On the Downlink Capacity of WCDMA Systems with Transmit Diversity

Vaibhav Singh, Oya Yilmaz, Jialing Wang, Karthigeyan Reddy, and S. Ben Slimane
Radio Communication Systems
Department of Signals, Sensors, and Systems
Royal Institute of Technology (KTH)
Electrum 418, 164 40 KISTA, Sweden

***Abstract*— Transmitter diversity at the base station has been included in WCDMA standard for third generation mobile systems as a means of increasing the downlink system capacity. In previous works, it has been shown that open loop transmitter diversity can significantly increase the downlink capacity. However, the performance in multipath environment is not known. In our study, we present the simulation results for downlink system capacity taking into account the effect of Doppler frequency and multipath fading. The results show that even in severe multipath wireless channel, diversity scheme can greatly improve the system capacity when no soft handover is used.**

I. Introduction

The Space Time Transmit Diversity (STTD) scheme adopted by 3GPP in the current WCDMA standard is based on a modification of the Alamouti space time coding scheme [1]. However this scheme is based on orthogonal design. In a WCDMA system, due to multipath propagation, the signals received will no longer be orthogonal. Previous works on this topic [2], [3], [4] have mainly focused on the impact of multipath fading on link level performance. In [3], [4], system level results have been presented for STTD but they do not consider the increase in interference caused by multipath propagation. In this paper, we present results for the downlink capacity of a WCDMA system both with STTD and without STTD. We focus on the STTD performance in typical urban macro cellular environment, assuming either the ITU Vehicular-A or the Pedestrian-A multi-path delay profile [5]. We consider only speech traffic over dedicated channel. In Section II, the concept of WCDMA system is introduced and the transmitter diversity scheme STTD is discussed. In Section III, the system model used in the simulation is described. In Section IV, the simulation results are presented and analyzed. In the last section, a conclusion is drawn.

II. WCDMA Cellular System

A. Cellular System Model

We consider a multi-cellular WCDMA system with hexagonal cells and three sectors per cell. Each sector is using an STTD encoding scheme according to Figure 1. In this work we only consider $R = 12.2$ kbps speech service over dedicated channels in the downlink. In order to model the intra-cell and inter-cell interference adequately, the link between each mobile and each base station is modeled explicitly. We do not model the pilot channel transmitted by each base-station.

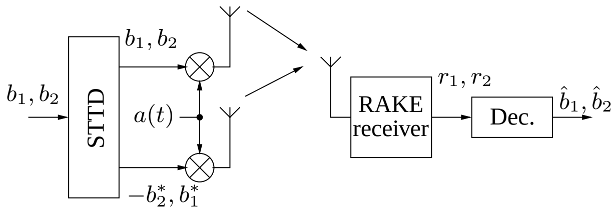

Fig. 1. WCDMA with Alamouti STTD encoding and decoding.

B. Channel Model

In cellular systems, the signals are exposed to both long term fading and short term fading effects. In general, the long term effect is modeled by a deterministic path loss and a stochastic part modeled as a lognormal process. In this paper, we model the long term effect between antenna 1 of the mth sector and mobile user i as [11]:

$$g_{mi} = d_{mi}^{-\mu} G_{mi} \tag{1}$$

where $d_{mi}^{-\mu}$ is the distance dependent pathloss, d_{mi} is the distance from the mobile to the mth cell site, and μ is the pathloss exponent. G_{mi} represents the log-normal shadow fading, i.e., $10\log_{10}(G_{mi})$ is a zero mean Gaussian random variable with standard deviation σ_s dB. As the transmit antennas of each sector are co-located, they are assumed to have the same long term effect.

The short term effect is modeled as frequency selective fading channel with equivalent lowpass channel impulse response given by

$$h(t,\tau) = \sum_{i=1}^{N} h_i \delta(\tau - \tau_i) \tag{2}$$

where N is the total number of paths, h_i is zero-mean complex Gaussian random variable with power spectral density $2\sigma_i^2$ representing the gain of path i, and τ_i is the time delay of path i. We further assume a normalized channel fading coefficients, i.e.,

$$\sum_{i=1}^{N} \overline{|h_i|^2} = \sum_{i=1}^{N} 2\sigma_i^2 = 1. \tag{3}$$

Two multipath delay profiles are considered in this paper: The ITU Pedestrian-A (Ped-A) and Vehicular-A (Veh-A) power delay profiles.The power of the multi-paths in the power delay profile has a chi-square distribution with two degrees of freedom while the amplitude is Rayleigh distributed with a classical Doppler spectrum. The channels of the different transmit antennas are assumed independent.

