Forward Link Power Control Strategy and Its Optimum Issue on CDMA Cellular Network

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Abstract

In this paper, we proposed a theoretical method in order to estimate the forward link outage probability and user capacity of a cellular system which are based on IS-95 CDMA standard, especially impact of power control strategy and voice activity monitoring on the system under long-term fading. According to the numerical results obtained in this paper, the power control strategy leads to approximately threefold the user capacity contrast to the situation without power control strategy. The power control strategy not only improves the desired signal to interference ratio in the reference user's receiver, but also offers uniform service to the user wherever it is located in the cell.

1. Introduction

In a CDMA system, all users share the same spectrum in each cell that the quality of transmission is susceptible to the well-known near-far effect. Power control[1][2][3] is exercised to reduce such impacts. The work in this paper is to be done for investigating forward link outage probability in the presence of power control strategy under long-term fading, which has not been fully estimated in previous papers, although there are the vast literature on CDMA cellular systems.

In order to solve the near-far issue and provide uniform service to all the users in the cell, which are the important issues in forward link, in this paper, we present a theoretical analysis of forward link in a CDMA cellular system. Our analytical characteristics are 1)Considering the fading effects, 2)Adopting the forward link power control strategy and voice activity monitoring and 3)Optimal analysis of the forward link when adopting the power control. It is validated against the simple analytical models proposed in Refs.[1],[2] and [7] under non-fading effect.

The practical *ISR* scheme[6],[9] adopted power allocation based on the *ISR* level in the user receiver, that means the BS transmits power according to the detected level of *ISR* to ensure it as constant value wherever the user is located in the cell. In this case, the system can provide perfect uniform service to all users in the system. Unfortunately, theoretical analysis can not be achieved on it using this way, only simulation methods are often used in many papers[6][8][9]. In this paper, we proposed a theoretical method under the same wireless medium in order to achieve the same purpose, i.e., perfect uniform service.

2. System Model and *FLPCS* Strategy

A. Interference Geometry

The geometry of the interference model is shown in Figs.1 and 2. The interference generated by the users in the reference cell(the 0-th BS) is defined as intracellular interference. The interference from the users located in surrounding cells is defined as intercellular interference. The reference mobile user is communicating with its base station(the 0-th BS) in the presence of intracellular interference and intercellular interference from other base stations(the 1-st BS to the 11-th BS) in our model.

For the reference mobile user located at a distance r_i in the reference cell(the 0-th BS) shown in Fig.2, the distance r_j from the reference mobile user point to the j-th interfering base station is calculated as

$$r_j = \sqrt{D_j^2 + r_i^2 - 2D_j r_i cos(\omega)} \qquad (1)$$

B. Propagation Model and Power Control Strategy

For general propagation loss of electronic signal, three factors are associated with the propagation loss, i.e., distance path loss, long-term fading and short-term fading(considered as negligible in this paper). Furthermore, in CDMA systems, the real advantage is the nature of human conversation,.i.e., the voice activity monitoring can been used for reducing mutual interference. The received signal, P_r because of the propagation loss between the BS and the user can be expressed as follows[4][9]

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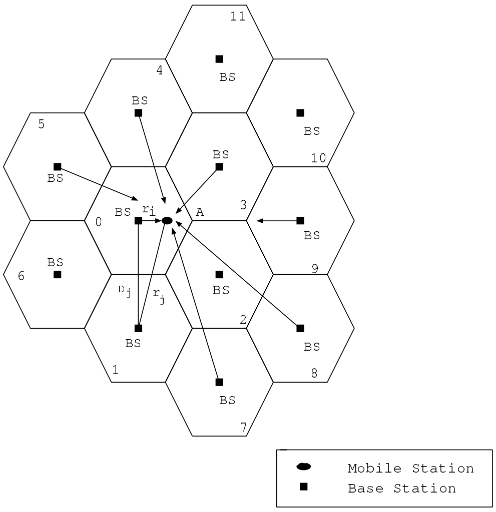

Fig. 1 Cellular system structure[2][6]

