Capacity Estimation for an SIR-Based Power-Controlled CDMA System Supporting ON–OFF Traffic

Duk Kyung Kim, Student Member, IEEE, and Dan Keun Sung, Member, IEEE

Abstract—Capacity estimation in code division multiple access (CDMA) systems is an important issue which is closely related to power control. Many previous studies assumed strength-based power control, which maintains received power at a desired level regardless of changes in the number of active users and in the amount of total other cell interference. However, in SIR-based power control systems, which maintain the received SIR at a desired level, the power level is a function of the above two variables. This study derives the reverse link capacity of an SIR-based power control system supporting ON–OFF traffic in a multiple cell environment. Two different power control systems are compared in terms of capacity in both CBR and ON–OFF traffic environments. The effects of activity factor, the required $E_b/I_o$, the maximum received power, and propagation parameters are also investigated.

Index Terms—Capacity estimation, CDMA, SIR-based power control.

I. INTRODUCTION

Capacity estimation in code division multiple access (CDMA) systems is an important issue which is closely related to traffic characteristics, power control, radio propagation, sectorization, and other factors. Power control is needed to minimize each user’s interference on the reverse link in varying radio environments and traffic conditions [1]. Many efforts have been made to estimate the capacity of power-controlled CDMA systems. However, previous studies [2]–[4] considered power control systems in which each user’s signal arrives at the home base station (BS) with the same signal strength. The BS measures the received power level and compares it with a desired level and then transmits power control bit(s). This system is herein referred to as a strength-based power control system. Call admission control [5], the effect of imperfect power control [6], and fixed/adaptive-step power control algorithms [7] were studied based on the strength-based power control scheme.

The signal-to-interference ratio (SIR) is more important than signal strength in determining channel characteristics (e.g., bit error probability). Ariyavisitakul [8] indicated, by simulations, the potential of higher system performance in an SIR-based power control system for a constant bit rate (CBR) traffic environment. However, there have been no analytical approaches for estimating the capacity of an SIR-based power control system. System capacity can be maximized by controlling the received power at the BS with the minimum required SIR. SIR-based power control determines the value of the power control bit by comparing the received SIR with the desired SIR threshold. The SIR ($E_b/I_o$) is then maintained at the desired level [9]. The received signal power level varies according to the number of active home-cell users and the amount of other cell interference. Thus, the analysis of an SIR-based power control system is significantly different from the analysis of strength-based power control systems.

This study extends the analysis model in [2]. The reverse link capacity of an SIR-based power control system which supports ON–OFF traffic is analytically calculated in a multiple cell environment. The effects of activity factor, propagation parameters, the required $E_b/I_o$, and the maximum received power level are investigated and compared with a strength-based power control system.

In Section II, the total other cell interference is derived and the reverse link capacity of an SIR-based power control system supporting ON–OFF traffic is obtained. Section III shows analytical results of the effects of activity factor, propagation parameters, the required $E_b/I_o$, and the value of maximum received power. These results are compared with results from the strength-based power control system. Conclusions are presented in Section IV.

II. REVERSE LINK CAPABILITY

In a multiple-cell CDMA system, a mobile station (MS) is power-controlled by a BS sending the highest strength pilot signal to the MS. This BS is called the home BS of the given MS. Fig. 1 shows an ideal hexagonal cell structure, however, cell boundaries are, in practical, irregular due to shadowing, varying traffic conditions, and various cell environments. The path loss $L$ is generally assumed to be proportional to

$$L \propto r^{-\mu} 10^{\xi/10}$$

where

- $r$ distance from an MS to a BS;
- $\mu$ deciding constant;
- $\xi$ Gaussian random variable with standard deviation $\sigma = 8$ dB and mean $= 0$. 

