Performance of Turbo Coded WCDMA with Downlink Space Time Block Coding in Correlated Fading Channels

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Abstract

In future wireless systems such as 3G and beyond, increasing the downlink capacity becomes more important due to potential high data rate applications such as wireless internet access. Turbo codes and downlink transmit diversity are two of the most explored techniques to improve performance and capacity. In this paper, we evaluate the performance of turbo coded WCDMA systems with downlink transmit diversity employing a space time block code on correlated fading channels. The performance improvement using downlink Space-Time Transmit Diversity (STTD) is found to be more significant in the case of slow fading when the temporal correlation is high. By considering the spatial correlation between the transmit antennas at the base station, we quantify the tolerable correlation between transmit antennas by means of simulation for which the turbo coded WCDMA systems with transmit diversity still attain performance gains compared to a single transmit antenna system.

Keywords: Turbo code, WCDMA, Correlated channels, Downlink transmit diversity

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1 Introduction

In future wireless systems such as 3G and beyond, increasing the downlink capacity becomes more important due to potential high data rate applications such as wireless internet access. To improve the downlink capacity, turbo codes and space-time processing are two of the most explored techniques. Turbo codes, which are also known as parallel concatenated convolutional codes (PCCC), are the most exciting and potentially important development in coding theory in recent years. They were first introduced by Berrou et al. in 1993 [1]. Turbo codes combine recursive systematic convolutional (RSC) codes along with a pseudorandom internal interleaver and maximum a posteriori probability (MAP) iterative decoding algorithm to achieve performance very close to the Shannon limit [1, 2]. Compared with convolutional codes with Viterbi decoding, the performance gain of turbo codes is mainly for large coding block size. Also due to the delay introduced by the turbo internal interleaver, turbo codes are more suitable for data transmissions. Turbo codes have been adopted in the 3rd generation mobile systems, such as WCDMA/UMTS, mainly for the high data rate applications [3]. A lot of attention has been drawn to the performance and analysis of turbo codes over Rayleigh fading channels as well as wideband frequency selective fading channels [4, 5].

Unlike the wireline system, the wireless mobile communication systems are susceptible to time-varying impairments, such as multipath fading and interference. Achieving high data rates over wireless channels is a challenging task. In general, time-varying fading due to multipath propagation can be effectively combated by employing various diversity techniques, including time, frequency, and space diversity. Interleaving is a way to break the channel temporal correlation and provide time diversity. However, the interleaving depth is usually limited by the interleaving delay constraints and memory requirement. With limited interleaving depth, the performance is often degraded by the temporally correlated errors, especially in slow fading situations at low vehicle speed [6, 7]. Wideband signals over frequency selective fading channels have certain inherent frequency or multipath diversity. In DS-CDMA based systems, rake receivers are used to take advantage of such diversity. The diversity gain of rake receiver depends on the number of combined branches, the branch strengths, and the correlation between different branches. Typical analyses of the performance of a CDMA rake receiver assume the rake branches to be separated from each other by at least a chip duration which leads to uncorrelated rake branches. This is especially true in relatively low chip rate CDMA systems, such as IS-95. However, when the chip-rate is higher and the over-sampled tracking system is used to obtain fine synchronization, which is the case in a WCDMA system, two multipath branches separated by a fractional chip (i.e., less than a chip duration) delay separation can be resolved. With such small delay spread, these two multipath branches might be cross correlated not only due to partially overlapped pulse shaping filtering but even otherwise. The assignment of rake branches to possibly correlated branches depends on the overall performance. Balachandran et al. [8] showed that two rake fingers should be assigned as long as their spacing is greater than 0.2 chip when only two multipath branches are present. Vejlgaard et al. [9] showed that grouped three Rake fingers with 0.5 chip spacing gives 0.2-0.4 dB gain compared to a single Rake finger assignment. Thus the cross correlations between rake branches can be a realistic issue that affects performance.

Both time and frequency diversity might be insufficient under certain conditions, especially at low vehicle speed [10]. The multiple antennas on transmitter and/or receiver provide the space diversity. It might be difficult, however, to have multiple antennas on the mobile handset due to the limitations on power, size and weight of mobile handsets. Hence, from the engineering point of view, it makes sense to place multiple antennas and additional complexity on base stations, which have fixed location and sufficient processing and energy resources compared to the mobile handsets. Transmit diversity techniques provide a relatively low cost solution to increase downlink capacity in 3rd generation mobile systems. In the recent literature, there has been a lot of work dedicated to the study of transmit diversity techniques [10, 11]. Downlink transmit diversity can be used to mitigate the degradation caused by channel correlations, especially in slow fading channels at low vehicle speeds. In this paper, we use the term space time transmit diversity (STTD) to specifically denote the space time block coding scheme in [10].

Even though turbo coding and downlink transmit diversity are two of the most explored techniques in improving the downlink capacity, there are only limited studies considering both techniques for WCDMA systems over temporally and spatially correlated fading channels [12–14]. Gaspa and Fonollosa [12] evaluated the UMTS performance with the combination of space-time coding and turbo coding. However, only the effect of temporal correlation was evaluated.

