Uplink Capacity and Required Transmit Power of DS-CDMA DAN

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Abstract—Antenna diversity is a powerful technique to mitigate the impact of multipath fading. In a conventional centralized antenna network (CAN), diversity antennas are co-located at base station and hence, the impacts of the propagation path loss and the shadowing loss cannot be mitigated. Distributed antenna network (DAN) is an effective way to mitigate all of the above impacts. The choice of the multi-access technique is a very important issue. In this paper, we consider broadband DS-CDMA with joint minimum mean square error based frequency domain-equalization (MMSE-FDE)/antenna diversity as the multi-access technique for DAN and investigate the link capacity and required transmit power to compare with CAN. It is shown by the computer simulation that DS-CDMA DAN can reduce the required transmit power for the given bit error rate (BER) and can obtain larger uplink cellular capacity than DS-CDMA CAN.

Keywords-component; DS-CDMA, DAN, Uplink capacity, CCI, MUI, TPC, extended diversity

I. INTRODUCTION

In a conventional centralized antenna network (CAN), since diversity antennas are co-located at base station, the impact of fading can be mitigated by using antenna diversity; however, the impacts of the propagation path loss and the shadowing loss cannot be mitigated. Therefore, a high transmit power is required for a user near the cell edge to meet the required transmission quality, producing large co-channel interference (CCI) to other cells. One attractive solution is to introduce the distributed antenna network (DAN) [1-3]. In DAN, many antennas are spatially distributed in each cell. Some antennas near a user can be found with a high probability and hence, the propagation path loss and the shadowing loss can be mitigated. Thus, the transmit power can be significantly reduced, thereby reducing the CCI to other cells.

Since the available bandwidth is limited, the choice of multi-access (MA) technique is an important technical issue. Well known MAs are time division multiple access (TDMA), frequency division multiple access (FDMA), and code division multiple access (CDMA) [4]. In FDMA, the available channels are grouped into several channel groups which are allocated to different base stations. The same group needs to be reused at spatially separated base stations so as to minimize the CCI. Basically TDMA requires the similar channel allocation to FDMA. There are many channel allocation algorithms [5-7]. The fixed channel allocation is quite difficult to adapt to changing CCI environment unlike the dynamic channel allocation. However, the dynamic channel allocation is quite difficult to implement if not impossible and therefore, no practical dynamic channel allocation has been developed. On the other hand, thanks to the CCI reduction through dispreading process, CDMA can use the single frequency reuse (i.e., available bandwidth can be reused every cell) and hence, can avoid the sophisticated channel allocation. DS-CDMA is adopted for the third generation (3G) systems [4].Coherent Rake combining combined with antenna diversity can mitigate the impact of multipath fading [8]. However, the severe multi-user interference (MUI) is produced due to the near-far problem caused by the path loss and the shadowing loss [9]. Therefore, the application of fast transmit power control (TPC) is essential [8-9]. Furthermore, CCI is the strongest for a user near the cell edge and therefore, the site diversity (or the soft handover) is also necessary [8].

In broadband DS-CDMA, the inter-chip interference (ICI) caused by the frequency-selective fading degrades the transmission performance. The minimum mean square error (MMSE) based frequency-domain equalization (FDE) can mitigate the ICI [10-11].

There have been many studies on DS-CDMA DAN [e.g., 12-15]. It was shown [12-14] that DS-CDMA CAN can achieve higher received signal-to-interference power ratio (SIR) than DS-CDMA CAN. Ref. [15] investigated the uplink power control for DS-CDMA DAN and showed that DAN can bring significant power saving. However, Refs. [12-15] consider the received SIR assuming Rake combining and do not evaluate the bit error rate (BER) performance. To the best of our knowledge, the uplink capacity of DS-CDMA DAN with joint MMSE-FDE/antenna diversity and comparison to DS-CDMA CAN have not been studied yet.

In this paper, we consider broadband DS-CDMA with joint MMSE-FDE/antenna diversity and investigate, by computer simulation, the uplink capacity of DS-CDMA DAN to show that DAN can achieve higher uplink capacity than CAN. We also show by the computer simulation that if antenna diversity is extended to involve multiple cells similar to site diversity, the link capacity can be further improved while reducing the transmit power.