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A. Calculation of Total Other Cell Interference

Total other cell interference $I_{\text{other}}$ is interference produced by all users who are power-controlled by other BS's. Fig. 1 shows the zeroth cell and other cells in the first and second tiers. Let $r_m$ and $r_0$ denote the distances from an MS to its home BS and the zeroth BS, respectively. Other cell interference at the zeroth BS is expressed as

$$I = S \left( \frac{10^{(\xi_0 - \xi_m)/10}}{r_0^\mu} \right) \left( \frac{r_m^{10^{(\xi_0 - \xi_m)/10}}}{10^{(\xi_0 - \xi_m)/10}} \right)$$

where $S$ is the received power at the home BS. The term $10^{(\xi_0 - \xi_m)/10}/r_0^\mu$ is the path loss to the zeroth cell’s BS and the term $r_m^{10^{(\xi_0 - \xi_m)/10}}$ is the effect of power control required to compensate for attenuation to its home cell’s BS. In a strength-based power control system [2], $r_0^\mu$ is a constant regardless of changes in the number of active users and in total other cell interference. In an SIR-based power control system, however, $r_0^\mu$ is a function of the number of active home users and total other cell interference. If it is assumed that the maximum received power is limited to $h_{\text{max}}$, then $S$ is a random variable within the range of $[0, h_{\text{max}}]$. Since $\xi_0$ and $\xi_m$ are assumed to be mutually independent, the zero mean and a variance of $2\sigma^2$. The value $r_m/r_0^{10^{(\xi_0 - \xi_m)/10}}$ should be less than unity because attenuation to the home cell is a minimum in a power control system.

Assuming a uniform density of users and normalizing the hexagonal cell radius to unity, the user density is given by

$$\rho = \frac{2}{3\sqrt{3}} N \text{ per unit area}$$

where $N$ is the number of users per cell. Then, the total other cell interference $I_{\text{other}}$ can be expressed as [2]

$$I_{\text{other}} = \int \int S \left( \frac{r_m^{10^{(\xi_0 - \xi_m)/10}}}{r_0^\mu} \right) \cdot \phi \left( \frac{r_0}{r_m} \right) \rho \, dA$$

where

$$\phi \left( \frac{r_0}{r_m} \right) = \begin{cases} 1, & \text{if } \left( \frac{r_m}{r_0} \right)^\mu 10^{(\xi_0 - \xi_m)/10} \leq 1 \\ 0, & \text{otherwise} \end{cases}$$

$m$ is the index for the cell site and is given by

$$r_m^\mu 10^{-\xi_m} = \min_{k \neq 0} r_k^\mu 10^{-\xi_k}. \quad (6)$$

This causes a slight increase in the moment statistics of $I_{\text{other}}$ [2].

A Gaussian model is considered for $I_{\text{other}}$. Assuming that the received power $S$, the distances, and the shadowing are mutually independent, the mean of $I_{\text{other}}$, $m_I$, can be expressed as [2]

$$m_I = E \left[ \int \int S \left( \frac{r_m^{10^{(\xi_0 - \xi_m)/10}}}{r_0^\mu} \right) \cdot \phi \left( \frac{r_0}{r_m} \right) \rho \, dA \right]$$

