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LETTER

Theoretical Study of Site Selection Diversity Transmission in DS-CDMA Cellular Mobile Radio

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SUMMARY Single cell reuse of the same frequency, which is possible in DS-CDMA cellular systems, yields the option of site diversity to increase link capacity. In this letter, a generalized case of site diversity transmission is considered where multiple base stations (BS's) are involved in weighted transmissions with constant total transmit power to a target mobile station (MS). A general equation of conditional bit error rate (BER) is derived based on the model of weighted transmissions combined with antenna diversity reception and rake combining. It turns out theoretically that the optimum set of weights to maximize forward link capacity makes site selection diversity transmission (SSDT) the best performer. This theoretical analysis is confirmed by performance evaluation based on the Monte-Carlo simulation.

key words: *DS-CDMA, site diversity, soft handoff, forward link capacity, rake combining*

1. Introduction

Wideband DS-CDMA is used for multiple access scheme in 3rd generation cellular systems due to its high spectrum efficiency. In cellular systems, the service area is divided into many cells, where each of the cells has a base station (BS) in the cell center to serve users in the respective cell [1]. However, the distance dependent path loss, shadowing and fast fading cause a large fluctuation of received signal level at a mobile station (MS). The probability of the received signal power failing to achieve the required signal quality or bit error rate (BER) is called outage probability. Near the cell's boundaries, the outage probability is high. However, remembering that the signals transmitted from two or more BS's are received at nearly equal levels near a cell boundary, the same data is sent simultaneously towards a target MS from two or more BS's and is combined by the MS receiver to improve the forward link transmission performance. This technique is called site diversity and is incorporated into soft handoff (SHO) which is helpful in a handoff transition from one cell to another [2].

Weighted transmissions from multiple BS's involved in site diversity operation are expected to render further improvement in transmission performance. This is because, there may exist a set of optimum weights that will optimize site diversity operation. In this letter, therefore, we first present the theoretical analysis, in which we assume weighted transmissions from multiple BS's to a target MS. After deriving the set of optimum weights that maximizes the received signal-to-noise plus interference power ratio (SINR), we show that the optimal solution to maximize the forward link capacity with constant total transmit power is to transmit only from the best BS that has the maximum channel gain, in other words it is SSDT as proposed in [3]. Furthermore, performance evaluation based on the Monte Carlo simulation confirms that SSDT gives better performance than SHO in terms of link capacity which is defined as the maximum number of users that can communicate simultaneously under the allowable outage probability. Some other studies of SSDT have been found in the open literature [4], [5]. In [4], SSDT, SHO and hard handover (HHO) are compared using BER as a performance measure, while in [5], the complexities that arise from the implementation of SSDT in a practical system are addressed. Unlike the above mentioned works, this letter studies macro-diversity transmissions in general by theoretical analysis and in the end finds SSDT rendering the best performance and thus it contributes a theoretical basis to SSDT.

The remainder of this letter is organized as follows. Sect. 2 describes the system model under consideration. The theoretical analysis is presented in Sect. 3. In Sect. 4, the performance evaluation is done by the Monte-Carlo simulation for various system parameters. Finally, this letter is concluded with Sect. 5.

2. System Model

2.1 Cellular Structure and Propagation Model

It is assumed that the service area consists of 19 identical hexagonal cells as illustrated in Fig. 1. The BS is located at the center of each cell. We do not consider cell sectorization and an omni transmit antenna is assumed at each BS. In Fig. 1, i and j denote cell and MS respectively where, j=0th MS is the target MS.

In mobile wireless communication, the propagation channel can be modeled as the product of distance dependent path loss, log-normally distributed shadowing loss and multipath fading channel gain. It is assumed that the fading channel consists of L discrete propagation paths having time delays (τ_l for the lth path) of integer multiple of DS-CDMA chip duration, each being subjected to independent Rayleigh fading and that rake combining can resolve all L paths to coherently combine them based on maximal ratio combining (MRC) method [6]. The instantaneous received

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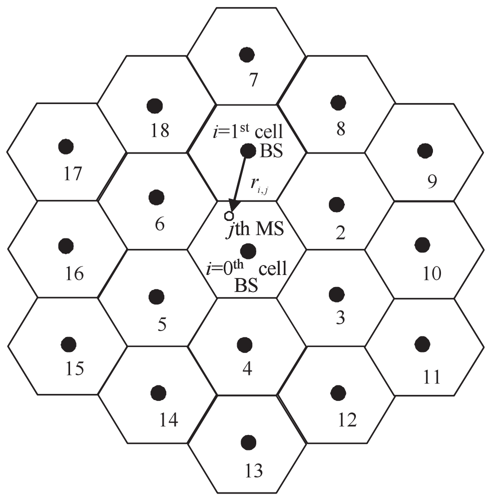