Using turbo space-time processing to improve wireless channel capacity was studied by Ariyavisitakul [13] from the point of view of information theory. In his paper, Ariyavisitakul studied the combination of turbo codes with a layered space-time architecture, which was originally proposed by Foschini et al. [15]. Multiple transmit antennas were used without using STTD technique. Wyk and Linde [14] evaluated the fading correlation and its effect on the capacity of space-time turbo coded DS-CDMA system. Again, the layered space-time code was considered. As we know from the studies of space-time processing [13,15], the large capacity gain from space diversity are achieved especially when the transfer functions between different transmit and receiver antenna pairs are uncorrelated. This presumes that the antennas can be placed apart from each other with large enough distance. However, in real scenarios this may not be the case due to limitations of size and cost of base stations [16]. Also the multipath angular spread of the direction of departure from a base station is usually small. Both facts, size limitations and small angular spread, will increase the spatial correlation between the base station antennas [17–19]. Thus it is of interest to evaluate the performance improvement by using space time coding in the turbo coded WCDMA system when both the temporal correlation in each multipath branch and the cross correlation between different multipath branches are presented. Also, it is of interest to evaluate the performance impact of spatial correlation of base station antennas and quantify the tolerable spatial correlation while the turbo coded WCDMA system with space time coding still yields a performance gain compared to a single antenna system. Since the analytical performance bounds, such as the union bound, for turbo codes generally "diverge" in the interesting SNR range [4], we will rely on simulations for our evaluations throughout this paper.

The paper is organized as follows. The model of a turbo coded WCDMA system with downlink space time coding is described in Section 2. In Section 3, the theory of turbo encoders and decoding algorithms is summarized. In Section 4, the space-time transmit diversity technique is described. In Section 5, the simulation results on the performance of turbo coded WCDMA systems with downlink transmit diversity are presented. The impact of temporal and spatial channel correlations on the performance is quantified. We summarize the results in Section 6.

2 System Model of Turbo Coded WCDMA

Figure 1 shows the system model of a turbo coded WCDMA downlink with space time block coding which is considered in this paper. A sequence of information bits is encoded by a turbo encoder defined in the 3rd Generation Partnership Project (3GPP) specification [3], which is described in the next section. The coded bits are fed into the rate match block, which will match the coded block to a certain number of radio frames by puncturing or repeating. After rate matching, the channel bits are interleaved [1]. Finally, the interleaved channel bits are modulated and encoded by a space-time encoder and transmitted from both antennas. The system without transmit diversity is similar but with only a single transmit antenna.

The wideband frequency-selective channel is modeled as a multipath channel. The number of fingers of the rake receiver is L. At the receiver, the space-time receiver computes the soft-symbol (bit) values of the transmitted symbols (bits) from the received signal $r_l(t)$ and channel estimates $\hat{h}_{il}(t),\ i = 1, 2$, and $l = 1, 2...L$, which represents the estimated complex channel value of the l-th path from transmit antenna i. After channel de-interleaving and rate de-matching, the soft-symbols are fed to the turbo decoder. Three types of channel correlations are considered in this paper. The first is the temporal correlation over each multipath branch, such as h_{11} in Figure 1. It is defined as in [20]

$$\rho_{11}(\tau) = \frac{1}{2}E[h_{11}(t)h^*_{11}(t+\tau)] = \sigma^2_{11}J_0(2\pi f_D \tau) \tag{1}$$

where σ^2_{11} is the variance of I or Q component in this multipath branch h_{11}, $f_D = vf_c/c$ is the maximum Doppler frequency with v being the mobile speed and f_c being the carrier frequency and c being the speed of light, and $J_0(\cdot)$ is the zero-order Bessel function. The second is the cross correlation between different multipath branches which might be due to partially overlapped pulse shaping filtering, such as the cross correlation between h_{11} and h_{12} as well as that between h_{21} and h_{22} in Figure 1. Notice that here the transmitted signal comes from the same antenna. This type of cross correlation is quantified by the cross-correlation coefficient ρ between the signal envelopes [20, 21] and is expressed as

$$\rho = \frac{(1+\lambda)E_i(\frac{2\sqrt{\lambda}}{1+\lambda}) - \frac{\pi}{2}}{2 - \frac{\pi}{2}}, \tag{2}$$

where

$$\lambda = \frac{\frac{1}{2}E[h_{11}(t)h^*_{12}(t)]}{\sigma_{11}\sigma_{12}}. \tag{3}$$

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[1] The simulation results presented in this paper use both 1st and 2nd interleavers as described in the 3GPP specification [3]

In the equation, $E_i(\cdot)$ denotes the complete elliptic integral of the second kind. In practical use, ρ is well approximated by λ^2 as stated in [20].

