Soft-Weighted Transmit Diversity for WCDMA

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Abstract

The transmit diversity concept adopted for the FDD mode of the third generation WCDMA system in 3G standardization has an open-loop and a closed-loop mode. The open-loop mode applies a space-time block code for two transmit antennas. The closed-loop mode has two sub-modes, which both utilize downlink measurements at terminal and subsequent feedback in controlling the phase and/or gain transmit weights in the transmit antennas in order to approximate matched beamforming. These concepts are summarized in this paper for two transmit antennas and they are compared to a soft-weighted transmit diversity concept, proposed here, in which the relative transmit powers of the space-time encoded signals are controlled by feedback signaling. This leads to a robust feedback mode in which the terminal is simplified in the sense that it does not require dedicated reference/pilot symbols, or weight verification, as opposed to the current feedback modes.

1 Introduction

Future wireless services (e.g remote web browsing) are expected to burden the downlink more heavily than uplink. Many of these services are likely to be used in low-mobility environments with limited temporal diversity (e.g to be captured by a RAKE receiver or by interleaving). The lack of diversity causes a capacity problem in the downlink in these channels. Space-diversity based on multi-antenna reception at the terminal provides one remedy to the problem. However, it is an expensive solution in terms of complexity and cost of the mobile handset. Instead, receive diversity, e.g. with two receive antennas, is seen as an add-on feature, not requiring standardization, and as a technique that can be applied at manufacturers discretion. On the other hand, diversity techniques based on multiple transmit antenna provide low complexity solutions for downlink capacity enhancement, and will be supported in 3G systems[18].

Considering the wide range of operating environments under which 3G systems would be used, different diversity techniques have been proposed each having advantages over the others in certain environments. Both open-loop and closed-loop concepts have been under consideration for the 3G WCDMA system. Many of the previously proposed open-loop techniques, see e.g. [17, 5, 3, 7] have been considered but the selected open-loop concept applies a two-dimensional space-time block code proposed by Alamouti [1]. The open-loop technique is applied when very little or nothing is known from the downlink channel at the base station. It is well known that additional performance improvements are achievable in closed-loop systems where the transmitter is provided with suitable side information on the downlink channel characteristics [9, 10, 12].
In this paper we review the open and closed-loop transmit diversity techniques adopted for WCDMA systems, along with a new concept in which feedback signaling and space-time block codes are combined. In all the feedback modes the capacity of the feedback channel is maintained at 1.5 kbps and this is used to achieve significant (3-6 dB) improvements over single-antenna transmission in low-mobility channels with only a few dominant multipath components.

The paper is structured as follows. Section 2 describes the key physical layer features of the WCDMA transmit diversity concept, including the open and closed-loop solutions. In Section 3 we propose the concept of a soft-weighted space-time block code and explain its characteristics. In Section 4 we provide a performance analysis of the new concept. Our conclusions are given in Section 5.

2 WCDMA Transmit Diversity Concept

We consider a CDMA system with two synchronously transmitting antennas. The antenna elements are assumed to be spaced sufficiently close to each other so that the propagation delays between each antenna and a given Mobile Station (MS) are approximately the same. This is important in order to maintain downlink orthogonality at least in a single-path channel. At the same time we assume that the antennas are sufficiently far apart from each other in order to reduce channel amplitude correlation between the antennas. In practice, both of these assumptions are usually satisfied when the antenna spacing of $10\lambda-20\lambda$, where $\lambda$ is the carrier wavelength. In addition it is desired that a user applying transmit diversity uses the same number of (orthogonal) channelization codes as it would in single-antenna transmission. These targets lead naturally to symbol-level transmit diversity techniques, many of which are not CDMA specific, but are applicable in other multiple access systems like TDMA. We summarize the main characteristics of currently accepted 3G concepts [18].

2.1 Open-Loop Diversity

Space-time codes, proposed in [1, 13, 4], were studied initially for TDMA systems, but as they can be applied at symbol-level, we can naturally use them also in WCDMA. Indeed, a two-dimensional space-time block code was adopted for WCDMA in ETSI in 1998 and subsequently in the 3G partnership project (3GPP) [18]. More advanced trellis designs, which attempt to maximize the distance of code words, have been recently proposed in [13, 14, 4], holding many of the previously proposed open-loop schemes as a special case. However, the block codes are easy to include in a concatenated coding concept as simple linear processing is required.