Fig. 1 Cellular structure under consideration.

signal power at the jth MS from the qth cell BS can be represented by [7]

$$S^R_{q,j} = C \cdot P_T \cdot r'^{-\alpha}_{q,j} \cdot 10^{-\eta_{q,j}/10} \sum_{m=0}^{M-1} \sum_{l=0}^{L-1} \left|\xi_{q,j}(m,l)\right|^2$$
$$= S \cdot L_{q,j} \cdot \left|\xi_{q,j}\right|^2, \quad (1)$$

where C is a constant, P_T is the transmit power in watt of each BS for each MS, $r'_{q,j}$ is the distance in km between the qth cell BS and the jth MS, α is the path loss exponent, $\eta_{q,j}$ is the shadowing loss expressed in dB and assumed to be a Gaussian process with zero-mean and standard deviation σ of about 4 to 10 and $\xi_{q,j}(m,l)$ is the lth path gain experienced by the mth antenna which is characterized as a zero-mean complex Gaussian process. In Eq. (1), $\xi_{q,j}$ is the equivalent fading channel gain after rake combining with M-antenna diversity combining for the communication link between the qth cell BS and the jth MS. S and $L_{q,j}$ are the nominal received signal power at the cell edge and the local average gain respectively, and are defined as

$$\begin{cases} S = C \cdot P_T \cdot R^{-\alpha} \\ L_{q,j} = r^{-\alpha}_{q,j} \cdot 10^{-\eta_{q,j}/10} \end{cases}, \quad (2)$$

where R is the cell radius in km and $r_{q,j}(= r'_{q,j}/R)$ is the normalized distance by cell radius between the qth cell BS and the jth MS.

2.2 Model of Weighted Transmission

Prior to the communication, an MS first sorts out the BS's in descending order out of 19 cells based on *local average* gain, as $L_{k=0,j} \geq L_{k=1,j} \geq \ldots \geq L_{k=K-1,j}$, and then the first K cell BS's are selected. The set of first K cell BS's from the sorted BS's is defined as the active set. While a communication is in progress, the MS selects BS from the active set based on *instantaneous* received signal power. In order to do this, the BS's of the active set are again sorted out in descending order and the first Q cell BS's are selected as follows: $L_{q=0,j}\left|\xi_{q=0,j}\right|^2 \geq L_{q=1,j}\left|\xi_{q=1,j}\right|^2 \geq \ldots \geq L_{q=Q-1,j}\left|\xi_{q=Q-1,j}\right|^2$. The same transmit signal is first weighted and then transmitted from the Q cell BS's (see Fig. 2 for Q=4) and these transmitted signals are received and combined at the MS receiver. Figure 3 shows the block diagram of a rake receiver where forward link multipath signals from multiple BS's are processed. Quadrature phase shift keying (QPSK) data modulation and binary PSK (BPSK) spreading modulation are assumed.

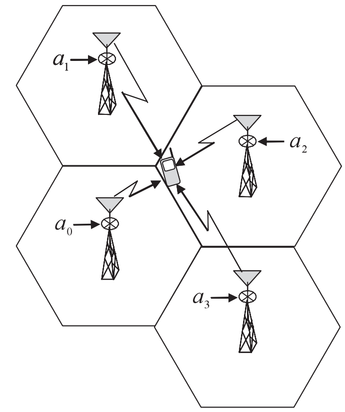

Fig. 2 Weighted transmissions from multiple BS's.