C. Receiver Model

The receiver (mobile unit side) consists of one omni-directional antenna and a RAKE receiver having a total number of fingers equals to the number of paths N. Considering a certain mobile unit within the coverage area of sector m, say mobile u, the equivalent lowpass of the received signal can be written as

$$r(t) = \sum_{l=0}^{1}\sum_{i=1}^{N} h_{il} \sum_{k=1}^{K_m} s_{kl}(t-\tau_{il}) + i_e(t) + z(t) \tag{4}$$

where K_m is the total number of active mobile users within sector m, $i_e(t)$ is the external interference coming from other sectors, $z(t)$ is complex Gaussian random process with zero-mean and power spectral density N_0, h_{il} is a complex process representing the fading coefficient of path i, $s_{kl}(t)$ is the transmitted signal of user k from transmit antenna l,

$$s_{kl}(t) = \sqrt{\phi_k g_m p_m} a_k(t) b_k(t),$$

where each data symbol is assumed to have unit amplitude, i.e., $|b_k(t)|^2 = 1$ and the spreading waveform is denoted by $a_k(t)$. Here p_m is the total transmitted power of base station m, g_m is the link gain between the mobile receiver and base station m, and ϕ_k is the portion of power allocated to user k. The spreading bandwidth is $W \approx 1/T_c$ where T_c is the chip duration. When the period of the spreading waveforms is larger than the information symbol duration T, the correlation properties follow

$$\begin{aligned} \rho_{ik}(\tau) &= \frac{1}{\sqrt{T}} \int_0^T a_i(t-\tau) a_k(t) b_i(t-\tau)\, dt \\ &\approx \frac{1}{\sqrt{T}} \int_0^T a_i(t-\tau) a_k(t)\, dt. \end{aligned} \tag{5}$$

For a spreading waveform defined as

$$a_i(t) = \sum_{n=-\infty}^{+\infty} a_{i,n} \sqcap_{T_c} (t - nT_c) \tag{6}$$

where $a_{i,n} = \pm 1$ with equal probability and $\sqcap_T(t)$ is a rectangular pulse of length T and amplitude equals to one, the cross correlations (5) can be determined from the results of [6]. Using our notation and considering users within the same cell, it can be shown that when $i \neq k$,

$$\mathrm{var}[\rho_{ik}(\tau)] = \begin{cases} 0, & \tau = 0 \\ \frac{\zeta}{W}, & \tau \neq 0 \end{cases} \tag{7}$$

and

$$\mathrm{var}[\rho_{ii}(\tau)] = \begin{cases} \frac{1}{R}, & \tau = 0 \\ \frac{\zeta}{W}, & \tau \neq 0 \end{cases} \tag{8}$$

where $\zeta = 1$ for synchronous waveforms and $\zeta = 1/3$ for asynchronous waveforms.

Assuming perfect channel state information and that the delays $\{\tau_i\}_{i=1}^N$ are known, the RAKE receiver output samples corresponding to the transmitted symbols, b_1, b_2, are obtained as follows:

$$r_l = \sum_{i=1}^{N} \int_{(l-1)T}^{lT} a_u(t) h_{i1}^* r(t+\tau_{i1}) dt, \qquad l = 1, 2 \tag{9}$$

where $a_u(t)$ is the spreading code of mobile user u. Assuming BPSK modulation, the two symbols, b_1 and b_2, after STTD combining are estimated as

$$\hat{b}_1 = \mathrm{sgn}\{y_1\} = \mathrm{sgn}\{r_1 + r_2^*\} \tag{10}$$

$$\hat{b}_2 = \mathrm{sgn}\{y_2\} = \mathrm{sgn}\{r_2 - r_1^*\} \tag{11}$$

Considering the receiver of mobile station 1 in sector m, the combined sample at the mobile station, y_1, can be represented as:

$$\begin{aligned} y_1 \;=\; & \sum_{n=1}^{N} \left(|h_{n,1}|^2 + |h_{n,2}|^2\right) \sqrt{\phi_1 g_m p_m} \rho_{11}(0) \\ + & \sum_{n=1}^{N} \sum_{\substack{p=1 \\ p\neq n}}^{N} \left[h_{n,1}^*(h_{p,1} - h_{p,2}) + h_{n,2}(h_{p,1}^* + h_{p,2}^*)\right] \\ & \times \sqrt{\phi_1 g_m p_m} \rho_{11}(\tau_{n,1} - \tau_{p,1}) \\ + & \sum_{n=1}^{N} \sum_{p=1}^{N} \sum_{k=2}^{K_m} \left[h_{n,1}^*(h_{p,1} - h_{p,2}) + h_{n,2}(h_{p,1}^* + h_{p,2}^*)\right] \\ & \times \sqrt{\phi_k g_m p_m} \rho_{k1}(\tau_{n,1} - \tau_{p,1}) \\ & + \sum_{n=1}^{N} \left(h_{n,1}^* i_{1,n} + h_{n,2} i_{2,n}\right) \\ & + \sum_{n=1}^{N} \left(h_{n,1}^* z_{1,n} + h_{n,2} z_{2,n}\right) \end{aligned} \tag{12}$$

where

$$z_{l,n} = \frac{1}{\sqrt{T}} \int_{(l-1)T}^{lT} z(t+\tau_{il}) a_1(t)\, dt \tag{13}$$

is zero-mean complex Gaussian with variance N_0,

$$i_{l,n} = \frac{1}{\sqrt{T}} \int_{(l-1)T}^{lT} i_e(t+\tau_{il}) a_1(t)\, dt \tag{14}$$

is the external interference sample, and $\rho_{km}(\tau)$ is as defined earlier.

The communication quality of interest for mobile user 1, related to the bit error probability, is given by

$$\begin{aligned}\left(\frac{E_b}{I_0}\right)_1 &= \frac{\mathbb{E}[y_k|b_k(t)]\mathbb{E}^*[y_k|b_k(t)]}{\operatorname{var}[y_k|b_k(t)]} \\ &= \left[\sum_{n=1}^{N}\left(|h_{n,1}|^2+|h_{n,2}|^2\right)\right]^2 \frac{\phi_1 g_m p_m}{2R\sigma_1^2} \quad (15)\end{aligned}$$

where $\mathbb{E}$ is the expectation operator, R is the information data rate, and the factor 2 comes from the fact that the user power is split between the two transmit antennas. With the assumption of the terms in the combined sample being Gaussian and mutually independent, the variance of the interference becomes

$$\begin{aligned}\sigma_1^2 &= \left[\sum_{n=1}^{N}\left(|h_{n,1}|^2+|h_{n,2}|^2\right)\right] \\ &\quad \times \left[\theta_N g_0 p_0 \frac{\zeta}{W} + \frac{\zeta}{W}\sum_{i=2}^{B} g_i p_i + N_0\right] \quad (16)\end{aligned}$$

where B is the total number of interfering base stations, θ_N is the total orthogonality factor caused by fading multipath channels and is given by

$$\theta_N = \sum_{n=1}^{N}\sum_{\substack{p=1\\p\neq n}}^{N} \frac{\left|h_{n,1}^*(h_{p,1}-h_{p,2}) + h_{n,2}(h_{p,1}^*+h_{p,2}^*)\right|^2}{2\sum_{m=1}^{N}\left(|h_{m,1}|^2+|h_{m,2}|^2\right)}$$

Replacing (16) in (15) and simplifying, the bit-energy-to-interference-spectral-density ratio of mobile user 1 can then be rewritten as

$$\left(\frac{E_b}{I_0}\right)_1 = \frac{W}{2R}\frac{\left[\sum_{n=1}^{N}\left(|h_{n,1}|^2+|h_{n,2}|^2\right)\right]\phi_1 g_m p_m}{\theta_N g_0 p_0 \zeta + \zeta\sum_{i=2}^{B} g_i p_i + N_0 W} \quad (17)$$