The third is the spatial correlation between different transmit antennas. It is characterized by the cross-correlation between the multipath branches arriving at the receiver from two base station transmit antennas at the same time, such as between h_{11} and h_{21} as well as between h_{12} and h_{22}. Similar to the second type of correlation, such spatial correlation is quantified by the cross-correlation coefficient ρ_{bs} between the signal envelopes and is expressed as

$$\rho_{bs} = \frac{(1+\lambda_{bs})E_i(\frac{2\sqrt{\lambda_{bs}}}{1+\lambda_{bs}}) - \frac{\pi}{2}}{2-\frac{\pi}{2}}, \tag{4}$$

where λ_{bs} in this paper and is defined as

$$\lambda_{bs} = \frac{\frac{1}{2}E[h_{11}(t)h_{21}^*(t)]}{\sigma_{11}\sigma_{21}}. \tag{5}$$

To generate cross-correlated Rayleigh fading signals, readers are referred to previous publications [21,22]. In the next two sections, the turbo code and transmit diversity techniques are described in detail.

3 Turbo Encoder and Decoding Algorithms

3.1 Turbo Encoder and Decoding Algorithms

The turbo code is also referred to as a Parallel Concatenated Convolutional Code (PCCC). It is composed of two parallel concatenated recursive systematic convolutional (RSC) encoders separated by a turbo code internal interleaver. Throughout this paper, we focus on the 8-state rate 1/3 turbo code defined in 3GPP specification [3]. The decoding for turbo code is split up into two sub-decoding phases where each code constituent is decoded separately. The RSC constituent decoders traditionally use the SISO (Soft Input Soft Output) algorithms [23]. Two typical SISO algorithms are the SOVA (Soft Output Viterbi Algorithm) by Hagenauer and Hoeher [24] and the MAP (Maximum A Posteriori probability) algorithm by Bahl et al [25]. In our work, we will focus on the MAP algorithm and its simplifications (Log-MAP and Max-Log-MAP), which are commonly used in the literature as well as for real systems.

The MAP algorithm was originally proposed by Bahl et al. [25] long time before the introduction of turbo codes and then studied extensively after the turbo codes were introduced in 1993 [1]. We will not repeat the derivation of the MAP algorithm but only state the results. The MAP algorithm minimizes the bit error probability. For each information input bit x_k, it generates the probability that this bit is 0 or 1, given the received sequence $\underline{r_1^N} = (r_1 r_2 ... r_N)$ with N being the received sequence length. The commonly used output format for such probability is the log-likelihood ratio (LLR)

$$LLR(x_k|\underline{r_1^N}) = \ln(\frac{\Pr\{x_k = 0|\underline{r_1^N}\}}{\Pr\{x_k = 1|\underline{r_1^N}\}}), \ 1 \le k \le N. \tag{6}$$

Each r_k includes received signals for both the systematic bit (x_k) and the parity bit (z_k or z'_k). The value of $LLR(x_k|\underline{r_1^N})$ represents the soft output associated with input bit x_k. It can be used in an iterative fashion between two RSC decoders. Eventually, this LLR value can be compared with a zero threshold to determine the hard-decision estimate $\hat{x}_k$

$$\hat{x}_k = \begin{cases} 0 & , \text{if } LLR(x_k|\underline{r_1^N}) \ge 0 \\ 1 & , \text{otherwise} \end{cases} \tag{7}$$

Using the MAP algorithm, the LLR can be expressed as

$$LLR(x_k|\underline{r_1^N}) = \ln \frac{\sum\limits_{(l',l) \in B_k^0} \alpha_{k-1}(l')\gamma_k^0(l',l)\beta_k(l)}{\sum\limits_{(l',l) \in B_k^1} \alpha_{k-1}(l')\gamma_k^1(l',l)\beta_k(l)} \tag{8}$$

where $(l', l) \in B_k^0$ is the set of transitions from the previous state $S_{k-1} = l'$ to the current state $S_k = l$ caused by the input $x_k = 0$, and similarly for $(l', l) \in B_k^1$ when the input is $x_k = 1$. l' and l are the state indices taken from the total possible 2^K states. The probability α is defined as

$$\alpha_k(l) = \Pr\{S_k = l, \underline{r_1^k}\} \tag{9}$$

where $\underline{r_1^k} = (r_1 r_2 ... r_k)$ is the received sequence from time index 1 to k. The probability α can be derived in a forward recursion fashion:

$$\alpha_k(l) = \sum_{all \ l'} \alpha_{k-1}(l')\gamma_k(l', l) \tag{10}$$

with initial condition due to state S_0 at time $k = 0$

$$\alpha_0(l) = \begin{cases} 1 & , l = 0 \\ 0 & , l \neq 0 \end{cases} \tag{11}$$

The branch transition probability γ is given by

$$\begin{aligned} \gamma_k^i(l', l) &= \Pr\{x_k = i, r_k, S_k = l | S_{k-1} = l'\} \\ &= \Pr\{x_k = i\}(\frac{1}{\sqrt{2\pi\sigma^2}})^2 \exp(-\frac{d^2(r_k, y_k)}{2\sigma^2}),\ i = 0,\ 1, \end{aligned} \tag{12}$$

where x_k is the input bit to cause the transition from state $S_{k-1} = l'$ to state $S_k = l$, y_k is the modulated encoder output associated with this transition and r_k is the corresponding received signal. The two-sided power spectral density of noise is $\sigma^2 = N_0/2$. $\Pr\{x_k = i\}$ is the a priori probability of input bit $x_k = i,\ i = 0, 1$. $d^2(r_k, y_k)$ is the squared Euclidean distance between r_k and the modulated symbol y_k.