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where

$$\phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-y^2/2} \, dy.$$
where $M(\mu, \sigma)$ is given as
\[
M(\mu, \sigma) = e^{(\sigma \frac{\ln(10)}{10})^2} \int \int \left( \frac{r_m}{\rho_0} \right)^{\mu} \Phi 
\]
\[
\cdot \left( \frac{10}{\sqrt{2\pi}} \log_{10}(\rho_0/r_m) - \sqrt{2\pi} \frac{\ln(10)}{10} \right) \rho \, dA \tag{10}
\]
and $\rho' = \rho/N$. Referring to [2], the variance of $L_{\text{txer}}$, $\sigma^2_F$ can be approximated as
\[
\sigma^2_F \approx \text{Var} \left[ \int \int S \left( \frac{r_m}{\rho_0} \right)^{\mu} 10 \log_{10} \phi \left( \xi_0 - \xi_m, \frac{\rho_0}{\rho} \right) \rho \, dA \right] 
\]
\[
\approx \int \int \left( \frac{r_m}{\rho_0} \right)^{2\mu} \cdot \left[ E[S^2] \cdot \left( e^{2\sigma \frac{\ln(10)}{10}} - \left( e^{\frac{\ln(10)}{10}} \right)^2 \phi \left( \xi_0 - \xi_m, \frac{\rho_0}{\rho} \right) \right) \rho \, dA \right] 
\]
\[
= \int \int \left( \frac{r_m}{\rho_0} \right)^{2\mu} \cdot \left[ E[S^2] \cdot \left( e^{2\sigma \frac{\ln(10)}{10}} - \left( e^{\frac{\ln(10)}{10}} \right)^2 \phi \left( \xi_0 - \xi_m, \frac{\rho_0}{\rho} \right) \right) \rho \, dA \right] 
\]
\[
+ \int \int \left( \frac{r_m}{\rho_0} \right)^{2\mu} \cdot \left[ E[S^2] e^{\sigma \frac{\ln(10)}{10}} \Phi \left( \xi_0 - \xi_m, \frac{\rho_0}{\rho} \right) \right. 
\]
\[
\cdot \left( \frac{10}{\sqrt{2\pi}} \log_{10}(\rho_0/r_m) - \sqrt{2\pi} \frac{\ln(10)}{5} \right) 
\]
\[
- E[S^2] e^{2\sigma \frac{\ln(10)}{10}} \Phi^2 
\]
\[
+ \int \int \left( \frac{r_m}{\rho_0} \right)^{2\mu} \cdot \left[ E[S^2] e^{\sigma \frac{\ln(10)}{10}} \Phi \left( \xi_0 - \xi_m, \frac{\rho_0}{\rho} \right) \right. 
\]
\[
\cdot \left( \frac{10}{\sqrt{2\pi}} \log_{10}(\rho_0/r_m) - \sqrt{2\pi} \frac{\ln(10)}{10} \right) \rho \, dA. \tag{11}
\]
This can be simplified as
\[
\sigma^2_F \approx \{A(\mu, \sigma)E[S^2] - B(\mu, \sigma)E[\Phi]\} N \tag{12}
\]
where $A(\mu, \sigma)$ and $B(\mu, \sigma)$ are expressed as
\[
A(\mu, \sigma) = e^{(\sigma \frac{\ln(10)}{10})^2} \int \int \left( \frac{r_m}{\rho_0} \right)^{2\mu} \Phi 
\]
\[
\cdot \left( \frac{10}{\sqrt{2\pi}} \log_{10}(\rho_0/r_m) - \sqrt{2\pi} \frac{\ln(10)}{5} \right) \rho \, dA \tag{13}
\]
\[
B(\mu, \sigma) = e^{2(\sigma \frac{\ln(10)}{10})^2} \int \int \left( \frac{r_m}{\rho_0} \right)^{2\mu} \Phi^2 
\]
\[
\cdot \left( \frac{10}{\sqrt{2\pi}} \log_{10}(\rho_0/r_m) - \sqrt{2\pi} \frac{\ln(10)}{10} \right) \rho \, dA. \tag{14}
\]
The values $M(\mu, \sigma)$, $A(\mu, \sigma)$, and $B(\mu, \sigma)$ can be numerically obtained. Thus, $m_f$ and $\sigma^2_F$ can be obtained by calculating $E[S]$ and $E[S^2]$.

Several assumptions are used in this paper to mathematically obtain eqns (9) and (12). All assumptions except the following one were previously used in [2]. One additional assumption is that the received power and the distance are mutually independent in a power-controlled system. Simulations are made in a cell placement shown in Fig. 1 under radio propagation conditions of $\mu = 4$ and $\sigma = 8$ dB. It is assumed that users are uniformly distributed in the cell. From these simulations, it is found that the additional assumption causes insignificant errors compared with the errors due to other assumptions.

B. Calculation of $E[S]$ and $E[S^2]$

The received power $S$ from a user at the home BS is assumed to be zero during OFF periods and to be a random variable $H$ with a probability density function (pdf) of $f_H(h)$ during ON periods. Let $p$ denote the activity factor. In power control systems, all the received power strengths from users in a home cell are identical, and $I_{\text{txer}}$ is also assumed to have identical distributions at all BS’s. $E_s/I_o$ can be given by [10], [11]
\[
\frac{E_s}{I_o} \leq \frac{h/R}{(HK + I_{\text{txer}})/2W + \eta_0} \tag{15}
\]
where $H$ received power of an active user;
$R$ data rate during ON periods;
$W$ chip rate;
$\eta_0$ background noise;
$K$ number of active users among $(N-1)$ users.

The above expression is based on a Gaussian density approximation to evaluate bit error probability in an asynchronous binary phase-shift keying (BPSK)-modulated DS-CDMA system when an additive white Gaussian noise (AWGN) process and rectangular chip waveforms are assumed [12], [13].