In the open-loop concept the channel symbols are divided into two element blocks and transmitted as $s[2n], s[2n+1]$ and $-s^*[2n+1], s^*[2n]$ from antennas one and two, respectively, at time instants $2n$ and $2n+1$ [1]. These symbols are transmitted using the same spreading code. The received signal (denoted by $z$) in a single-path case can be written as

$$
\begin{bmatrix}
  z[2n] \\
  z[2n+1]
\end{bmatrix} =
\begin{bmatrix}
  s[2n] & s[2n+1] \\
  -s^*[2n+1] & s^*[2n]
\end{bmatrix}
\begin{bmatrix}
  h_1 \\
  h_2
\end{bmatrix} +
\begin{bmatrix}
  n[2n] \\
  n[2n+1]
\end{bmatrix}
$$

(1)

where it is assumed that the channels, $h_1$ and $h_2$, remains stationary during the transmission of the successive symbols[14]. The receiver then uses linear orthogonal processing
using the estimated channel coefficients $\hat{h}_1$ and $\hat{h}_2$ to detect transmitted symbols as is shown below.

$$
\begin{bmatrix}
\hat{s}[2n] \\
\hat{s}[2n + 1]
\end{bmatrix} =
\begin{bmatrix}
\hat{h}_1 & \hat{h}_2 \\
-\hat{h}_1 & \hat{h}_2
\end{bmatrix}
\begin{bmatrix}
\hat{z}[2n] \\
\hat{z}[2n + 1]
\end{bmatrix}
$$

(2)

In order to maintain full orthogonality the channel estimates need to be perfect, but the loss due to imperfect channel estimates is not severe. In WCDMA systems reasonably accurate estimates can be obtained by using the common channel pilots (CPICH) transmitted continuously from the two antennas. This simple symbol level orthogonal coding scheme doubles the diversity of the system (using two transmit antennas) without any bandwidth expansion.

### 2.2 Feedback Modes

Feedback modes are designed to provide additional gain over the open-loop techniques, and in particular over single-antenna transmission, in low mobility environments. These environments may face the most severe capacity bottleneck in the future both due to lack of diversity and due to projected services. Therefore it is sensible to use a small portion of uplink capacity to achieve significant gains in downlink capacity.

In the feedback modes the MS measures the downlink channels and signals to the network/base station partial information about the phase/power settings for the transmit antennas. This information is transmitted in the Feedback Signaling Message (FSM) as a part of the FBI field of uplink dedicated physical control channel (DPCCH). Each message is of length $NW = Np0 + Nph$ bits and one bit is transmitted in each slot resulting in 1500 bps signaling overhead.

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>phase bits per word ($Np0$)</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>gain bits per word ($Nph$)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>feedback bit rate</td>
<td>1500 bps</td>
<td>1500 bps</td>
</tr>
<tr>
<td>update rate</td>
<td>1500 Hz</td>
<td>1500 Hz</td>
</tr>
<tr>
<td>filtering at BS</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>

**Table 1: Feedback Mode Parameters**

The two feedback modes approximate optimal (e.g. matched) beamformer with a limited feedback channel capacity. Mode 1 maintains equal power transmission for the two antennas by selecting the transmit weight from 4 possible (constant amplitude) values. Mode 2 can provide some additional gain in very low-mobility environments with selection from 16 possible transmit weights (See Fig. 5). Both include novel signaling strategies in order to minimize the control delay in applying the transmit weight. A detailed description of the frame and slot structures can be found in [18].

### 2.2.1 Preliminaries

It is instructive to first consider the ‘optimal’ approach in controlling the transmit weights before detailing the particular signaling solutions with low feedback overhead. The unquantized feedback weight can be calculated as follows. Assume for simplicity that there are two transmit antennas each transmitting a common pilot channel (CIPCH). A given
terminal obtains channel estimates $\hat{h}_1$ and $\hat{h}_2$ for both antennas. Then, the terminal determines how the transmit weights (beam coefficients) in the dedicated channel have to be modified in order to maximize the signal-to-noise ratio. We assume that only one complex coefficient is transmitted to the base station to minimize signaling overhead. It is easy to see that this collapses the following problem,

$$ w = \arg \max_w (w_1 h_1 + w_2 h_2)^H (w_1 h_1 + w_2 h_2), \quad ||w||^2 = 1 $$