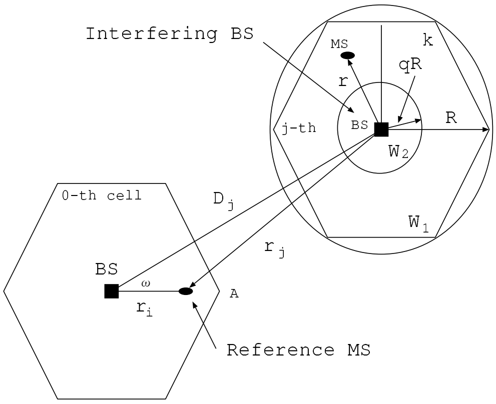

Fig. 2 Intercellular interference architecture ($Z=W_1+W_2$, based on the power control strategy, i.e., Eq.(3))

$$P_r = \begin{cases} (\frac{\lambda}{4\pi})^2 \frac{\psi}{r^2} P_t 10^{\frac{\zeta}{10}} & r \leqq d \\ (h_{bs}h_m)^2 \frac{\psi}{r^4} P_t 10^{\frac{\zeta}{10}} & r > d \end{cases} \tag{2}$$

where,

$$d \equiv \frac{4\pi h_{bs} h_m}{\lambda}$$

In Eq.(2), P_t is the transmitting power from the base station, r is the distance between the mobile user and the BS, λ is the wavelength(i.e., carrier frequency), h_{bs} is the base station antenna height, and h_m is the mobile antenna height. ψ denotes the voice activity variable, which is equal to one with probability of α and to zero with probability of 1-α, where α is defined as voice activity monitoring factor[2][4][8]. ζ is a Gaussian random variable because of long-term fading, with typical standard deviation, $\sigma=$ 8dB and zero mean[6][7][9].

The forward link power control strategy is assumed to be similar to Ref.[1] termed as the τ-th power of distance driven. The transmitting power $P(r)$ for a user MS located at a distance r from the base station BS as shown in Fig.2 is obtained by

$$P(r) = \begin{cases} P_{req} \ (\frac{r}{R})^{\tau} & r > qR \\ P_{req} \ q^{\tau} & r \leqq qR \end{cases} \tag{3}$$

where in Eq.(3), R is a radius of the cell. P_{req} is the transmitting power required to reach the users located at the boundary between cells. q is the power control parameter($0 \leqq q \leqq 1$) so that each user located at a distance r less than the qR is assumed of receiving a minimum amount of transmitting power from the BS. As shown in Fig.2, W_1 and W_2 are defined as the area of $r > qR$ and area of $r \leqq qR$.

Mobile users are assumed here to be uniformly distributed in an equivalent disc of radius R shown in Fig.2. The density function of mobile users in a cell is

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

where N is the total number of active users in one cell. The total transmitting power with the τ-th power of distance driven control as

$$\begin{aligned} P_t &= \iint_{W_2} P_{req} q^{\tau} \rho dW + \iint_{W_1} P_{req} (\frac{r}{R})^{\tau} \rho dW \\ &= N P_{req} \{ q^{\tau+2} + \frac{2}{\tau+2}(1-q^{\tau+2}) \} \end{aligned} \tag{5}$$

If we do not adopt the distance driven control strategy, the full power P_{req} is necessary for each user in a cell, then the total transmitting power $P_t = NP_{req}$. Comparing the total transmitting power with Eq.(5), we obtained the reduction function η when adopting the power control strategy as

$$\eta = q^{\tau+2} + \frac{2}{\tau+2}(1-q^{\tau+2}) \tag{6}$$

where we select different τ-th power of distance control law, τ to obtain the reduction of transmitting power. If we select τ=0, we obtain the situation without power control strategy, i.e., η=1. As q decreases, the function η becomes flat. If we set q=0, we obtain the basic situation in Ref.[2], i.e., $\eta = \frac{2}{(\tau+2)}$.

3. Theoretical Analysis for Forward Link

A. Spread-Spectrum Interference Analysis

In the CDMA systems, interfering sources cover all the base stations for forward link. There are no Guard-bands between users and cells. The geometry of the interference model is shown in Figs.1 and 2. We will consider the i-th reference user located at a distance r_i on the line from the base station BS to the point A in Fig.2. In this case, we will consider the intracellular interference and the intercellular interference generated by the surrounding eleven cells as shown in Fig.1.