The probability β is defined as

$$\beta_k(l) = \Pr\{\underline{r_{k+1}^N} | S_k = l\} \tag{13}$$

with $\underline{r_{k+1}^N} = (r_{k+1} r_{k+2} ... r_N)$. The probability β can be derived in backward recursion fashion:

$$\beta_k(l) = \sum_{all\ l'} \beta_{k+1}(l') \gamma_k(l, l') \tag{14}$$

with initial condition due to the trellis termination

$$\beta_N(l) = \begin{cases} 1 & , l = 0 \\ 0 & , l \neq 0 \end{cases} \tag{15}$$

The probability $\gamma_k(l, l')$ is similar to $\gamma_k(l', l)$ defined in equation (12). The MAP algorithm generally requires large memory and a large number of computation involving exponentiations and multiplications. It is generally too complicated to be implemented in real systems. Some modified algorithms, such as Max-Log-MAP algorithm and Log-MAP algorithm [26, 27], are generally used with computational approximation and possible sub-optimal performance.

3.2 Iterative MAP Decoding Method

Each constituent RSC code is decoded by the MAP algorithm. The decoding of the turbo code is performed iteratively by two RSC decoders as shown in Figure 2. The block I in the figure is the turbo internal interleaver and block I^{-1} is the de-interleaver block. The inputs of the first RSC decoder (RSC1) are the received information sequence $\{r_{xk}\}$ and the received parity sequence $\{r_{zk}\}$ from the first encoder. The decoder generates the log-likelihood ratio (LLR_1) using the MAP algorithm. From the log-likelihood ratio (LLR_1), the extrinsic information (LLR_{1e}) can be computed, which is a function of the redundant information introduced by the encoder. LLR_{1e} does not contain the contribution from the systematic decoder input r_{xk}. This information can be used to improve the a priori probability estimate for the next decoding phase. Thus, the extrinsic information (LLR_{1e}) is interleaved and used to produce an estimate of the a priori probabilities of the information sequence for the second RSC decoder (RSC2). RSC2 uses this information as well as the received information sequence (interleaved version) $I(r_{xk})$ and parity sequence $r_{z'k}$ to produce the extrinsic information LLR_{2e} as soft output. LLR_{2e} is then used to improve the estimate of the a priori probability for the information sequence at the input of the first RSC decoder.

This decoding cycle is repeated. With the increase of the iteration number, the performance is improved but the improvement typically saturates after several iterations. To trade-off complexity and performance, in systems such as WCDMA usually 8 to 10 iterations are used [3]. Finally, the hard-decision estimate of each decoded bit is derived based on the final LLR value.

4 Downlink Transmit Diversity Technique

Downlink transmit diversity using two transmit antennas at the base station has been adopted for the WCDMA/UMTS standards [28]. The usage of more than two antennas, such as four antennas, is under evaluation in the 3GPP standard committee. In this section, we will give an overview of the space-time transmit diversity technique.

4.1 Space-Time Transmit Diversity (STTD)

The space-time transmit diversity (STTD) technique employs a space-time block coding (STBC) scheme. This technique was originally proposed by Alamouti [10]. As shown in Figure 3, after modulation, two consecutive channel symbols are mapped to a 2x2 space-time matrix given by

$$\mathbf{G}_2 = \begin{pmatrix} S_1 & S_2 \\ -S_2^* & S_1^* \end{pmatrix}. \tag{16}$$

where $*$ denotes complex conjugate operation. The channel symbols (S_1, S_2) and $(-S_2^*, S_1^*)$ are sent to antenna 1 and 2, respectively, for transmission from left to right symbol. In the WCDMA/UMTS system, the same channelization code and scrambling code are applied at both antennas [28].

At the receiver side, the signals on l-th path at time instants T_s and $2T_s$ corresponding to symbols S_1 and S_2, respectively, are given by

$$R_l(1) = h_{1l}S_1 - h_{2l}S_2^* + n_l(1), \tag{17}$$

$$R_l(2) = h_{1l}S_2 + h_{2l}S_1^* + n_l(2), \tag{18}$$

where T_s is the symbol duration, h_{1l} and h_{2l} are the complex-valued channel gain of l-th path from antenna 1 and 2 respectively and it is assumed that the channel gains do not change during the transmission of S_1 and S_2. Thus the time dependencies of h_{1l} and h_{2l} are omitted here for simplicity of notation. The terms $n_l(1)$ and $n_l(2)$ are the corresponding complex noise/interference realizations at the time instants T_s and $2T_s$. The soft output for the symbol S_1 and S_2 can be generated by linear processing

$$s_{1,l} = R_l(1){h_{1l}}^* + R_l^*(2)h_{2l}, \tag{19}$$

$$s_{2,l} = -R_l^*(1)h_{2l} + R_l(2){h_{1l}}^*. \tag{20}$$

In the above equations, ideal channel estimation (ICE) is assumed. However, the real channel estimates can also be incorporated in this scheme. Substituting $R_l(1)$ and $R_l(2)$ of equation (18) into equation (20), the soft symbol outputs of the symbol S_1 and S_2 can be expressed as

$$s_{1,l} = (|h_{1l}|^2 + |h_{2l}|^2)S_1 + {h_{1l}}^* n_l(1) + h_{2l}n_l^*(2), \tag{21}$$

$$s_{2,l} = (|h_{1l}|^2 + |h_{2l}|^2)S_2 - h_{2l}n_l^*(1) + {h_{1l}}^* n_l(2). \tag{22}$$

To generate the overall soft output for symbol S_1 and S_2 in the rake receiver, the soft outputs from all the multipath branches are combined such that $\sum_{l=1}^{L} s_{1,l}$ and $\sum_{l=1}^{L} s_{2,l}$ are obtained. Note that the total effective path diversity becomes $2L$ which is twice of the diversity than as without STTD.