The remainder of this paper is organized as follows. The uplink model of DS-CDMA DAN is described in Sect. II. Section III presents the DS-CDMA transmission system model. The computer simulation results on the BER outage probability, the transmit power distribution, and the uplink capacity is presented in Sect. IV. Sect. V offers some conclusions.
II. **UPLINK DAN MODEL**

A. **Uplink Model**

In this paper, multiuser and multi-cell environment is considered. Figure 1 illustrates the models of DAN and CAN with \(N_{total}=7\) antennas in a multi-cell environment. The center cell (\(c=0\)) is assumed to be the cell of interest. Assuming the cluster size \(N=1\), there are 6 CCI cells (\(c=1\)–6) for the cell of interest (\(c=0\)). In our DAN model, it is assumed that each distributed antenna covers the hexagonal area with a radius of \(R' = R / \sqrt{3}\), where \(R\) represents the cell radius of the CAN. All distributed antennas are connected to the SPC by optical links (ideal signal transmission between each distributed antenna and the SPC is assumed). In CAN, all antennas are co-located at the center of the cell.

It is assumed that there are \(U\) active users in each cell and user terminal is equipped with single antenna (i.e., \(N_t=1\)). In this paper, distributed antennas are selected from \(D_{max}=7\) surrounding cells including the cell of interest for diversity combining (we call this diversity as an extended diversity). Each user selects \(N_r\) antennas in order of decreasing the instantaneous received power from \(D_{max}N_{total}\) antennas. Note that there are 6 CCI cells in the first tier of each surrounding cell (\(c=1\)–6) which has antennas user in the interest cell (\(c=0\)) communicates with. For example, if the user in \(c=0\) cell selects an antenna in \(c=1\) cell, there are 6 CCI cells (\(c=7, 8, 2, 0, 6, 18\)) for the antenna.

In this paper, we measure the distribution of local average BER by computer simulation to find the outage probability of BER, which is defined as the probability with which the local average BER exceed the required BER. We define the uplink capacity as the maximum \(U_{max}\) of supportable users normalized by the spreading factor \(SF\) for the given allowable outage probability \(Q\).

B. **Channel Model**

The broadband propagation channel is characterized by the propagation path loss, the log-normally distributed shadowing loss, and the frequency-selective fading. Assuming a frequency-selective channel composed of \(L\) paths, the channel impulse response, \(\tilde{h}^{(c,c',\alpha)}(t)\), of the link between the \(u\)-th user in \(c\)-th cell and the \(n\)-th received antenna in \(c'\)-th cell is expressed as

\[
\tilde{h}^{(c,c',\alpha)}(t) = \sum_{l=0}^{L-1} \tilde{h}^{(c,c',\alpha)}_{l} g(t - \tau^{(c,c',\alpha)}_{l}),
\]

where \(\tilde{h}^{(c,c',\alpha)}_{l}\) is the \(l\)-th complex valued path gain, including the impact of the propagation path loss and the shadowing loss, of the link between the \(u\)-th user in \(c\)-th cell and the \(n\)-th received antenna in \(c'\)-th cell. It is expressed as

\[
h^{(c,c',\alpha)}_{l} = \left[ D^{(c,c',\alpha)} - \eta^{(c,c',\alpha)} \right]^{\alpha/10} \cdot g^{(c,c',\alpha)}_{l},
\]

where \(D^{(c,c',\alpha)}\) is the distance between the \(u\)-th user in \(c\)-th cell and the \(n\)-th received antenna in \(c'\)-th cell. \(\alpha\) denotes the path loss exponent and \(\eta^{(c,c',\alpha)}\) is the shadowing loss in dB between the \(u\)-th user in \(c\)-th cell and the \(n\)-th received antenna in \(c'\)-th cell. \(g^{(c,c',\alpha)}_{l}\) and \(\tau^{(c,c',\alpha)}_{l}\) are the \(l\)-th complex-valued path gain with \(E \left[ \sum_{l=0}^{L-1} \left| g^{(c,c',\alpha)}_{l} \right|^2 \right] = 1\) and the time delay of the \(l\)-th path, respectively.