In the service area, if the base station transmits power $P(r_i)$ for the i-th reference user, substituting Eq.(3) into Eq.(2), the wanted signal power received by the reference user located at the distance r_i with the τ-th power of distance driven control is

$$S = \begin{cases} k_1 \frac{1}{r_i^2} P_{req} q^{\tau} 10^{\frac{\zeta_i}{10}} & 0 < r_i \leqq d \\ k_2 \frac{1}{r_i^4} P_{req} q^{\tau} 10^{\frac{\zeta_i}{10}} & d < r_i \leqq qR \\ k_2 \frac{1}{r_i^4} P_{req} \big(\frac{r_i}{R}\big)^{\tau} 10^{\frac{\zeta_i}{10}} & qR < r_i \leqq R \end{cases} \quad (7)$$

where,

$$k_1 = (\frac{\lambda}{4\pi})^2, \qquad k_2 = (h_{bs} h_m)^2$$

Based on the wanted signal in Eq.(7), the cell is composed of three areas according to the location of the reference user. In the following section, we induce the formulations about the situation of the reference user located in outer area ,$qR < r_i \leqq R$ in the 0-th cell. The formulations about the reference user located in the area,$d < r_i \leqq qR$ and the area, $0 < r_i \leqq d$ in the cell can be derived by the same method depicted in this section. In all formulations, if we set τ=0, the situation of the system becomes a cellular system without power control strategy used in the forward link investigation as Refs.[1] and [2].

The intracellular interference is the interference generated by the users which are power controlled by the reference base station(the 0-th BS) shown in Fig.2. As the reference user located in its cell receives a composite signal from its cell base-station composed of the desired signal and N interfering signals for the users uniformly distributed in the cell. The mean of the total intracellular interference-to-signal ratio $(\frac{I_{int}}{S})_t$ from other channel transmitting power in its own cell when the reference user located at $qR < r_i \leqq R$ area of is

$$\begin{aligned} M[(\frac{I_{int}}{S})_t] &= \iint_{W_1} \alpha (\frac{r}{r_i})^{\tau} \rho dW + \iint_{W_2} \alpha q^{\tau} (\frac{R}{r_i})^{\tau} \rho dW \\ &= \eta N \alpha (\frac{R}{r_i})^{\tau} \end{aligned} \quad (8)$$

Using the same method, we can obtain the mean of the total intracellular interference-to-signal ratio $\big(\frac{I_{int}}{S}\big)_t$ from other channel transmitting power in its own cell when the reference user located at each area of the 0-th cell summarized as

$$M[(\frac{I_{int}}{S})_t] = \begin{cases} \eta N \alpha \frac{1}{q^{\tau}} & 0 < r_i \leqq qR \\ \eta N \alpha \big(\frac{R}{r_i}\big)^{\tau} & qR < r_i \leqq R \end{cases} \quad (9)$$

The interference from the users which are controlled by surrounding base stations is defined as intercellular interference. The intercellular interference-to-signal ratio $\big(\frac{I_{ext}}{S}\big)_{W_1}$ for the reference user located at the area, $qR < r_i \leqq R$ of the 0-th cell, from one external user located in the inner area, W_1 in surrounding j-th cell modelled as shown in Fig.2 is

$$(\frac{I_{ext}}{S})_{W_1} = \psi k_3 r^{\tau} 10^{\frac{\zeta_j - \zeta_i}{10}} \quad (10)$$

where,

$$k_3 = (\frac{r_i}{r_j})^4 (\frac{1}{r_i})^{\tau}.$$

Using the same method, the intercellular interference-to-signal ratio $\big(\frac{I_{ext}}{S}\big)_{W_2}$ for the reference user located at the same area from one external user located in the outer area, W_2 in surrounding j-th cell modelled as shown in Fig.2 is obtained as