5 Simulation Results

Since the turbo code is mainly being considered for high rate data applications, we will focus on the frame error rate (FER) for the performance evaluation by simulation. The simulation results of the frame error rate are presented for turbo coded WCDMA systems with space time block coding. Exploiting transmit diversity leads to a performance gain compared to a single antenna system is shown when the temporal correlation and the cross correlation between rake branches are presented. We also evaluate the effect of the spatial correlation between the two transmit antennas at the base station. Through simulations, we quantify the tolerable spatial correlation to which the turbo coded WCDMA system with transmit diversity still attains a performance gain compared to a single antenna system. To obtain results closer to that in practice, we apply a typical pilot aided moving average channel estimation method in our simulations. The signal used for channel estimation is the common pilot channel (CPICH) in WCDMA systems [28]. The power of the pilot signal is assumed to be 10% of the total power of the base station transmitted signal in both single antenna and STTD (equally spilt up in two antennas) cases. The simulation parameters and assumptions used in this section are listed in Table 1.

5.1 Reduction of the Degradation Due to Temporal Correlation

Figure 4 shows the performance comparison between the 1-antenna system and the STTD system. Notice that the STTD system achieves a 2-3 dB gain over the 1-antenna system at medium to high vehicle speeds (30 Kmph, 120 Kmph) and a much higher gain at lower vehicle speeds (3 Kmph).

5.2 Reduction of the Degradation Due to Spatial Correlation between Multipath Branches

To improve the performance of WCDMA, rake fingers with fractional chip (as small as 0.2 chip) delay separation could be assigned [8, 9] compared to single rake finger. With 0.2 chip spacing, two independent multipath components will have cross correlation coefficient $\rho = 0.81$ ($\lambda = 0.9$) due to the pulse shaping filter. The 0.4 chip spacing will cause cross correlation with $\rho = 0.49$ ($\lambda = 0.7$). With space time transmit diversity, the performance can be further improved. Figure

5 shows the performance improvement of STTD system over a single antenna system when the cross correlation exists between multipath branches. Note that the STTD system provides significant gain over the single transmit antenna system when there is cross correlation between multipath branches. Higher gain is obtained for higher cross correlation cases.

5.3 Impact of Spatial Correlation between Transmit Antennas

One major concern with transmit diversity is the antenna spacing at the base station, which may limit the diversity gain from multiple antennas. As we mentioned before, the antenna spacing is usually kept to a minimum to reduce size and cost. Also the angle spread of the directions of departure from the base station is generally small. All these factors will increase the spatial correlation between different transmit antennas, such as that between h_{11} and h_{21} as well as the correlation between h_{12} and h_{22} as shown in Figure 1. Such spatial correlation can be as high as $\rho_{bs} = 0.9$ with two antennas spaced at half wavelength [17, 19]. Thus it is important to evaluate impact of the spatial correlation of base station antennas on the performance and to what degree that correlation can be tolerated while the turbo coded WCDMA system with transmit diversity still attains performance gains compared to a single transmit antenna system.

Figures 6 and 7 show the performance comparison between the STTD system and a single antenna system when the spatial correlation of the base station antennas ρ_{bs} are 0.49 and 0.81 (λ_{bs} are 0.7 and 0.9), respectively. It is noted that for medium to high vehicle speeds the STTD gain diminishes when ρ_{bs} reaches 0.81 (λ_{bs} reaches 0.9). However, for slow vehicle speeds, the STTD scheme achievers significant gains even at $\rho_{bs} = 0.81$ ($\lambda_{bs} = 0.9$).

5.4 Performance with Two Types of Cross Correlations

Finally, we show an example with both types of cross correlations as well as temporal correlation. Figure 8 shows the performance of turbo coded system with transmit diversity. When both types of spatial correlations exist ($\lambda = 0.7, \lambda_{bs} = 0.7$), the performance degrades further compared with only one type of spatial correlation ($\lambda = 0.0, \lambda_{bs} = 0.7$ and $\lambda = 0.7, \lambda_{bs} = 0.0$) and without spatial correlation ($\lambda = 0.0, \lambda_{bs} = 0.0$). In this example, with four equal power diversity branches (h_{11}, h_{12}, h_{21} and h_{22}), the effect of spatial correlation between multipath branches (such as between h_{11} and h_{12} as well as between h_{21} and h_{22}) is equal to the effect of spatial correlation between antennas (such as between h_{11} and h_{21} as well as between h_{12} and h_{22}). However, these two types of spatial correlations have different physical meaning and should be treated differently in real systems. The spatial correlation between multipath branches comes from the fading channel characteristics and/or partially overlapped pulse shaping. The signals on these multipath branches should be combined whenever possible even with high correlation. The possible cost of implementation here is just the additional rake fingers on the receiver, which are quite minimal. This was also showed in [8, 9] without considering turbo coding. The spatial correlation between transmit antennas will reduce the potential gain when using STTD or other multiple-antenna techniques. However, the implementation cost of multiple antennas is usually much higher. Thus in system design such spatial correlation should be considered and controlled in tolerable range.