Furthermore, as it is only necessary to consider the difference of the channels in order to do optimize the beam, it is sufficient to calculate, e.g., $w_2$ only, while keeping $w_1 = 1$. One solution is provided by

$$ w_2 = z e^{j\phi} = \arg \max_{z,\phi} (\sqrt{1 - z^2} h_1 + z e^{j\phi} h_2)^H (\sqrt{1 - z^2} h_1 + z e^{j\phi} h_2), \quad z \in [0, 1] $$

which yields

$$ e^{j\phi} = \frac{h_1^H h_2}{\sqrt{||h_1^H h_2||}} $$
$$ z = \frac{||h_2||}{\sqrt{||h_1||^2 + ||h_2||^2}} $$

In the following we describe two approaches on how the FSM message (see Table 1) can be used to signal these weights to the network. Both approaches control only the diversity antenna corresponding to $w_2$.

2.2.2 Mode 1

In feedback Mode 1 terminal updates the channel estimates, obtained from the common pilot channel (CPICH) every slot. The phase information $\exp(j\phi)$ is quantized to constellations $S_1 = \{\exp(j\pi0), \exp(j\pi)\}$ and $S_2 = \{\exp(j\pi/2), \exp(-j\pi/2)\}$ at even and odd time slots, respectively. The corresponding feedback commands are '0' and '1', where '0' designates that the first constellation point was closer to phase information. Similarly, '1' designates that the second constellation point was closer to phase information. These are transmitted to the network using the $FSMph$ field. The quantization constellations are known and synchronized for both the terminal and the network. Effectively, the use of two reference constellations $S_1$ and $S_2$ results in a concept where a terminal signals the imaginary part and the real part of the downlink channel alternately in successive slots. This concept is similar to set-partitioning, where e.g. the minimum distance between points in multiple constellations is maximized.

This quantization and signaling concept alone enables only crude beamforming with 180 degree resolution. However, the resolution is increased by filtering the feedback signal/weights at the base station. Although different filtering methods are possible the WCDMA concept currently applies simple averaging over two successive weights which enhances the resolution to 90 degrees. Assuming a hard decision is made on each feedback bit prior averaging we end up with four possible weights, i.e., the transmit weight is selected from a QPSK constellation, where transitions only to neighboring weights are possible (due to the memory imposed by the filter).
Since there are only 4 possible weights we can use the dedicated channel pilots (and channel estimate) in order to verify which one of the four weights was in fact transmitted. The verification allows to use the continuous common channel estimate in maximal ratio combining. The actual verification algorithm is not specified in the 3GPP specification[18].

2.2.3 Mode 2

Mode 2 provides more accurate weight signaling to the BS transmitter with 16 possible weights. As opposed to Mode 1, no constellation rotation is done at the terminal and no filtering of the received weights is performed at the base station. The estimated phase difference is quantized to a 8-PSK constellation, and transmitted to the base station using Gray coding to reduce the effects of feedback errors. In addition to adjusting phase, Mode 2 is able to change the relative power of the two antennas using one gain control bit. The weights for antennas 1 and 2 are either \{0.8, 0.2\} or \{0.2, 0.8\} depending on the value of the \textit{FSMpo} field, but phase adjustment is applied always to the diversity antenna. The weights are optimized at the terminal on a slot by slot basis. The value of the phase/gain bit per slot is calculated by conditioning on previously transmitted bits. This enables an update rate of once per slot both at the terminal and at the base station. Mode 2 relies solely on channel estimation from the dedicated channel as weight verification with 16 states is considered unreliable.

2.2.4 Discussion

Although there are similarities between the two feedback modes it should be noted that they are based on slightly different design philosophies. Mode 1 provides a minimum-delay low resolution channel state information to the transmitter using set-partitioning. The resolution is then enhanced by appropriate filtering. Clearly, the filter length should be matched (among other things) to the channel time-coherence/Doppler for best performance and the Mode 1, with length 2 filter, is a compromise which improves performance over a variety of environments. It is not claimed that the specified filter as such is optimum and further work involves optimizing the FIR (or IIR) filter at the transmitter. However, Mode 1, as defined above, has only four possible transmit weights and while this may compromise resolution it enables efficient weight verification and subsequently the use of common channel estimates in decoding a given dedicated channel. Mode 2, on the other hand has 16 possible transmit weights and this exacerbates weight verification, and therefore only dedicated pilots are used in channel for a given slot estimation. On the other hand, the weight/beam of the dedicated channel may be better matched to the channel.