The instantaneous received signal power at the \(n\)-th received antenna in \(c'\)-th cell from the \(u\)-th user in \(c\)-th cell, \(P_{r}^{(c,c',\alpha)}\), is expressed as

\[
P_{r}^{(c,c',\alpha)} = P_{i}^{(c,c',\alpha)} \cdot \sum_{l=0}^{L-1} |h^{(c,c',\alpha)}_{l}|^2.
\]

where \(P_{i}^{(c,c',\alpha)}\) represents the actual transmit power of the \(u\)-th user in \(c\)-th cell, and Eq. (3) can be rewritten as

\[
P_{r}^{(c,c',\alpha)} = P_{i}^{(c,c',\alpha)} \cdot D^{(c,c',\alpha)} \cdot 10^{-\eta^{(c,c',\alpha)} / 10} \cdot \sum_{l=0}^{L-1} \left| g^{(c,c',\alpha)}_{l} \right|^2,
\]

where \(P_{i}^{(c,c',\alpha)}\) and \(D^{(c,c',\alpha)}\) denote the normalized transmit power and the normalized distance, respectively. \(h^{(c,c',\alpha)}_{l}\) is the normalized \(l\)-th complex valued path gain and expressed as

\[
h^{(c,c',\alpha)}_{l} = \sqrt{ \left[ D^{(c,c',\alpha)} / R \right]^{\alpha/10} \cdot \eta^{(c,c',\alpha)} \cdot g^{(c,c',\alpha)}_{l}}.
\]

III. **DS-CDMA WITH JOINT MMSE-FDE/ANTENNA DIVERSITY**

A. **Transmit/Receive Signal Representation**

The DS-CDMA uplink transmitter/receiver structure is illustrated in Fig. 2. In the paper, the chip-spaced discrete-time signal representation is used.
then spread by multiplying it with a user-specific long pseudo 
the desired user receives the signals from the desired user 0 and 
baseband representation as 
each block.
The last 
cell is the desired user 0. The 
transmitter of the

...
FDE and diversity combining. The FDE weight $W_{\ell}(k)$ can be derived as [10]

$$W_{\ell}(k) = \frac{\sum_{n=0}^{N_c-1} \Gamma(n) H_{\ell}(n,0,\alpha_n)(k)}{1 + \sum_{n=0}^{N_c-1} \sum_{l=0}^{L-1} \Gamma(n) H_{\ell}(n,0,\alpha_n)(k)^2}$$

(12)

where

$$\Gamma(n) = \frac{P_t(n) T}{N_0}$$

(13)

After joint FDE and diversity combining, the frequency-domain signal is transformed by $N_c$-point inverse FFT (IFFT) into the time-domain signal. Finally, the signal is despread, and the received signal is demodulated.

C. SNR-based fast TPC

In this paper, we consider fast TPC so that the instantaneous signal-to-noise power ratio (SNR) after despreading is kept at the target SNR. The normalized transmit power $P_t(\ell)$ of the $\ell$-th user is given by

$$P_t(\ell) = \frac{N_0}{2T} \sum_{n=0}^{N_c-1} \sum_{l=1}^{L-1} \frac{SIR_n}{SF},$$

(14)

IV. COMPUTER SIMULATION

The simulation condition is summarized in Table 1. QPSK data modulation is considered. Long PN sequence is used as the spreading code and spreading factor $SF$ is set to $SF=16$. FFT block size $N_t$ and CP length $N_c$ are respectively set to $N_t=256$ and $N_c=32$. The channel is assumed to be a frequency-selective fading having symbol spaced $L=16$ path uniform power delay profile. The path loss exponent $\alpha$ and the shadowing loss standard deviation $\sigma$ are assumed to be $\alpha=3.5$ and $\sigma=7.0$dB, respectively. We assume the interference-limited channel ($\text{SNR}_{\text{target}}=1$) and ideal TPC. Perfect channel estimation is also assumed.

The outage probability is defined as the probability that the local average BER exceeds the required BER. The uplink capacity is defined as the maximum number $U_{\text{max}}$ of supportable users normalized by the spreading factor $SF$. In this paper, the required BER and the allowable outage probability are set as $\text{BER}=10^{-2}$ and $Q=0.1$, respectively.

Figure 3 illustrates the outage probability as a function of the normalized number of users $U/SF$, when $N_t=3$. For CAN, the outage probability significantly increases with $U/SF$. In contrast, DAN can achieve lower outage probability than CAN. The reason for this is given below. In CAN, antennas are co-located at the BS. On the other hand, in DAN, distributed antennas are geographically separated and hence, the interference from other users can be more mitigated by antenna diversity against not only the fading but also the propagation path loss and the shadowing loss.

