Transmit Diversity with Constrained Feedback

Leonid G. Krasny[1], Jiann-Ching Guey[2], and Ali Khayrallah[3]
Ericsson Research, 8001 Development Drive, RTP, NC 27709, USA
[1]leonid.krasny@ericsson.com, [2]jiann-ching.guey@ericsson.com, [3]ali.khayrallah@ericsson.com

***Abstract*— Closed-loop MISO (multiple-input/single-output) antenna systems are attractive for achieving diversity in the downlink of cellular systems. However, closed-loop transmission scheme requires the terminal to use the uplink channel to inform the base station the full state of its downlink channels. The amount of feedback is proportional to the number of transmit antennas and the channel's delay spread, and it can be substantial. In this paper we present an alternative transmit diversity scheme called TDCF (Transmit Diversity with Constrained Feedback) which uses only partial channel feedback. Our approach is based on approximation of the downlink channels with simple FIR filters with limited number of taps. One variant of TDCF chooses these filters based on the channel's first few strongest taps. Another variant of TDCF uses a short block of taps on a fixed grid. Information about FIR filter taps is fed back to the base station, where they are used as pre-filters to match the transmitted signals to the channels. Our simulations results indicate that TDCF scheme gives substantial gains over SISO (single-input/single-output) system, even when the extremely simple pre-filters are used at the base station.**

I. Introduction

Using knowledge of the downlink channel state at the transmitter of a multiple-input/single-output (MISO) antenna system is an attractive approach for achieving diversity in the downlink of cellular systems while minimizing complexity at the mobile terminals. For example, in [1]- [2], the complexity is shifted from the mobile to the base station using a ”pre-RAKE” transmission scheme. In this scheme, which we refer to as TDRF (Transmit Diversity with Rich Feedback), knowledge of the downlink channels is used to prefilter the signals on each transmit antenna so that the multipath components of the received signal coherently combine, thus exploiting both antenna gain and implicit frequency diversity in the MISO channel. In [2], it is shown that TDRF scheme is able to achieve data rates very close to the capacity of the MISO channel. However, this scheme requires that the forward link channel knowledge be fed back explicitly from the receiver if the forward link and reverse link operate in different frequency bands. The amount of feedback, which is proportional to the number of transmit antennas and the channel's delay spread, can be substantial.

Alternative solutions for MISO systems are open-loop schemes which generally require no explicit forward link channel information except for perhaps a low rate channel quality report for resource allocation purpose. An example of this category is Per-Antenna Rate Control (PARC) [3]. The scheme is based on a combined transmit/receive architecture that performs separate encoding of the antenna streams at different rates followed by successive interference cancellation (SIC) at the terminal. The rate control information for each stream is based upon feedback of the signal-to-interference-plus-noise ratio at each state of SIC. With this scheme, it has been shown that the open-loop capacity of flat fading channels may be achieved [4].

In certain scenarios, however, there is a large gap between the open-loop and closed-loop capacities of the MISO channels. For instance, in the 3GPP Typical Urban channel the TDRF scheme with 4 transmit antennas has 6 dB advantage over PARC [2]. This result indicates significant room for improvement over PARC.

Since the TDRF scheme achieves the gain at the cost of high feedback overhead, in this paper we consider an alternative closed-loop transmit diversity scheme called TDCF (Transmit Diversity with Constrained Feedback) which uses only partial channel feedback. Our approach is based on using at the base station transmitter simple FIR pre-filters with limited number of taps. The coefficients for these pre-filters can be chosen equal to the L strongest channel coefficients or based on the fixed-grid approach [5] where the grid of evenly-spaced L fingers is placed on a “region” of signal energy indicated by the power/delay profile.

The outline of the rest of this paper is as follows. In Section II, a model for the MISO system is presented. The structure of the TDCF scheme for MISO channels and several partial feedback methods are then given in Section III. In Section IV we evaluate performance of TDCF scheme in terms of channel capacity. The simulation results presented in Section V verify our capacity analysis. Finally, Section VI concludes the paper.

II. System Model

Our system model is presented in Figure 1. In this figure, $b[n]$'s are the information bits at the transmitter which are coded and modulated to get the analog, complex, baseband signal $s(t)$. The base station (BTS) transmitter has M transmit antennas, and on the m-th antenna the signal $s(t)$ is passed through a pre-filter with impulse response $h(t,m)$ which has Fourier transform $H(\omega,m)$.

The impulse response of the channel from the m-th transmit antenna to the single receive antenna at the mobile is denoted by $g(t,m)$ which has Fourier transform $G(\omega,m)$. Therefore, the received signal at the mobile due to the data signal $s(t)$ is given by

$$x(t) = \sum_{m=1}^{M} h(t,m) * g(t,m) * s(t)\,, \tag{1}$$

where $*$ denotes convolution.