For the case of one transmit antenna, the bit-energy-to-interference-spectral-density ratio of mobile user 1 takes the following form:

$$\left(\frac{E_b}{I_0}\right)_1 = \frac{W}{R}\frac{\left[\sum_{n=1}^{N}|h_{n,1}|^2\right]\phi_1 g_m p_m}{\tilde{\theta}_N g_0 p_0 \zeta + \zeta\sum_{i=2}^{B} g_i p_i + N_0 W} \quad (18)$$

where now the total orthogonality factor, denoted $\tilde{\theta}_N$, is given by

$$\tilde{\theta}_N = \sum_{n=1}^{N}\sum_{\substack{p=1\\p\neq n}}^{N}\frac{|h_{n,1}|^2|h_{p,1}|^2}{\sum_{m=1}^{N}|h_{m,1}|^2} \quad (19)$$

Comparing the two schemes, it is observed that the STTD scheme has a better diversity order and has the capability to resolve the fading multipath components from the two transmit antennas. However, it is not clear which of the two methods perform better since they have different total orthogonality factors. The strength of this orthogonality factor will affect the system performance and it will be interesting to see the interaction between the increase in diversity order and the increase in experienced interference when STTD is used in WCDMA systems.

Assuming that each user requires a maximum tolerable bit error probability that can be mapped into equivalent minimum E_b/I_0 value, denoted γ_t. Hence, the signal quality of mobile user 1 can be measured using the outage probability defined as

$$O_1 = Pr\left[\left(\frac{E_b}{I_0}\right)_1 < \gamma_t\right] \quad (20)$$

where γ_t is the minimum required SIR for good signal quality.

III. Simulation Model

The simulation is performed over a system with 19 sites and each site has 3 sectors. Wrap-around is used to eliminate the edge effects. The available system bandwidth is $W = 5$ MHz. The system offers speech service at a data rate of $R = 12.2$ kbps. The maximum base station power is limited to 20 W [4]. The maximum transmission power per link is 2 W [4] and the initial power is set to 0.1 W. The environment we assume is an urban environment. So we set the propagation constant μ to 4. The gain constant is chosen to be -28 dB. The standard deviation for lognormal shadow fading is chosen as 10 dB. We use soft handover with a handover margin of 3 dB. The SIR balancing algorithm is used for power control and the power control is done in steps of 1 dB. Hence in transmitter diversity case, the power of each antenna is changed in steps of 1 dB. In our model, the active mobile users are assumed to be uniformly distributed over the cells. The cell load is Poisson distributed. We consider two types of traffic models.

- Mobiles with low mobility (3 km/hr)
- Mobiles with high speed (60 km/hr)

The SINR threshold after despreading, γ_t, is set to 7 dB corresponding to a BER of 10^{-3} (standard for voice communication systems) [2]. All the simulation parameters considered in the paper are summarized in the following table:

TABLE I
SIMULATION PARAMETERS

Item	Symbol	Value
System Bandwidth	W	5 MHz
Chip Rate	R_c	3.84 Mcps
Information Bit Rate	R	12.2 Kbps
Gain Constant	c	-28 dB
Cell Radius	r	1000 m
Propagation Constant	μ	4
Maximum Transmission Power per link	$p_{\max}$	33 dBm [4]
Initial Transmission Power	p_{init}	20 dBm
Total Base Station Power	P_{tot}	20 W
Noise Floor	N_0	-107 dBm [4]
SIR Threshold	γ_t	7 dB
Lognormal Standard Deviation	σ_s	10 dB

IV. Simulation Results

The simulation is done for with and without diversity cases. The results obtained without diversity are used as reference to evaluate the gain obtained with STTD. This is done for the two channel profiles and the two different mobile speeds. The SIR of the user after despreading is averaged over the last five frames after the power control algorithm has converged. If this averaged SIR is less than the target SIR of 7 dB, the user is considered to be in outage. The outage probability is the ratio of the number of users in outage to the total number of users in the system. To reduce the statistical variance, we run five independent simulations and average the results obtained for these simulations.