6 Discussion and Summary

In this paper, we evaluated the performance of a downlink with turbo coded WCDMA systems with downlink space time block coding in correlated fading channels. We compared the performance between the single antenna system and STTD system. It was observed that the improvement by using downlink space-time block coding is significant, especially in slow fading when the temporal correlation is high. The space-time block coding also improves the performance when the cross correlation between multipath branches is present. By considering the spatial correlation between the transmit antennas at the base station, we quantified the tolerable correlation between transmit antennas while the transmit diversity system still attains performance gains compared to a single antenna system. Our results seem to indicate that downlink transmit diversity in conjunction with turbo coding provides a relatively low-cost method to improve the performance and thus increase the downlink capacity of the 3rd generation mobile communication systems.

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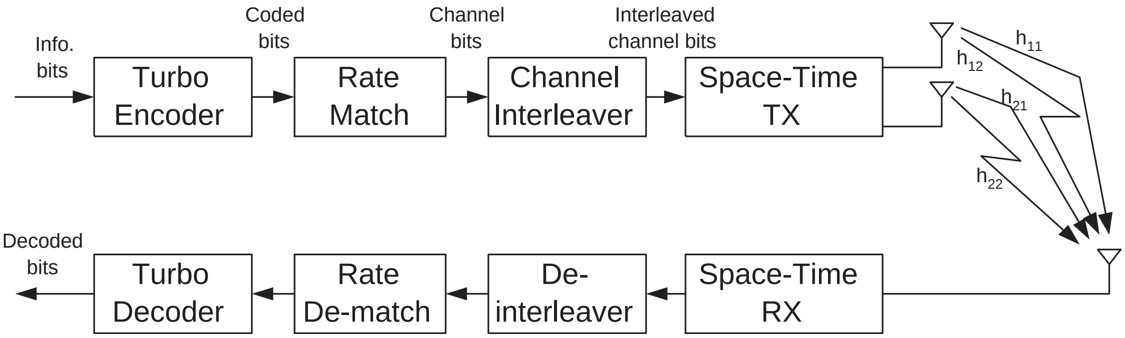

Figure 1: Simplified system model of turbo coded WCDMA downlink with transmit diversity.

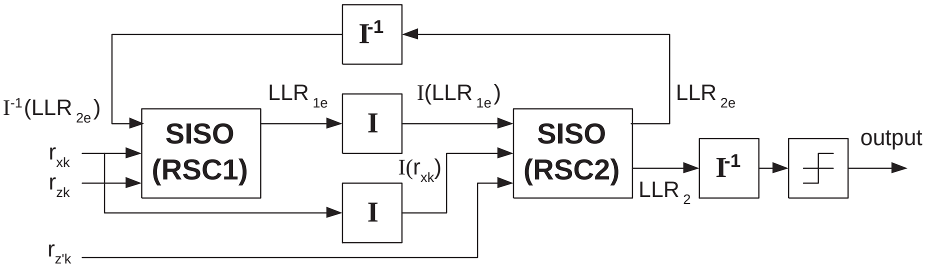

Figure 2: Iterative turbo decoding scheme using the SISO algorithm.

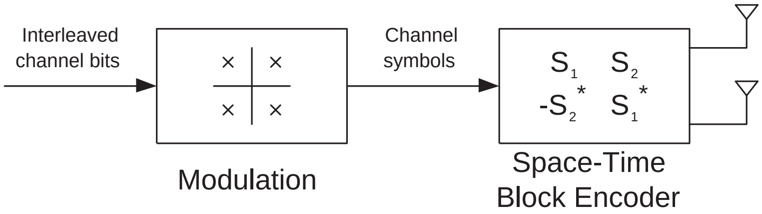

Figure 3: Block diagram of a space-time block encoder.