In this letter, the chip-spaced discrete-time representation of the signal is used. The transmit signal from the qth cell BS at time t is expressed using equivalent lowpass representation as

$$s_q(t) = \sqrt{2P_T} \sum_{j=0}^{U_q-1} d_{q,j}(\lfloor t/SF \rfloor)\, c_{PN_q}(t)\, c_j(t \bmod SF)$$
$$\times a_{q,j}(\lfloor t/SF \rfloor), \quad (3)$$

where U_q is the number of MS's connected to the qth cell BS, $d_{q,j}(g)$ is the gth transmit QPSK symbol to jth MS from qth cell BS with $|d_{q,j}(g)| = 1$, $c_{PN_q}(t)$ is the scramble code with $\left|c_{PN_q}(t)\right| = 1$, $c_j(t)$ is the orthogonal channelization spreading code with $|c_j(t)|$=1, SF denotes the spreading factor, $\lfloor x \rfloor$ denotes the largest integer smaller than or equal to x and $a_{q,j}(g)$ is the transmit weight multiplied to the transmit signal of the qth cell BS destined for jth MS with the following constraint:

$$\sum_{q=0}^{Q-1} \left|a_{q,j}(g)\right|^2 = 1 \quad (4)$$

so that the total transmit power of the Q BS's for a target MS is always kept to be P_T. In the following, the subscript g is dropped for the sake of simplicity.

3. Theoretical Analysis

3.1 Derivation of Conditional BER

Q transmitted signals are received by M antennas and coher-

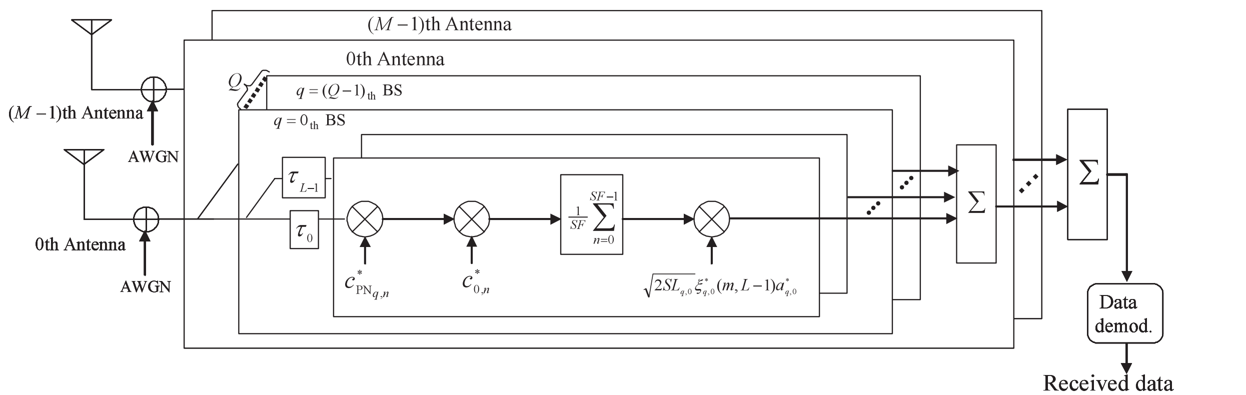

Fig. 3 Mobile receiver block diagram.

ently combined by the rake receiver of the j=0th MS. The rake combined output y is expressed as

$$y = Z_{signal} + Z_{IPI} + Z_{ICI} + Z_{noise}, \tag{5}$$

where Z_{signal} is the desired signal part, Z_{IPI} is the inter-path interference (IPI), Z_{ICI} is the inter-cell interference (ICI) and Z_{noise} is the noise part due to additive white Gaussian noise (AWGN) and they are given by

$$\begin{cases} Z_{signal} = 2S \displaystyle\sum_{q=0}^{Q-1} \left|a_{q,0}\right|^2 L_{q,0} d_{q,0} \sum_{m=0}^{M-1} \sum_{l=0}^{L-1} \left|\xi_{q,0}(m,l)\right|^2 \\ Z_{IPI} = \dfrac{2S}{SF} \displaystyle\sum_{q=0}^{Q-1} a^*_{q,0} L_{q,0} \sum_{j=0}^{U_q-1} a_{q,j} d_{q,j} \\ \quad \times \displaystyle\sum_{m=0}^{M-1}\sum_{l'=0}^{L-1} \xi^*_{q,0}(m,l') \sum_{\substack{l=0 \\ l\neq l'}}^{L-1} \xi_{q,0}(m,l) \sum_{n=0}^{SF-1} c^*_{0,n} c^*_{PN_{q,n-\tau_{l'}}} c_{j,n} c_{PN_{q,n-\tau_l}} \\ Z_{ICI} = \dfrac{2S}{SF} \displaystyle\sum_{q=0}^{Q-1} a^*_{q,0} \sqrt{L_{q,0}} \sum_{\substack{i=0 \\ i\neq q}}^{18} \sqrt{L_{i,0}} \sum_{j'=0}^{U_i-1} a_{i,j'} d_{i,j'} \\ \quad \times \displaystyle\sum_{m=0}^{M-1}\sum_{l'=0}^{L-1} \xi^*_{q,0}(m,l') \sum_{l=0}^{L-1} \xi_{i,0}(m,l) \sum_{n=0}^{SF-1} c^*_{0,n} c^*_{PN_{q,n-\tau_{l'}}} c_{j',n} c_{PN_{i,n-\tau_l}} \\ Z_{noise} = \dfrac{\sqrt{2S}}{SF} \displaystyle\sum_{q=0}^{Q-1} a^*_{q,0} \sqrt{L_{q,0}} \\ \quad \times \displaystyle\sum_{m=0}^{M-1} \sum_{l=0}^{L-1} \xi^*_{q,0}(m,l) \sum_{n=0}^{SF-1} w_n(m) c^*_{0,n} c^*_{PN_{q,n-\tau_l}}, \end{cases} \tag{6}$$