The outage probability as a function of the cell load for the case of no TD and the case of STTD for low mobility and Ped-A channel profile is shown in Figure 2. It is observed that STTD provides significant gain in WCDMA system capacity. For example, for a 2% outage probability, a 30% capacity gain is obtained with STTD.

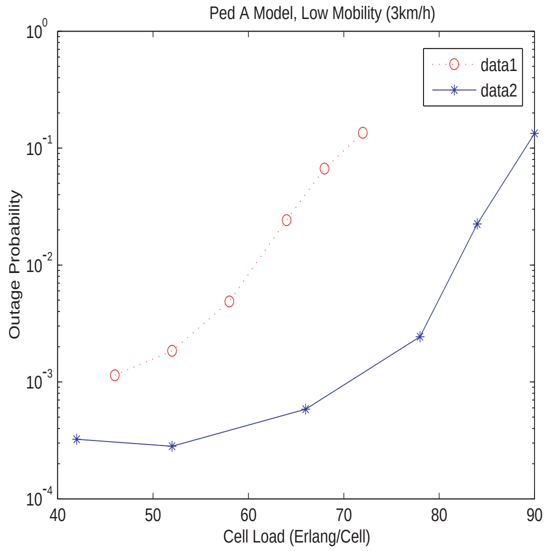

Fig. 2. Outage Probability as a function of the cell load for Pedestrian-A model (3 km/h) and low mobility with data1 corresponding to the case of No STTD and data2 to the case with STTD.

The results obtained with Vehicular-A model are shown in Figure 3. For this case, the capacity gain for 2% outage is 13%. It is seen that the gain obtained for Veh-A channel is less than that for the Ped-A channel. Since the number of paths in Veh-A model is higher, there is already a higher degree of multi-path diversity which the RAKE receiver can take advantage of. This is the reason why the gain with STTD is less for Veh-A environment than for Ped-A environment. Using STTD helps to ”smooth out” the fading effect, which results in a lower transmitted power. If a user is in a bad position, the transmitted power for that user has to be increased in order to achieve the target SIR. This increases the interference for the other users. For low mobility case, the fading will last for a longer time. By using transmitter diversity, we are able to negate the effect of fading and achieve improved system capacity. Thus for low mobility there is more diversity gain and less interference averaging.

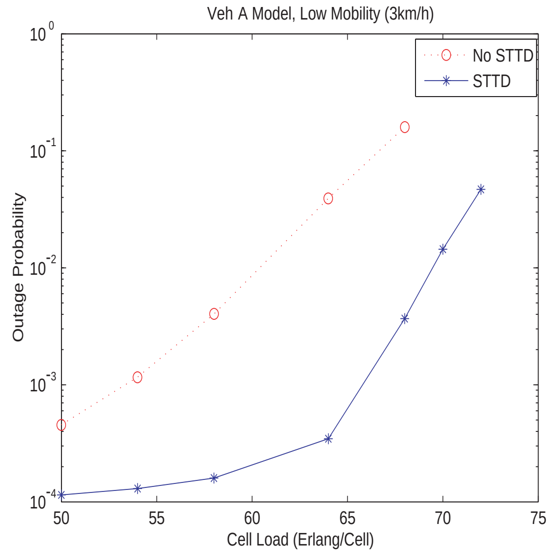

Fig. 3. Outage Probability as a function of the cell load for Vehicular-A model and low mobility (3 km/h).

A. System Capacity for High Mobility

In order to find the effect of mobility on capacity, we also evaluate the system capacity for high mobility. Results obtained for Ped-A channel are shown in Figure 4. Figure 5 shows the capacity for Veh-A environment. The gain in