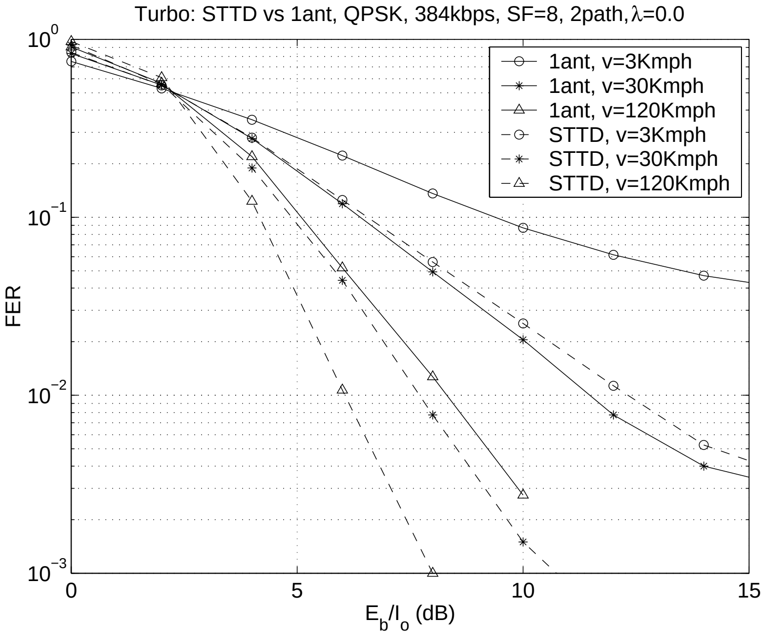

Figure 4: STTD vs Single Antenna: QPSK, 2-path equal power, SF=8, speed=3, 30, 120 Kmph, cross correlation $\rho = 0.0$ ($\lambda = 0.0$), spatial correlation $\rho_{bs} = 0.0$ ($\lambda_{bs} = 0.0$), pilot aided moving average channel estimation.

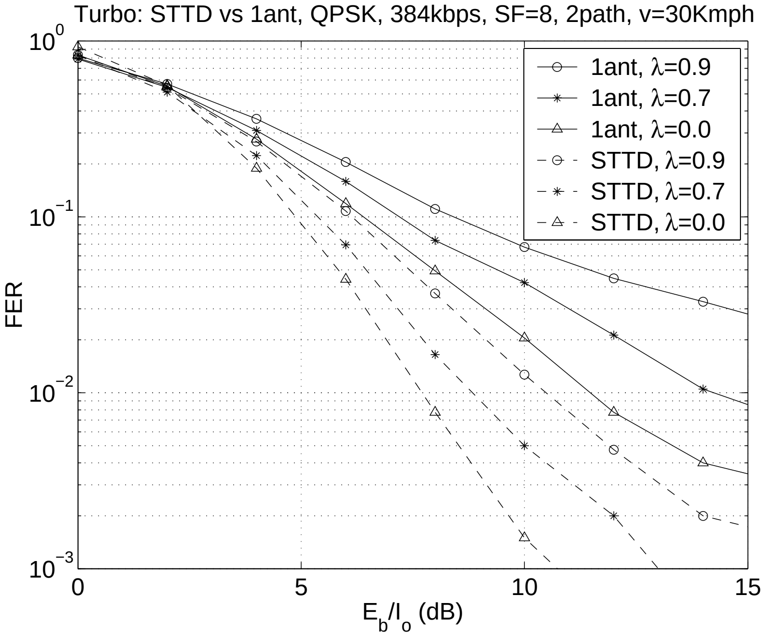

Figure 5: STTD vs Single Antenna: QPSK, 2-path equal power, SF=8, speed=30 Kmph, cross correlation between multipath branches $\rho = 0.0, 0.49, 0.81$ ($\lambda = 0.0, 0.7, 0.9$), spatial correlation $\rho_{bs} = 0.0$ ($\lambda_{bs} = 0.0$), pilot aided moving average channel estimation.

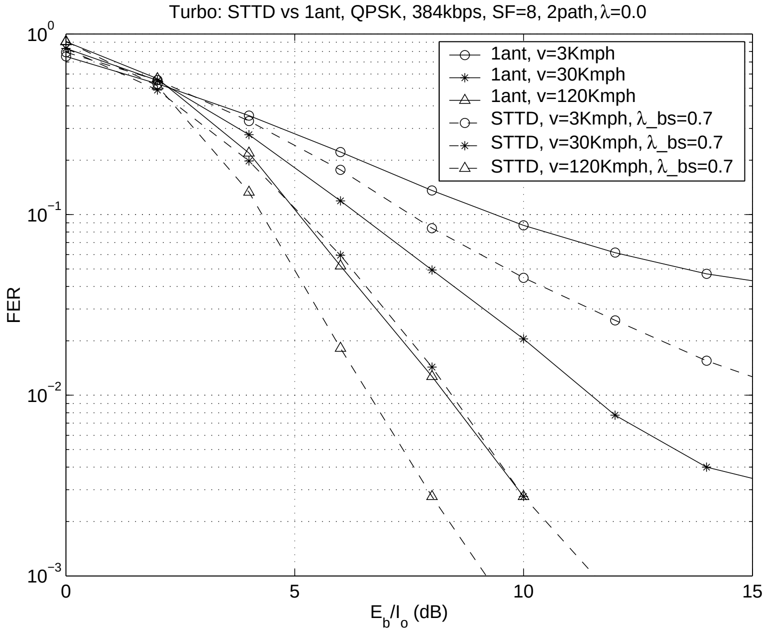

Figure 6: STTD vs Single Antenna: QPSK, 2-path equal power, SF=8, speed=3, 30, 120 Kmph, cross correlation between multipath branches $\rho = 0.0$ ($\lambda = 0.0$), spatial correlation between transmit antennas $\rho_{bs} = 0.49$ ($\lambda_{bs} = 0.7$), pilot aided moving average channel estimation.