where S, $L_{q,j}$ and $\xi_{q,j}$ are shown in Eq. (1). Due to the employment of orthogonal codes for user separation, the same path interference can be removed. In Eq. (6), $w_n(m)$ is the noise with zero mean and variance of $2N_0/T$, where N_0 is the AWGN single sided power spectral density and $T = SF \cdot T_c$ is the symbol length. As long scramble code is used, the interference part with spreading code can be approximated as a zero mean complex Gaussian variable using the central limit theorem [6].

Without the loss of generality, all 1's transmission is assumed, i.e., $d_{q,0}(g) = (1 + j)/\sqrt{2}$ for all g. The real part of y, Re(y), is approximated as a complex Gaussian random variable with the mean μ and the variance σ^2 as

$$\begin{cases} \mu = \sqrt{2}S \displaystyle\sum_{q=0}^{Q-1} \left|a_{q,0}\right|^2 L_{q,0} \sum_{m=0}^{M-1}\sum_{l=0}^{L-1} \left|\xi_{q,0}(m,l)\right|^2 \\ \sigma^2 = \dfrac{2S^2}{SF} \displaystyle\sum_{q=0}^{Q-1} \left|a_{q,0}\right|^2 L^2_{q,0} \sum_{j=0}^{U_q-1} \left|a_{q,j}\right|^2 \\ \qquad \times \displaystyle\sum_{m=0}^{M-1}\sum_{l'=0}^{L-1} \left|\xi_{q,0}(m,l')\right|^2 \sum_{\substack{l=0 \\ l\neq l'}}^{L-1} \left|\xi_{q,0}(m,l)\right|^2 \\ \quad + \dfrac{2S^2}{SF} \displaystyle\sum_{q=0}^{Q-1} \left|a_{q,0}\right|^2 L_{q,0} \sum_{\substack{i=0 \\ i\neq q}}^{18} L_{i,0} \sum_{j'=0}^{U_i-1} \left|a_{i,j'}\right|^2 \\ \qquad \times \displaystyle\sum_{m=0}^{M-1}\sum_{l'=0}^{L-1} \left|\xi_{q,0}(m,l')\right|^2 \sum_{l=0}^{L-1} \left|\xi_{i,0}(m,l)\right|^2 \\ \quad + \dfrac{2SN_0}{T} \displaystyle\sum_{q=0}^{Q-1} \left|a_{q,0}\right|^2 L_{q,0} \sum_{m=0}^{M-1}\sum_{l=0}^{L-1} \left|\xi_{q,0}(m,l)\right|^2 \end{cases}, \tag{7}$$

Once we know the mean and the variance, the BER P_e can be expressed as [6]

$$P_e = \frac{1}{2} erfc \sqrt{\gamma_R/2}, \tag{8}$$

where $\gamma_R = \mu^2/\sigma^2$ is the received SINR at 0th MS and $erfc(x)$ is the complementary error function given by

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} \exp(-t^2) dt.$$

The received SINR γ_R needs to be maximized to render the P_e minimum, which eventually maximizes the link capacity. For the theoretical analysis, we assume a large spreading factor and neglect the first and second parts of the variance σ^2. γ_R can be approximated as

$$\gamma_R = \frac{ST}{N_0} \sum_{q=0}^{Q-1} \left|a_{q,0}\right|^2 h_q, \tag{9}$$

where h_q is the equivalent channel gain given by

$$h_q = L_{q,0} \sum_{m=0}^{M-1} \sum_{l=0}^{L-1} \left|\xi_{q,0}(m,l)\right|^2. \tag{10}$$