$$(\frac{I_{ext}}{S})_{W_2} = \psi k_4 10^{\frac{\zeta_j - \zeta_i}{10}} \quad (11)$$

where,

$$k_4 = (\frac{r_i}{r_j})^4 (\frac{q r_i}{R})^{\tau}.$$

Consequently, the total intercellular interference-to-signal ratio $\big(\frac{I_{ext}}{S}\big)_t$ for the reference user located at the same area from all surrounding cells rather than the reference cell can been calculated by integrating the above Eqs.(10) and (11) mixed with a continuous and uniform user density over a circular region approximating an hexagonal cell shown in Fig.2 as follows

$$\begin{aligned} (\frac{I_{ext}}{S})_t = \sum_{j=1}^{n} \Big\{ & \iint_{(W_2)_j} (\frac{I_{ext}}{S})_{W_2} \rho dW \\ & + \iint_{(W_1)_j} (\frac{I_{ext}}{S})_{W_1} \rho dW \Big\} \end{aligned} \quad (12)$$

where, n is the total number of surrounding cells considered in the cellular mobile system as shown in Fig.1. Substituting Eqs.(10) and (11) into (12) yields (13), i.e., $\big(\frac{I_{ext}}{S}\big)_t$ is a convex function of external cell BS's interference. We have the mean of the total intercellular interference-to-signal ratio as[6][7]

$$\begin{aligned} M[(\frac{I_{ext}}{S})_t] = \frac{2\alpha N}{R^2} \sum_{j=1}^{n} \Big\{ & \int_{qR}^{R} k_4 r F(\xi, r_i/r_j) dr \\ & + \int_{0}^{qR} k_3 r^{\tau+1} F(\xi, r_i/r_j) dr \Big\} \end{aligned} \quad (13)$$

where in Eq.(13), $\xi = \zeta_j - \zeta_i$ is a normal random variable have zero mean and standard deviation of $\sigma_\xi^2(\sigma_\xi^2 = 2\sigma^2)$ as ζ_j and ζ_i are independent fading random variables. $F(\xi, r_i/r_j)$ in the denominator of Eq.(13) can be obtained as

$$\begin{aligned} F(\xi, r_i/r_j) &= M[\phi(\xi, r_i/r_j)10^{\xi/10}] \\ &= \int_{-\infty}^{\nu} exp(\xi ln10/10) \cdot \frac{exp(-\xi^2/2\sigma_\xi^2)}{\sqrt{2\pi\sigma_\xi^2}} d\xi \quad (14) \end{aligned}$$

where $\phi(\xi, r_i/r_j)$ is the unit function limited by a constraint function of ν for W_1 and W_2, which accounts for the user located at the boundary between cells tending to communicate to a BS that offers the least signal attenuation under the long-term fading effects, otherwise soft-handoff may occur[8][9]. Based on the principle and Eqs.(10) and (11), that is, $I_{ext}/S \leqq 1$, we can obtain the constraint functions as

$$\begin{aligned} \nu_{W_1} &= -10log(k_3) - 10\tau log(r), \\ \nu_{W_2} &= -10log(k_4), \end{aligned}$$

We use the similar method to the calculation of the second moment, then the variance of total intercellular interference-to-signal ratio $V[(\frac{I_{ext}}{S})_t]$ for the same reference user can been obtained as

$$\begin{aligned} V[(\frac{I_{ext}}{S})_t] = \sum_{j=1}^{n} \Big\{ \iint_{(W_2)_j} V[(\frac{I_{ext}}{S})_{W_2}]\rho dW \\ + \iint_{(W_1)_j} V[(\frac{I_{ext}}{S})_{W_1}]\rho dW \Big\} \quad (15) \end{aligned}$$

where,

$$V[(\frac{I_{ext}}{S})_{W_1}] = \alpha k_3^2 r^{2\tau} H(\xi, r_i/r_j) \quad (16)$$

