12] is also considered. Voice with the information bit rate of 12.2 kbps in a single SPF model and multiple SPF model is calculated under the standard deviations of power control error 2.0 dB and 1.0 dB for shadowed and unshadowed users, respectively, is considered.

Fig. 11 shows numerical results with the comparison of using original array antenna (proposed in [12]) and adaptive antenna with various sidelobes level for a single SPF model. It is found that for 10^{-2} outage probability, about 50 users can be supported in each cell when the fixed multi-beam antenna is employed. When adaptive antenna with the sidelobe level of 30 dB lower than the maximum gain is employed, the number of users supported in the system increase up to 58 users per cell. A slightly improved in capacity is observed due to a little difference of the sidelobe level between fixed antenna and adaptive antenna. When the sidelobe level of adaptive antenna is increased, however, the capacity is improved significantly. For example the system capacity can reach 78 users per cell when the sidelobe level is –35 dB. Furthermore, if the sidelobe level can be decreased to –40 dB and –45 dB, the number of users per cell will go up greatly to 100 and 138 users, respectively.

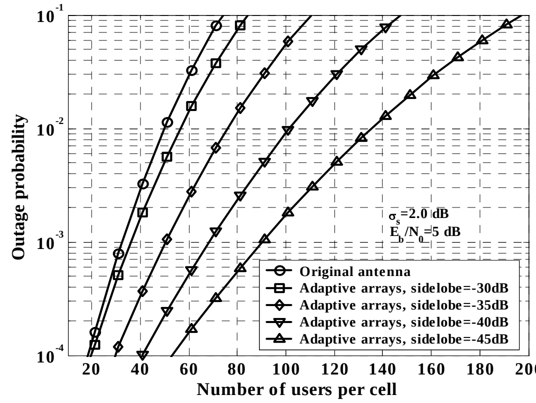

Figure 11. Effect of adaptive antenna on the outage probability for a single SPF CDMA model with different sidelobe level (*R* = 12.2 kbps, σ_S = 2 dB, minimum elevation angle 10^0)

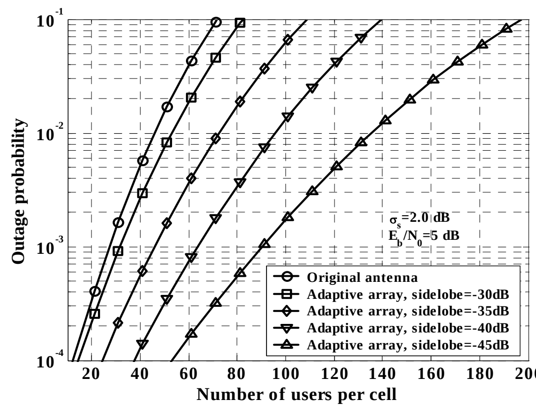

Figure 12. Effect of adaptive antenna on the outage probability for a multiple SPF CDMA model with different sidelobe level (*R* = 12.2 kbps, σ_S = 2 dB, minimum elevation angle 10^0)

Fig. 12 demonstrates the capacity improvement by using adaptive antenna in multiple SPF model. The tendency of capacity improvement because of the usage of adaptive antenna is similar as of in the single SPF model. Moreover, when the adaptive antenna with sidelobe of –45 dB is employed, we found that the capacity for multiple SPF model is equal with that of the capacity for single SPF model. This is because an adaptive antenna can work properly to suppress the interference produced by the users outside the reference coverage of the desired platform.

5. Conclusions

This paper has demonstrated an analysis of the reverse link CDMA system capacity in a multispot beam SPF environment. The system capacity of a single SPF model and multiple SPF model is evaluated in terms of the outage probability requirement. It is found that because of the effect of imperfect power control, the system capacity is significantly decreased.

In multiple SPF model, multiple access interference produced by the users within an overlapped region is a nontrivial reduction of the system capacity. Therefore, the capacity reduction caused by these users has to be compensated. One solution is to increase the minimum elevation angle defined for each platform's coverage. For the model we consider in this paper, with the setting of minimum elevation angle is 20^0, the system capacity can be improved so as nearly as the capacity brought by a single SPF model.

However, the increasing of minimum elevation angle means the required number of platform is also increased to cover global coverage. For the reason, adaptive antenna has been proposed in this paper to solve the system capacity reduction problem due to the interference produced by the users within the other cell. Significant improvement in the capacity can be achieved by setting the sidelobe level of the array antenna.

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