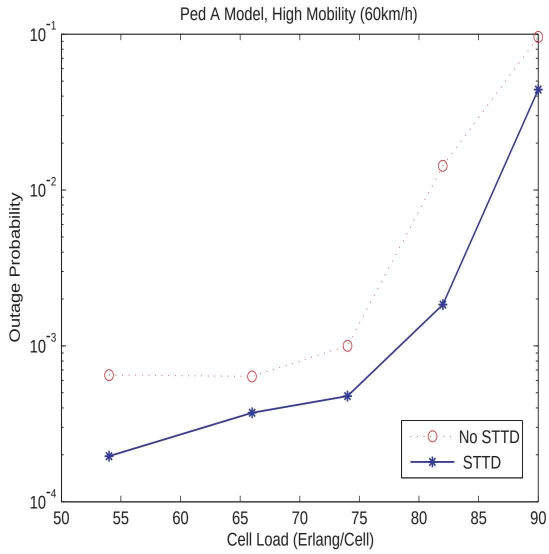

Fig. 4. Outage Probability as a function of the cell load for Pedestrian-A model and high mobility (60 km/h)

system capacity for 2% outage is 8% for Ped-A channel. For Veh-A channel the gain obtained is very small. Compared to low mobility case, we have much lower gain with STTD in high mobility case. When we have high mobility, a user does not stay in a bad position for long. Thus the interference is averaged out. Hence the interference in the system decreases

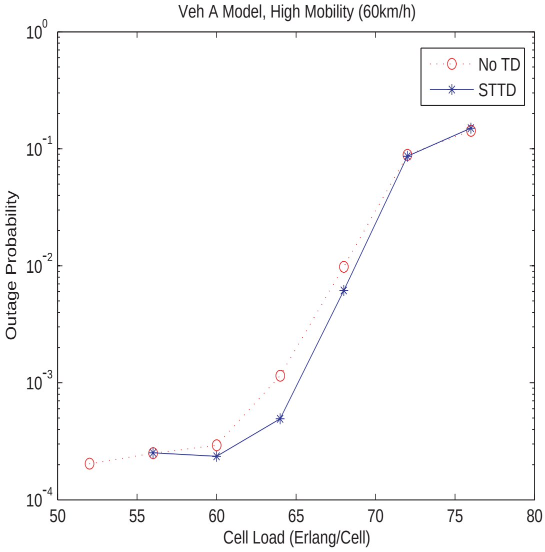

Fig. 5. Outage Probability as a function of the cell load for Vehicular-A model and high mobility (60 km/h)

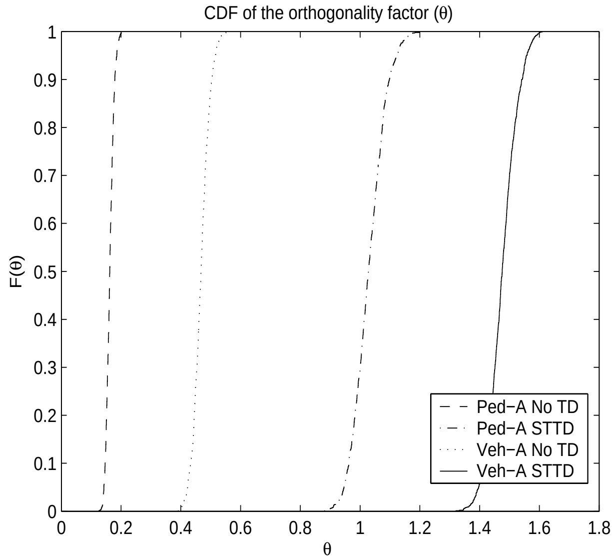

Fig. 6. The cumulative distribution function of the orthogonality factor for the 2 channel models with and without STTD

leading to an increase in capacity. Since in high mobility we already have an interference averaging effect, the gain obtained by introducing diversity is lower as compared to the low mobility case.

The cumulative distribution function of the orthogonality factor for the two channel models is illustrated in Figure 6 for the case of WCDMA with single transmit antenna and the case of WCDMA with STTD.

It is observed that the orthogonality factor increases when the number of paths from the base-station to the mobile increase. It is also seen that introducing transmitter diversity into the system increases the orthogonality factor and hence the intra-cell interference increases. In low mobility, the diversity gain is sufficient to compensate for the increased interference and additionally provide a capacity gain.

V. Conclusions

The results have shown that transmitter diversity provides downlink capacity improvement. The gain obtained is much higher for low mobility case as compared to high mobility case. The gain obtained decreases as the number of paths increases. The effect of using STTD in combination with various receiver diversity combining schemes has been studied on the link level in [13]. Future work can look into the system level gain obtained when using both transmit and receiver diversity in WCDMA systems.

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