Note that both Mode 1 and Mode 2 could be applied analogously in the presence of more that two transmit antennas. To maintain the same overhead in feedback signaling we can apply coherent array transmission where the feedback word designates the relative phase difference between neighboring antenna elements. Furthermore, in environments where the Doppler spread is very low Mode 2 weights could be filtered to further improve resolution. These evolutionary concepts, mostly relevant in indoor environments or pico cells have to be evaluated in detail when the structure of common channels are defined in 3GPP standardization for more than two transmit antennas.
3 Soft-weighted space-time transmit diversity

Both Mode 1 and Mode 2 rely heavily on the use of dedicated pilots. Mode 1 requires them for efficient weight verification and Mode 2 for channel estimation and maximal ratio combining in the dedicated channel. As it is possible that some future frame formats do not include dedicated pilots it is interesting to study a feedback-mode which provides robustness to feedback errors by some other means.

In light with 3G acronyms we call the proposed concept Soft-Weighted Space-Time Transmit Diversity (SW-STTD). We describe the soft-weighting below as a form of soft antenna selection but it can be equally applied in the beam domain. The received signal in SW-STTD can be written as

\[
\begin{bmatrix}
    z[2n] \\
    z[2n + 1]
\end{bmatrix} = \begin{bmatrix}
    g_1 s[2n] & g_2 s[2n + 1] \\
    -g_1 s^*[2n + 1] & g_2 s^*[2n]
\end{bmatrix} \begin{bmatrix}
    h_1 \\
    h_2
\end{bmatrix} + \begin{bmatrix}
    n[2n] \\
    n[2n + 1]
\end{bmatrix}
\] (6)

which is otherwise identical to STTD except that relative weighting factors \(g_1\) and \(g_2 = 1 - g_1\) are imposed on signals transmitted from antennas 1 and 2, respectively. The weight corresponding to the stronger antenna (as measured from CPICH) is set to have the larger weight. This (the result of ranking of the CPICH powers) can be signaled with 1 bit/slot feedback as specified e.g. in [6].

Of course, for optimal reception the receiver needs to know precisely the weights that are applied in the transmitter. This is not possible unless either the feedback channel from the terminal to the base station is perfect, or unless the weight verification procedure (as in Mode 1) is perfect. Rather than devising a weight verification procedure for SW-STTD we propose a simpler solution. We propose that in decoding the SW-STTD transmission the terminal uses STTD processing, thus applying effectively equal gain combining to the two transmit antennas. Furthermore, we propose that the transmit weight is changed based two successive feedback commands, rather than for each command independently.

When the base station estimates that feedback bits are \([1, 1]\) or \([0, 0]\) the transmit gains are set to \([g_1, g_2]'\), where \(g_1 > g_2\) or \(g_1 < g_2\), respectively. When the successive feedback bits are different, i.e. \([1, 0]\) or \([0, 1]\), equal power (STTD) transmission is applied, where \(g_1 = g_2\). For simplicity we assume that the actual values of the asymmetric weights are fixed \textit{a priori} to \(\sqrt{0.8}\) and \(\sqrt{0.2}\), which are applied also in Mode 2. Thus, we have effectively defined three possible transmit weights for the STTD encoded signals, \(w = [\sqrt{0.8}, \sqrt{0.2}]'\), \(w = [\sqrt{0.5}, \sqrt{0.5}]'\), and \(w = [\sqrt{0.2}, \sqrt{0.8}]'\). Note that the state transitions reduce the effect of feedback errors since two consecutive errors are needed to create a significant mismatch between the transmit weight and the downlink channel. Clearly, this procedure could be extended to include different state/weight transitions, but we do not pursue this path further in this paper.