3.2 Finding the Optimum Weight

The whole process of finding the optimum weight is carried out for 0th MS. For simplicity, therefore, the subscript 0 is dropped from $a_{q,0}$ and the optimum transmit weight a_q that maximizes γ_R is obtained below. Letting $\psi = \gamma_R/(ST/N_0)$, maximization problem of γ_R is equivalent to maximizing

$$\psi = \sum_{q=0}^{Q-1} x_q h_q, \tag{11}$$

where

$$x_q = |a_q|^2 \tag{12}$$

with the constraint

$$\sum_{q=0}^{Q-1} x_q = 1, \tag{13}$$

where the constraint for $\{x_q\}$ can be written as

$$\begin{cases} x_0 + x_1 + \cdots + x_{Q-1} = 1 \\ x_q \geq 0, \text{ for } q = 0, 1, \cdots, Q-1 \end{cases}. \tag{14}$$

The objective function ψ is given by

$$\begin{cases} \psi = x_0 h_0 + x_1 h_1 + \cdots + x_{Q-1} h_{Q-1} \\ \text{where } h_0 > h_1 > \cdots > h_{Q-1} > 0 \end{cases}. \tag{15}$$

Simplex algorithm for linear programming [8] is applied to find the maximum value of ψ. Firstly x_0 is determined that satisfies $h_0 = \max_{q=\{0,1,\cdots,Q-1\}} \{h_q\}$. Replacing the right hand side of Eq. (14) by $b'_0 (= 1 \geq 0)$, Eq. (14) becomes

$$x_0 = b'_0 - (x_1 + x_2 + \cdots + x_{Q-1}). \tag{16}$$

The following relation is obtained from Eq. (15) and Eq. (16):

$$\begin{cases} \psi = \left(b'_0 - x_1 - x_2 - \cdots - x_{Q-1}\right) h_0 \\ \quad + x_1 h_1 + \cdots + x_{Q-1} h_{Q-1} \end{cases}, \tag{17}$$

from which, we have

$$\psi - \psi'_0 = x_1 h'_1 + x_2 h'_2 + \cdots + x_{Q-1} h'_{Q-1}, \tag{18}$$

where $\psi'_0 = b'_0 h_0$ and $h'_n = h_n - h_0$ for $n = 1 \sim Q-1$. Supposing that $h_0 = \max_{q=\{0,1,\cdots,Q-1\}} \{h_q\}$, we have $h'_n < 0$. ψ is maximized only with the following condition:

$$\begin{cases} x_0 = b'_0 = 1 \\ x_n = 0 \text{ for } n = 1, 2, \cdots, Q-1 \\ \psi_{\max} = \psi'_0 = b'_0 h_0 = h_0 \end{cases}. \tag{19}$$

Therefore, the maximum ψ and optimum x_q are given by

$$\begin{cases} x_q = \delta_{qv} \\ \psi_{\max} = h_v \\ \nu = \arg \max_{q=\{0,1,\cdots,Q-1\}} \left\{h_q\right\} \end{cases}, \tag{20}$$

where δ_{qv} is Kronecker's delta function [9] which is defined by

$$\delta_{qv} = \begin{cases} 1 & \text{for } q = v \\ 0 & \text{for } q \neq v \end{cases}. \tag{21}$$

Eventually, we get the optimum value of a_q and the maximum γ_R as follows

$$\begin{cases} a_q = \delta_{qv} \\ \gamma_R = \frac{ST}{N_0} h_v \\ \nu = \arg \max_{q=\{0,1,\cdots,Q-1\}} \left\{h_q\right\} \end{cases}. \tag{22}$$

Equation (22) states that signal transmission only from one BS, that has the maximum channel gain among all the BS's in the active set, optimizes site selection technique. Thus, it is shown analytically that the very basic idea of SSDT has a theoretical basis.

4. Numerical Computation

The forward link capacity is evaluated by Monte-Carlo simulation. The simulation condition is given at Table 1. In the simulation, interference limited channel is assumed where the effect of AWGN can be neglected, i.e., $ST/N_0 \rightarrow \infty$. Using Eq. (8), the instantaneous BER is calculated for each generation of the independent complex Gaussian variable ($\xi_{q,0}$, $\xi_{i,0}$). By taking the average of this repeatedly computed instantaneous BER, the average BER is obtained. In the simulation, we focus on the centered cell where outage probability is measured for each MS by comparing the average BER with the required one. In SSDT, the transmit channel gain must be estimated to determine the transmitting BS. However, in the computer simulation, perfect knowledge of transmit channel gain is assumed.