and

$$V[(\frac{I_{ext}}{S})_{W_2}] = \alpha k_4^2 H(\xi, r_i/r_j) \quad (17)$$

In Eqs.(16) and (17), the functions of $H(\xi, r_i/r_j)$ are

$$H(\xi, r_i/r_j) = G(\xi, r_i/r_j) - \alpha F^2(\xi, r_i/r_j) \quad (18)$$

where, $F(\xi, r_i/r_j)$ is obtained by Eq.(14). Using the same processing method which is used to obtain Eq.(14), we can obtain the equation $G(\xi, r_i/r_j)$ as

$$\begin{aligned} G(\xi, r_i/r_j) &= M[\phi^2(\xi, r_i/r_j)10^{\xi/5}] \\ &= \int_{-\infty}^{\nu} exp(\xi ln10/5) \cdot \frac{exp(-\xi^2/2\sigma_\xi^2)}{\sqrt{2\pi\sigma_\xi^2}} d\xi \quad (19) \end{aligned}$$

We substitute Eqs.(16) and (17) into Eq.(15), after some mathematical manipulations, the variance of total intercellular interference-to-signal ratio is obtained as

$$\begin{aligned} V[(\frac{I_{ext}}{S})_t] = \frac{2\alpha N}{R^2} \sum_{j=1}^{n} \Big\{ \int_0^{qR} k_3^2 r^{2\tau+1} H(\xi, r_i/r_j) dr \\ + \int_{qR}^{R} k_4^2 H(\xi, r_i/r_j) r dr \Big\} \quad (20) \end{aligned}$$

B. Principle of Optimum Power Control Curve Shape

Based on the analysis of the subsection 3-A, we use Eqs.(9) and (13) to write the total interference-to-signal ratio, i.e.,*ISR*=$\left(\frac{I}{S}\right)_t$ as the sum of interference-to-signal ratio for the reference user located in the area ,$qR < r_i \leqq R$ in the 0-th cell as

$$(\frac{I}{S})_t = M[(\frac{I_{int}}{S})_t] + M[(\frac{I_{ext}}{S})_t] \quad (21)$$

In Eq.(21), the first fraction is the mean of the total intracellular interference-to-signal ratio obtained by Eq.(9). The second fraction is the mean of the total intercellular interference-to-signal ratio by Eq.(13). In order to obtain the highest possible user capacity, we need to minimize the maximum value of Eq.(21).

Eq.(21) was numerically evaluated for the values of q to obtain that q=0.55 and 0.7 are the optimal values when τ=2 and 3 as shown in Figs.3 and 4, in which this means that the high q benefits the users located in intermediate region, while the opposite condition benefits the users in the boundary. For intermediate location users, there can be considerable variation in performance, depending on the values of q and τ. On the optimal curves of *ISR*, the worst service points are upper bounds of *ISR* at the power control parameter points, q as P1 and P2 which is termed as 'hole' [1]. When q=0, *ISR* is as shown in Fig.5, the worst point termed as P0, is at the boundary between cells.

C. Analysis of User Capacity and Outage Probability

The outage probability is defined as the probability that Bit-Error-Rate(*BER*) exceeds a certain level of performance for digital voice communication. The outage probability of the reference user in the 0-th cell is given by[9]

$$\begin{aligned} P_{out} &= P_{out}(BER < 10^{-3}) \\ &= P_{out}\Big\{M[\Big(\frac{I_{ext}}{S}\Big)_t] \geqq \kappa\Big\} \quad (22) \end{aligned}$$

We adopt the Gaussian approximation for simplification, and the outage probability of the reference user is described as[6][9]

$$P_{out} = \frac{1}{2} erfc\Big\{\frac{\kappa - M[\Big(\frac{I_{ext}}{S}\Big)_t]}{\sqrt{V[\Big(\frac{I_{ext}}{S}\Big)_t]}}\Big\} \quad (23)$$

where,

$$\kappa = \frac{1}{\delta_{req}} - M[\left(\frac{I_{int}}{S}\right)_t], \qquad \delta_{req} = \frac{1}{G}\left(\frac{E_b}{I_0}\right)_{req} (24)$$

where, $G = \frac{W_{ss}}{R_b}$, $\left(\frac{E_b}{I_0}\right)_{req}$ is the required bit energy to the noise density ratio. Eq.(25) shows that the outage probability is determined by κ, the mean $M[\left(\frac{I_{ext}}{S}\right)_t]$, and the variance $V[\left(\frac{I_{ext}}{S}\right)_t]$, of intercellular interference. The user capacity is defined as the total number of users, N in the cell when the outage probability of the reference user is equal to 0.01[6][9] in this paper.