When MS’s are power controlled to maintain the minimum power satisfying the required $E_s/I_o$ (i.e., $\gamma$) the power level $H$ is given by
\[
H = \frac{3}{2} \frac{W \eta_0 + I_{\text{txer}}}{G \gamma} - K \tag{16}
\]
where $G \triangleq W/R$ is the processing gain. The following variables are defined for simplicity:
\[
\eta \triangleq \frac{3}{2} W \eta_0 \\
\alpha \triangleq \frac{3}{2} \frac{G}{\gamma} \\
Y \triangleq I_{\text{txer}} \\
H \in (16)$ is the required MS power to satisfy $E_s/I_o = \gamma$. The system cannot handle more than $(3/2)(G/\gamma) + 1$ users with power limitation. If $K$ exceeds $(3/2)(G/\gamma)$, the required power becomes negative value and system enters an outage state. With a power limit of $h_{\text{max}}$, the system is also in an outage state when the required power exceeds $h_{\text{max}}$. Thus, outage occurs...
when the required power is higher than $h_{\text{max}}$ or less than 0 in a power-limited system. It is here assumed that the received power is controlled to be zero in an outage state, which reduces the interference to other users due to users being in an outage state.

Under a condition of $K = i$, $F_{H|K=i}(h)$ is expressed as

$$F_{H|K=i}(h) = \begin{cases} 0, & h < 0 \\ A_0 + A_{\text{max}} + \int_0^h |\alpha - i| f_H(x) \, dx, & 0 \leq h \leq h_{\text{max}} \\ 1, & h > h_{\text{max}}, \end{cases}$$

(17)

where $A_0$ and $A_{\text{max}}$ denote the probabilities that $H$ is below zero and exceeds $h_{\text{max}}$, respectively. These probabilities are given by

$$A_0 = \int_{-\infty}^0 (\alpha - i) f_H(x) \, dx,$$

$$A_{\text{max}} = \int_{h_{\text{max}}}^\infty (\alpha - i) f_H(x) \, dx.$$

Then, $f_H(h)$ can be obtained as

$$f_H(h) = \sum_{i=0}^{N-1} f_{H|K=i}(h) \pi_i,$$

(18)

where $\pi_i \triangleq \Pr\{K = i\}$.

Fig. 2 illustrates an ON–OFF traffic model, where ON and OFF periods are exponentially distributed with means of $1/\mu$ and $1/\lambda$, respectively. The activity factor $p$ is the probability that the state is ON.

$$p = \frac{E[\text{ON duration}]}{E[\text{ON duration}] + E[\text{OFF duration}]} = \frac{1/\mu}{1/\mu + 1/\lambda} = \frac{\lambda}{\lambda + \mu}.$$

(19)

Using a birth-death model with $(N-1)$ ON–OFF sources [15], $\pi_i$ can be obtained as

$$\pi_i = \frac{(N-i)\lambda}{i\mu} \pi_{i-1},$$

(20)

where $\sum_{i=0}^{N-1} \pi_i = 1$.

Finally, $E[S]$ and $E[S^2]$ are given by

$$E[S] = p \int_0^{h_{\text{max}}} h f_H(h) \, dh = p \int_0^{h_{\text{max}}} h \sum_{i=0}^{N-1} \pi_i f_{H|K=i}(h) \, dh = p \sum_{i=0}^{N-1} \pi_i \int_0^{h_{\text{max}}} h f_{H|K=i}(h) \, dh,$$

(21)

$$E[S^2] = p \int_0^{h_{\text{max}}} h^2 f_H(h) \, dh = p \sum_{i=0}^{N-1} \pi_i \int_0^{h_{\text{max}}} h^2 f_{H|K=i}(h) \, dh.$$

(22)

Since $S$ and $I_{\text{other}}$ are closely related with each other, they are calculated recursively according to the following steps:

Step 1) Set $m_I$ and $\sigma_I^2$ at zeros.

Step 2) Calculate $E[S]$ and $E[S^2]$ from (21) and (22), respectively.

Step 3) Calculate $m_I$ and $\sigma_I^2$ from (9) and (12), respectively.

Step 4) Repeat steps 2 and 3 until the errors of $m_I$ and $\sigma_I$ are within a given bound.