4.1 Comparison of SSDT and SHO

As noted before, here Q stands for the number of best BS's selected by a particular MS instantaneously from the active set, while a communication is in progress. For SSDT, Q is set as 1. However for the case of $Q > 1$ (so called SHO), the transmit weight attached to each of the Q BS's is set as

Table 1 Simulation condition.

Modulation scheme	QPSK
Cellular structure	Hexagonal cell
User distribution	Uniform
Path loss exponent	$\alpha = 3.5$
Standard deviation of shadowing loss	$\sigma = 6$ dB
Multipath fading channel	L-path Rayleigh fading
Rake combining	L-finger coherent Rake combining
Antenna diversity	M-antenna MRC
Required BER	10^{-2}
Spreading factor	$SF = 32$

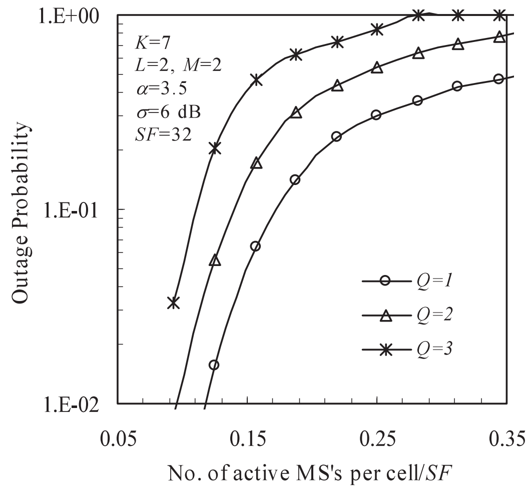

Fig. 4 Comparison of SSDT and SHO for K=7.

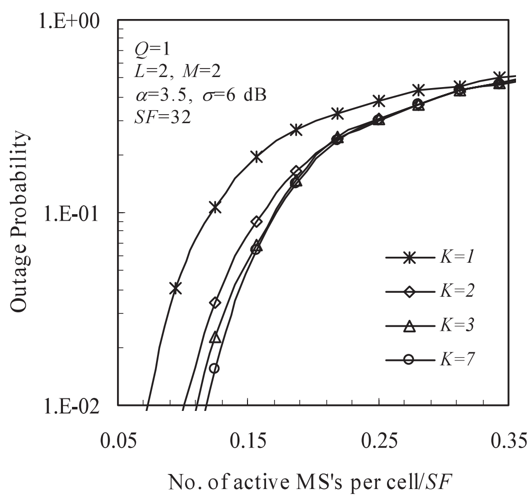

Fig. 5 Effect of K for Q=1.

$$a_{q=0} = a_{q=1} = \cdots = a_{q=Q-1} = \frac{1}{\sqrt{Q}}, \tag{23}$$

so that each of the Q BS's transmits with equal power and their total transmit power for a target MS is always kept to be P_T, the same as in case of SSDT. In Fig. 4, outage probability is plotted against the normalized number of active MS's. This figure shows that with Q=1, the maximum link capacity can be obtained. For instance, in a multipath (L=2) environment with antenna diversity reception (M=2), the normalized link capacity for an allowable outage probability of 0.1 is 0.175 in case of Q=1, while it is 0.14 and 0.11 for Q=2 and 3 respectively.

4.2 Effect of Instantaneous Site Selection

Figure 5 shows how the number K of BS's in the active set affects the link capacity, where the case of K=1 is the average power based SSDT and $K > 1$ is an instantaneous power based SSDT. With more than one BS in the active set ($K > 1$), the MS can switch between the BS's of active set instantaneously that prevents the received signal from dropping below the desired level. This leads to the decrease of outage probability, which in turn, improves the link capacity. This figure demonstrates this fact where the increase of K especially from K=1 to K=3 gives a capacity improvement of about 40%.

5. Conclusion

In this letter, we have considered the weighted transmission from multiple BS's combined with antenna diversity reception. The optimum set of weights to maximize the forward link capacity has been found to transmit only from the best BS that has the maximum channel gain. In other words, through the theoretical analysis, SSDT proves to be the optimal way of forward link transmission. Monte Carlo simulation has confirmed the theoretical analysis and proved that an instantaneous SSDT ($K > 1$) improves the link capacity significantly compared to the average power based SSDT (K=1).

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