4. Numerical Results and Discussions

The following parameters are used in our calculation, such as:

- · Fading parameter σ=6 dB to 9 dB
- · Voice activity monitoring factor α=3/8
- · Frequency F=900 MHz
- · Spread bandwidth W_{ss}=1.228 MHz
- · Required $E_b/I_0 = 5dB$
- · Information bit rate $R_b = 9.6kbps$
- · Radius of cell R = 10 km
- · Height of BS $h_{bs} = 60m$
- · Height of MS $h_m = 1.5m$

According to the description in Sect.3, all the results given here are the worst points P0, P1 and P2, e.g., the outage probability is calculated according to the worst values as the reference user is located at those points, otherwise, better than them. At the worst points, e.g., P0, P1 and P2, the effect of the power control strategy, voice activity monitoring and fading (slight ~ heavy) on the cellular forward link outage probability and user capacity were fully estimated.

A. Outage Probability

Fig.6 shows the forward link outage probability with and without power control strategy under the slight fading effect, σ=6 dB versus the number of active users in each cell, N. It is found from Fig.6 that the forward link user capacity increases to approximately 2 times and 2.5 times at P1 and P2 contrast to P0 without power control strategy when the outage probability is equal to 0.01. Fig.7 shows the same situation under the heavy fading effect. The forward link user capacity is very sensitive to the value of σ. Without power control strategy, about 6.7 percents the user capacity is maintained with the value of σ=9 dB contrast to the situation when σ=6 dB. In the presence of power control strategy, about 16.4 percents and 18.2 percents are maintained at P1 and P2 points, respectively.

B. Comparison

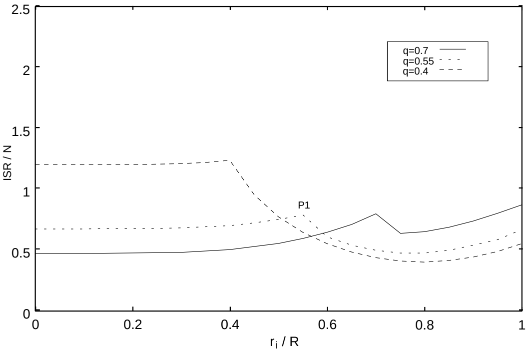

Fig. 3 Relative total *ISR* versus distance r_i/R with the power control ($\tau = 2$, $\sigma = 8dB$, $\alpha = 3/8$)

As a numerical example for comparison with the results of Refs.[1] and [2] under non-fading effect, we note that at the same typical parameters, e.g., $E_b/I_0 = 5dB$, $W_{ss} = 1.228Mhz$, $R_b = 9.6kbps$, $\sigma = 8dB$ and voice activity monitoring factor, α=3/8. Based on them, we obtained the numerical results of user capacity at P1 and P2, such as 40 users/cell and 44 users/cell. The corresponding value reported in Ref.[1] is 96 users/cell under non-fading effect. From these results, we can see the decrease is over 50 percents under the typical fading effect which plays an important role on the cellular system. In design of cellular mobile system, particular attention of selection of BS and the power control strategy should be paid carefully.

In comparison with the *ISR* Driven power control strategy reported in Refs.[6] and [9], the results obtained by a computer simulation using Monte Carlo method were estimated by Gillhousen et al. It is clear that the capacity increases to 38 users/cell by introducing the *ISR* Driven power control strategy. We theoretically calculated the situation of forward link by introducing the distance driven control strategy and obtained the optimum results at P1 and P2, such as capacity of 40 users/cell and 44 users/cell, respectively. In summary, the simulation[9] and the theoretical results calculated in this paper are based upon the more practical propagation models and the fading environments, which prove the validity of them. This theoretical analysis is validated against the simple analytical models proposed in Refs.[1] and [2] under non-fading effect or Ref.[4] without power control strategy.