C. System Capacity

Although the MS transmitted power is limited in real systems, it is necessary to model the system from the viewpoint of the BS to make the problem mathematically tractable. Then, in an SIR-based power control system, $P_{\text{out}}$ can be defined as

$$P_{\text{out}} \triangleq \Pr\{\text{The required power is higher than } h_{\text{max}}|K \leq \alpha\} \cdot \Pr\{K \leq \alpha\} + \Pr\{K > \alpha\}.$$

Equation (23) can be rewritten as

$$P_{\text{out}} = \Pr\left\{\frac{\eta + Y}{\alpha - K} > h_{\text{max}}|K \leq \alpha\right\} \cdot \Pr\{K \leq \alpha\} + \Pr\{K > \alpha\}$$

$$= \Pr\{Y > \alpha h_{\text{max}} - K h_{\text{max}} - \eta|K \leq \alpha\} \cdot \Pr\{K \leq \alpha\} + \Pr\{K > \alpha\}$$

$$= \sum_{k=0}^{\lfloor \alpha \rfloor} \pi_k \Pr\{Y > \alpha h_{\text{max}} - kh_{\text{max}} - \eta|K = k\}$$

$$+ \sum_{k=\lfloor \alpha \rfloor + 1}^{N-1} \pi_k \Pr\{Y > \alpha h_{\text{max}} - kh_{\text{max}} - \eta - m_I|K = k\},$$

(24)

where $\lfloor x \rfloor$ is the greatest integer which is less than or equal to $x$. Now system capacity can be obtained in terms of the maximum
TABLE I
SYSTEM PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>1.2288 Mcps</td>
</tr>
<tr>
<td>R</td>
<td>9.6 kbps</td>
</tr>
<tr>
<td>G</td>
<td>128</td>
</tr>
<tr>
<td>$\eta_0$</td>
<td>$1.3 \times 10^{-20}$ W/Hz</td>
</tr>
<tr>
<td>$h_{\text{max}}$</td>
<td>$2 \times 10^{-14}$ W</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>7 dB</td>
</tr>
<tr>
<td>$p$</td>
<td>3/8</td>
</tr>
<tr>
<td>$\mu$</td>
<td>4</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>8 dB</td>
</tr>
</tbody>
</table>

admissible number of users satisfying the outage probability $P_{\text{out}}$ less than or equal to the threshold.

III. NUMERICAL EXAMPLES

Table I shows system parameters which are based on the Qualcomm CDMA specification [14]. These parameters are used in this paper unless otherwise stated. System capacities based on two different power control schemes are compared in CBR traffic and ON-OFF traffic environments. The system capacity of the SIR-based power control system is calculated for various values of $p$, $\gamma$, $h_{\text{max}}$, $\mu$, and $\sigma$.

A. Comparison Between Strength-Based Power Control and SIR-Based Power Control

Gilhousen et al. [2] showed that $m_I$ and $\sigma_I^2$ in the strength-based power control system are expressed as

$$m_I \approx p M(\mu, \sigma) S N,$$

$$\sigma_I^2 \approx \{p A(\mu, \sigma) - p^2 B(\mu, \sigma)\} S^2 N.$$ 

In the strength-based power control system, $S$ is a constant. $P_{\text{out}}$ is given by

$$P_{\text{out}} = \Pr\{E_k/I_0 < \gamma\} \quad (25)$$

and the strength-based power control system is assumed to be power-limited to $h_{\text{max}}$. From (15), (25) is simplified as

$$P_{\text{out}} = \sum_{k=0}^{N-1} \pi_k Q\left(\frac{\alpha h_{\text{max}} - \eta h_{\text{max}} - \gamma - m_I}{\sigma_I}\right). \quad (26)$$

It is interesting to note that system capacities based on two different power control schemes are identical in a single cell environment because of no other cell interference.

Fig. 3 shows $P_{\text{out}}$ versus the number of users for two different power control systems. The values of $M(4, 8)$, $A(4, 8)$, and $B(4, 8)$ are numerically obtained as 0.659, 0.223, and 0.04, respectively, by considering the first and the second tiers for $\mu = 4$ and $\sigma = 8$ dB. For $P_{\text{out}} = 0.01$, an SIR-based power control system can accommodate approximately 22% more users than a strength-based power control system. With SIR-based power control, the capacity of a multiple-cell system corresponds to approximately 76% of the capacity of a single-cell system.