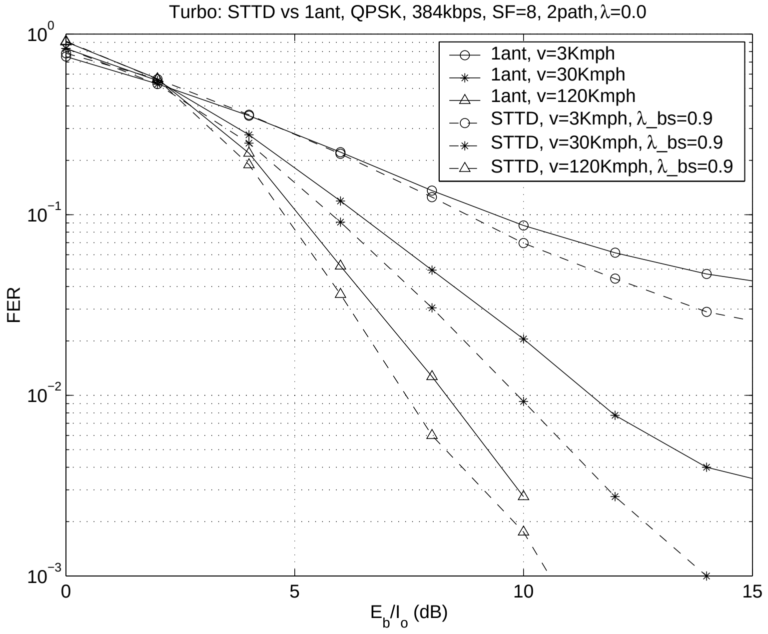

Figure 7: STTD vs Single Antenna: QPSK, 2-path equal power, SF=8, speed=3, 30, 120 Kmph, cross correlation between multipath branches $\rho = 0.0$ ($\lambda = 0.0$), spatial correlation between transmit antennas $\rho = 0.81$ ($\lambda_{bs} = 0.9$), pilot aided moving average channel estimation.

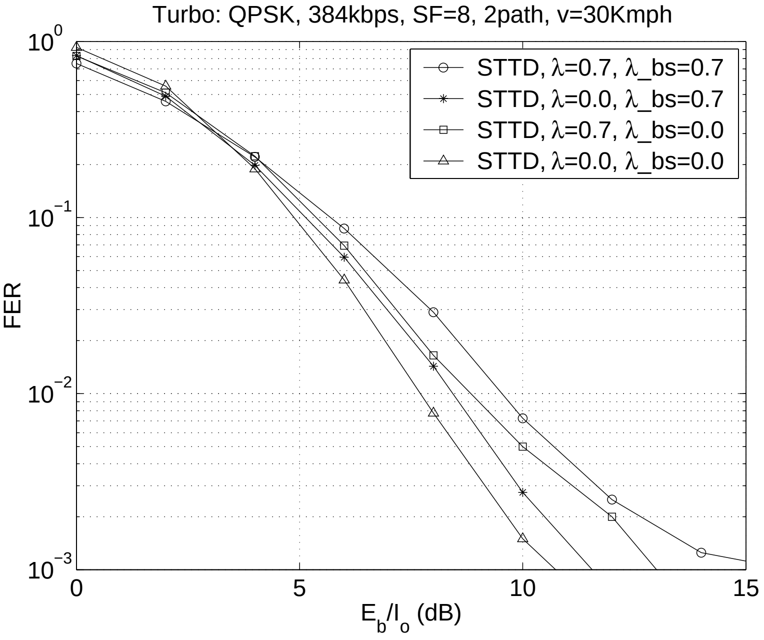

Figure 8: STTD vs Single Antenna: QPSK, 2-path equal power, SF=8, speed=30 Kmph. With cross correlations between multipath branches and between transmit antennas, pilot aided moving average channel estimation.

Parameter	Value	Comments
Carrier Frequency	2GHz	
Propagation Condition	2-path equal power	each is Rayleigh fading
Correlation between 2 paths	$\lambda = 0.0, 0.7, 0.9$	
Rayleigh Fading Model	Jakes model [20]	
Vehicle Speed	3/30/120 Km/h	
Channel Estimation	moving average	10 pilot symbols window
Channel Coding	8-state turbo code	per 3GPP TS25.212 [3]
Turbo Decoding Algorithm	Max-Log-MAP	
Maximum Iteration Number	8	
Code Rate	1/3	
Frame Length	3856	information bits
Rate Match	1/6 puncture	1 parity bit/6 coded bits
Turbo Interleaver	prime interleaver	per 3GPP TS25.212
1st/2nd Interleaver	per 3GPP TS25.212	
STTD	on/off	1 antenna vs. STTD
Correlation between 2 antennas	$\lambda_{bs} = 0.0, 0.7, 0.9$	
Spreading Factor (SF)	8	
Data Rate	384kbps	
Modulation	QPSK	
Symbol Duration	$2.0833\mu s$	chip rate 3.84Mcps
Frame Duration	$10ms$	1 radio frame

Table 1: Simulation parameters for the simulation of the turbo coded WCDMA system.