4 Simulations

The target of this section is to determine the performance of a transmit diversity system with system imperfections such as channel estimation errors and feedback errors, and therefore we resort to simulations. We compare the performance of open and closed loop modes (including the proposed SW-STTD) and single antenna transmission. Simulation parameters are given in Table 2 and all transmit diversity schemes employ two transmit antennas.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>carrier frequency</td>
<td>2150 GHz</td>
</tr>
<tr>
<td>chip rate</td>
<td>4.096 Mcps</td>
</tr>
<tr>
<td>physical channel rate</td>
<td>32 ksps</td>
</tr>
<tr>
<td>data rate</td>
<td>8 ksps</td>
</tr>
<tr>
<td>channel estimation</td>
<td>weighted average of pilot symbols over three slots</td>
</tr>
<tr>
<td>modulation</td>
<td>QPSK</td>
</tr>
<tr>
<td>encoding</td>
<td>rate 1/3, K=9 convolutional</td>
</tr>
<tr>
<td>interleaving</td>
<td>10 ms</td>
</tr>
<tr>
<td>PCCPCH power</td>
<td>10 times dedicated channel power</td>
</tr>
<tr>
<td>PC/FB errors</td>
<td>4%</td>
</tr>
<tr>
<td>PC delay</td>
<td>1 slot/ 0.625 ms</td>
</tr>
<tr>
<td>FB delay</td>
<td>1–4 slots depending on mode</td>
</tr>
<tr>
<td>PC step</td>
<td>1 dB</td>
</tr>
<tr>
<td>Pilot symbols/slot</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 2: Simulation Parameters

Bit–error rates of SW-STTD, STTD, Modes 1 and 2, and single antenna transmission are presented in Figures 2 and 3 as a function of transmitted $E_s/N_0$ with mobile speeds 10 km/h and 42.3 km/h in a single path Rayleigh fading channel and Vehicular A channel, respectively. It is assumed that the two transmit antennas are uncorrelated. With single path channel SW-STTD provides the best performance with 10 km/h and its performance is also close to Mode 1 in the case of 40 km/h mobile speed. However, Mode 1 here assumes ideal Tx weight verification in the mobile station, i.e. the mobile always knows the Tx weight even when there are errors in the feedback channel. In practice, the performance of Mode 1 would deteriorate with a fraction of dB (0.2–0.4 dB) due to the imperfect verification.

Average powers of channel taps in the Vehicular A channel model are $[0, -2.4, -6.5, -9.4, -12.7]$ dB. The multipath channel provides diversity to the system so that the transmit diversity methods do not offer as much improvement over single-antenna transmission as in the case of single path channel. Multipath channel and consequently deteriorated channel estimates destroy the symbol level orthogonality of space-time coding so that Modes 1 and 2 clearly outperform SW-STTD and STTD.

5 Conclusion

We have summarized the open and closed loop transmit diversity concepts adopted for the third generation WCDMA system in 3GPP standardization. In addition, we proposed a new concept, soft-weighted space-time transmit diversity (SW-STTD), which improves the system performance over the current WCDMA transmit diversity modes when there is little time diversity offered by multipath propagation. Furthermore, unlike the current WCDMA closed loop transmit diversity modes, SW-STTD does not require dedicated pilot symbols leading to a more efficient usage of the downlink dedicated channels. Also, the complexity of the mobile receiver is reduced and the base station can 'optimize' the transmit weights dynamically without signaling it to the mobile.
References


[18] 3GPP RAN WG1, Physical Layer- General Description, v. 2.0.0, April, 1999.

Figure 1: Sixteen possible transmit weights $w_2$ (with associated feedback bit states) for feedback Mode 2, where the power of each point in the inner constellation is 0.2 and the power of each point in the outer constellation is 0.8. The resulting transmit weights for the two antennas are thus $w = [g (1 - g)w_2]'$, where $g = \{\sqrt{0.2}, \sqrt{0.8}\}$ and $w_2 \in \{\exp(i\pi\phi/180)|\phi = 180, -135, -90, -45, 0, 45, 90, 135\}$.
Figure 2: Coded Bit–error rates of SW-STTD (—), STTD ( - - ), Mode 1 ( - - - ), Mode 2 (+), and single antenna transmission (▽) as a function of transmitted $E_s/N_0$ in a flat Rayleigh fading channel with mobile speeds 10 km/h (left) and 40 km/h (right).

Figure 3: Coded Bit–error rates of SW-STTD (—), STTD ( - - ), Mode 1 ( - - - ), Mode 2 (+), and single antenna transmission (▽) as a function of transmitted $E_s/N_0$ in a Vehicular A channel with mobile speeds 10 km/h (left) and 40 km/h (right).