Fig. 4 shows the statistics of $S$ and $I_{\text{other}}$ for varying the number of users. As expected, the SIR-based power control system has smaller $S$ and $I_{\text{other}}$ values than the strength-based power control system. For 50 users per cell, the means of $S$ and $I_{\text{other}}$, $m_S$ and $m_I$, are approximately 17.3% and 16.8% of the strength-based power control system, respectively. These reduced power levels and reduced other cell interference increase system capacity. In the strength-based power control system, since the power level is identical during ON periods regardless of the number of users, $I_{\text{other}}$ increases as the number of users increases. In the SIR-based power control system, power level is more frequently controlled to be zero as $P_{\text{out}}$ increases. The decrease due to this power control overwhelms the increase due to an increase in the number of users, for more than 60 users. Thus, the statistical values of $S$ and $I_{\text{other}}$ decrease as the number of users increases above 60.

B. Effects of Activity Factor

Fig. 5 shows $P_{\text{out}}$ versus the number of users for various values of the activity factor $p$. As $p$ decreases, more users can be accommodated by statistical multiplexing. Table II summarizes
the system capacity satisfying $P_{\text{ext}} = 0.01$. As traffic becomes more bursty, the SIR-based power control system can accommodate more users than the strength-based system. SIR-based power control can increase system capacity by approximately 10%, compared with strength-based power control in a CBR traffic environment ($p = 1$). However, as indicated, the capacity of the SIR-based power control system increases by approximately 22% more than the strength-based power control system for $p = 3/8$. It is noted that statistical multiplexing is more efficiently used in SIR-based power control than in strength-based control. For example, when $p$ is 1/8, the capacity of the SIR-based power control system is approximately 7.6 times the capacity for $p = 1$. The capacity of the strength-based power control system for $p = 1/8$ is approximately 6.5 times greater than the capacity for $p = 1$. It is interesting that capacity degradation in a multiple-cell system compared with a single-cell system is mitigated for a small value of $p$. As an example, the capacity of a single-cell system is 37 and 74 for $p = 1$ and 3/8, respectively. Using SIR-based power control, the capacity of a multiple-cell system degrades by approximately 40% for $p = 1$ and by approximately 24% for $p = 3/8$, compared with a single-cell system. If strength-based power control is used, the capacity of a multiple-cell system corresponds to approximately 54% and 60% of a single-cell system for $p = 1$ and 3/8, respectively.

C. Comparison with the Previous Works

Before investigating the effects of other parameters, our results are now compared with two previous works: Gilhousen et al. [2] analytically estimated the capacity of a strength-based power control system and Ariyavisitakul [8] simulated an SIR-based power control system. In both works, they assumed 1 instead of 3/2 in eqn (15). This term is denoted by $\zeta$ in this paper and is a factor which is dependent on the particular PN chip waveform and the cross-correlation property of the PN codes. When the voice activity is set at 3/8, the same capacity can be obtained in a strength-based power control system as in [2] by setting $\zeta$ at 1. Ariyavisitakul [4], [8] found that the system capacity can be approximately increased by 25% in a CBR traffic environment if the SIR-based power control is adopted instead of the strength-based power control. This gain is well consistent with our results when $\zeta$ is set at 1 instead of 3/2. The system capacity largely depends on $\zeta$ and is shown in Table III when the voice activity $p$ is equal to 3/8 and 1 in strength-and SIR-based power control systems, respectively, for $\zeta = 1$.

D. Effect of $\gamma$

Fig. 6 shows $P_{\text{out}}$ versus the number of users for varying $\gamma$. As expected, increasing $\gamma$ decreases system capacity. SIR-based power control increases system capacity by 22% and 30%, compared with the strength-based control for $\gamma = 5$ dB and $\gamma = 10$ dB, respectively.

E. Effect of $h_{\text{max}}$

The maximum power received from the MS is generally used to define the system capacity. Fig. 7 illustrates $P_{\text{out}}$ versus the number of users for varying values of the maximum received power $h_{\text{max}}$. As $h_{\text{max}}$ increases, system capacity increases to saturation. When $h_{\text{max}}$ is equal to $4 \times 10^{-14}$ W, system capacity satisfying $P_{\text{out}} = 0.01$ increases by approximately 10%, compared with for $h_{\text{max}} = 1 \times 10^{-14}$ W.
Perfect power control is assumed here in this paper. However, system performance may be degraded due to various factors, such as estimation errors of power and $E_b/N_0$, power control loop delay, and power control bit error. This performance degradation will be investigated in a further study.

### References


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