5. Conclusion

This paper presented a theoretical analysis approach of forward link in CDMA cellular system under the slight and heavy fading effects. Based on the numeri-

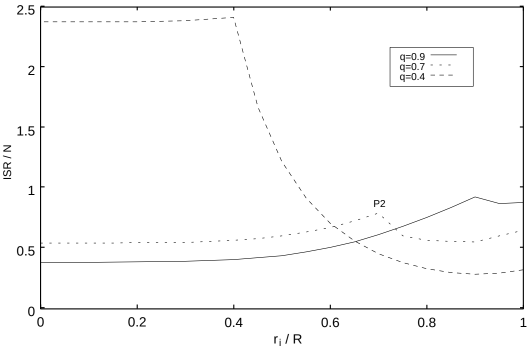

Fig. 4 Relative total ISR versus distance r_i/R with the power control ($\tau = 3$, $\sigma = 8dB$, $\alpha = 3/8$)

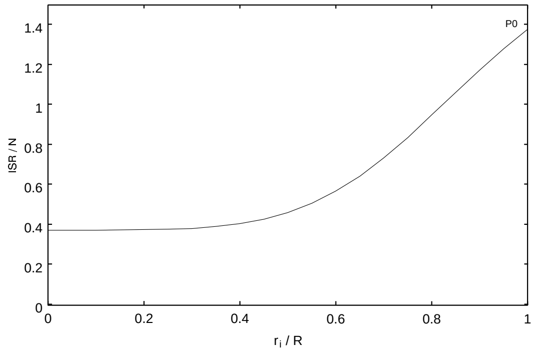

Fig. 5 Relative total ISR versus distance r_i/R without the power control ($\tau = 0$, $\sigma = 8dB$, $\alpha = 3/8$)

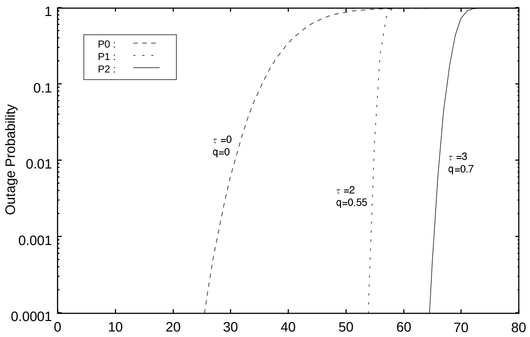

Fig. 6 Forward link outage probability, P_{out} versus the various worst points P0, P1 and P2. ($\sigma = 6dB$, $\alpha = 3/8$)

cal results, we see that the forward link user capacity is theoretically pessimistic evaluated without power control strategy. In the system, the power control strategy achieve the uniform services provided to all the users and increase the user capacity. We also see that the user capacity increases approximately threefold in the forward link because of adopting power control whether we adopted distance driven power control or ISR power allocation depicted in Ref.[9]. About the fading effects, it can be concluded that the forward link is a very heavy restriction for the user capacity, especially under the heavy fading effect. Under the typical fading effect, the deduction of the user capacity is over half the capacity under non-fading effect. Finally, because of estimation of outage probability of the system, the method could be easily extended to investigate throughput and delay in data packet transmission, which will be the future works.

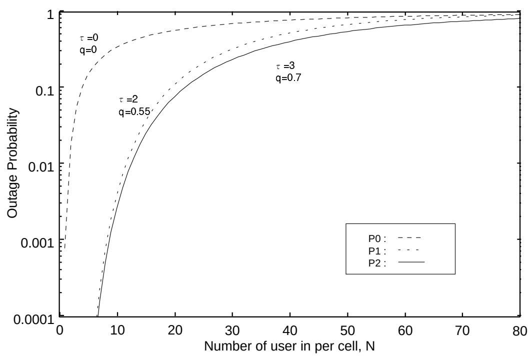

Fig. 7 Forward link outage probability, P_{out} versus the various worst points P0, P1 and P2. ($\sigma = 9dB$, $\alpha = 3/8$)

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