Figure 4 plots the probability density function (PDF) of the normalized transmit power-to-TPC target ratio $P_t(\ell) / P_{\text{target}}$ when $N_t=3$, where $P_{\text{target}} = \text{SNR}_{\text{target}} (N_t / 2T) / SF$. It can be seen from Fig. 4 that DAN with extended diversity can reduce the required transmit power.

Figure 5 plots the uplink capacity, $U_{\text{max}}/SF$, with the number of receive antennas $N_r$ as parameter. It is shown in Fig. 5 that the uplink capacity of CAN without extended diversity is upper limited when $N_r>3$. In CAN without extended diversity, the user who is located cell edge requires large transmit power, and thereby, the transmit performance is degraded by large CCI. On the other hand, DAN can mitigate the impact of CCI, and hence can achieve 6 times higher uplink capacity than that of CAN without extended diversity. It is also seen from Fig. 5 that the difference of uplink capacity between DAN with extended diversity and CAN with extended diversity decreases as $N_r$ increases. The reason for this is explained as follows. In CAN, all antennas of each cell are co-located at the center of the cell, and hence, the received SIRs are the same among selected antennas. Therefore, the spatial diversity gain which is proportional with the number of selected antennas can be obtained. On the other hand, in DAN, antennas are spatially distributed in the cell. Therefore, the received SIRs are different among selected antennas and decreases as the distance between desire user and the selected antenna increases. As a consequence, the spatial diversity gain is upper limited by the interference from other users when $N_r$ is large.

According to the above simulation results, it can be concluded that DAN achieve higher uplink capacity than CAN while using smaller number of received antennas.

V. CONCLUSIONS

In this paper, we investigated the uplink capacity of DS-CDMA DAN with joint MMSE-FDE/antenna diversity. In DAN, several antennas are found near a user with a high probability and hence, the negative impact of the path loss and the shadowing loss can be mitigated. We showed by the computer simulation that DAN can reduce the required transmit power and achieve a higher uplink capacity than CAN. Furthermore, the uplink capacity becomes higher as the number of received antennas increases due to antenna diversity while reducing the transmit power. However, when too many antennas are involved in diversity, some of the selected antennas may be far from a user and thereby, the spatial diversity gain may be saturated. As a result, the capacity difference between DAN and CAN decreases as $N_r$ increases.

In DAN, the number of simultaneously accessing users per antenna is few and hence, the use of a simple interference cancellation technique can improve the uplink capacity. The interference cancellation for DS-CDMA DAN is left as our future study. In addition, we will also study the effect of signal-interference plus noise power ratio (SINR) based TPC.
TABLE I. COMPUTER SIMULATION CONDITION

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Modulation</th>
<th>QPSK</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of FFT points</td>
<td>$N_c=256$ chips</td>
<td></td>
</tr>
<tr>
<td>Guard interval length</td>
<td>$N_c=32$ chips</td>
<td></td>
</tr>
<tr>
<td>Spreading factor</td>
<td>SF=16</td>
<td></td>
</tr>
<tr>
<td>Spreading codes</td>
<td>Long PN code</td>
<td></td>
</tr>
<tr>
<td>SNR-based fast TPC</td>
<td>$SNR_{target}&gt;&gt;1$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Channel</th>
<th>Fading type</th>
<th>Frequency-selective block Rayleigh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power delay profile</td>
<td>$L=16$-path uniform power delay profile</td>
<td></td>
</tr>
<tr>
<td>Path-loss exponent</td>
<td>$\alpha=3.5$</td>
<td></td>
</tr>
<tr>
<td>Standard deviation of shadowing loss</td>
<td>$\sigma=7.0$ dB</td>
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</table>

<table>
<thead>
<tr>
<th>Receiver</th>
<th>No. of distributed antennas</th>
<th>$N_{can}=7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum no. of diversity cells</td>
<td>$D_{can}=7$</td>
<td></td>
</tr>
<tr>
<td>Channel estimation</td>
<td>Ideal</td>
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<tr>
<td>Required quality</td>
<td>Required BER</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Allowable outage probability</td>
<td>$Q=0.1$</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Outage probability.

Figure 4. PDF of $P_i^{\text{can}}/P_{\text{target}}$.

Figure 5. Uplink capacity.

REFERENCES