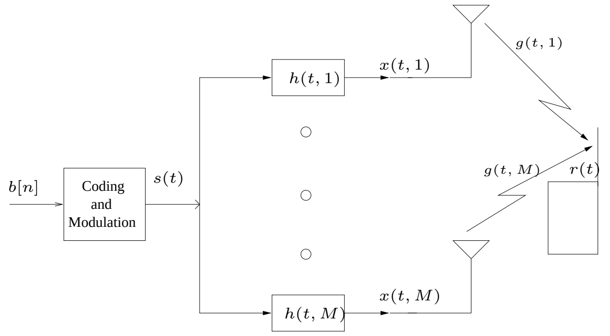

Fig. 1. MISO System with Transmit Diversity

The total power transmitted from all M antennas is fixed at σ_X^2, i.e. the impulse responses $\{h(t,m)\}_{m=1}^{M}$'s are always normalized so that the total transmit power is σ_X^2.

For the TDRF scheme in [2], the impulse response of the pre-filter on the m-th transmit antenna is given by

$$h(t,m) = \lambda\, g^*(-t,m), \tag{2}$$

where

$$\lambda = \left(\sqrt{\sum_{m=1}^{M} \int_{\omega} |G(\omega,m)|^2 \; d\omega} \right)^{-1} \tag{3}$$

is a real, positive scaling factor used to ensure that the total transmit power is constant, regardless of the actual channel realization.

One can see that TDRF scheme requires that the forward link channel knowledge be fed back explicitly from the receiver. The amount of such feedback can be substantial, because it is proportional to the the number of the channel's taps times the number of transmit antennas. In the next section, we consider an alternative transmit diversity scheme called TDCF (Transmit Diversity with Constrained Feedback) which uses only partial channel feedback.

III. Transmit Diversity with Constrained Feedback (TDCF)

In the TDCF scheme, each pre-filter $h(t,m)$ is a simple FIR filter with limited number of the taps:

$$h(t,m) = \bar{\lambda} \; \sum_{i=1}^{L} \alpha_i(m) \; \delta(t-\tau_i), \tag{4}$$

where $\alpha_i(m)$ are the coefficients for the m-th pre-filter, τ_i is a delay corresponding to the coefficients $\alpha_i(m)$ and $\bar{\lambda}$ is a real, positive scaling factor used to ensure that the transmitted power is σ_X^2. The problem now becomes one of finding the optimal solutions for these parameters with respect to a certain performance criterion under some constraint on the amount of feedback.

There are different approaches to choose coefficients $\alpha_i(m)$ and delays τ_i.

1) The coefficients $\alpha_i(m)$ and delays τ_i can be chosen to maximize the information rate that can be reliably transmitted from the base station to the mobile:

$$R \;=\; \int_{\omega} \log\,(\,1 + |\sum_{m=1}^{M} H(\omega,m)\; G(\omega,m)|^2\,)\; d\omega, \tag{5}$$

where

$$H(\omega,m) \;=\; \bar{\lambda}\; \sum_{i=1}^{L} \alpha_i(m)\; \exp\{-j\omega\tau_i\} \tag{6}$$

is the frequency response of the m-th pre-filter. However, the optimization problem

$$\{\;\alpha_i(m),\;\tau_i\;\} = \arg \max_{\alpha_i(m),\tau_i} R \tag{7}$$

over the parameters $\alpha_i(m)$ and τ_i is generally difficult to solve. Besides, the channel capacity given in Eq. (5) can only be approached by using an optimal Maximum Likelihood (ML) receiver. In practice, a sub-optimal receiver such as the Minimum Mean Square Error (MMSE) estimator may be used instead and the designing criterion needs to be changed accordingly. In the following, we give several approaches to design pre-filters for TDCF scheme with various degree of reduction in feedback overhead.

2) MAX L-Taps approach.
Since solving the optimization problem (7) over all the parameters is computationally difficult, the coefficients $\alpha_i(m)$ can be chosen equal to the L maximal channel coefficients. This approach requires the mobile to feed back to the base station both the L channel coefficients and the corresponding delays.

3) Fixed-Grid L-Taps approach.
An alternative to choosing the L strongest taps for each transmit antenna is to use the fixed-grid approach [5] where the grid of evenly-spaced L fingers is placed on a "region" of signal energy indicated by the power/delay profile, and the mobile receiver searches the best position of the grid. Since the grid positions and the finger positions are the same for all antennas, the absolute delay of the grid is irrelevant. Therefore, no feedback information for the tap delays is required for this approach.

In the next sections, we analyze the performance of the TDCF scheme.

IV. Channel Capacity Analysis

In this section, we consider a single noise-limited WCDMA link, with $M = 4$ transmit antennas at the base station and with 1 receive antenna at the mobile. The total transmitted power from all transmit antennas at the base station is always fixed at σ_X^2, and SNR is defined as a ratio of σ_X^2 to the power of the thermal noise at the mobile receiver (band limited to approximately 4 MHz). In all simulations, the downlink channels are modeled as random realizations of the dispersive

3GPP Typical Urban channel from the WCDMA standard. This channel has 10 chip-spaced taps with slowly decaying powers relative to the zero-delay tap. For each realization, we generate a set of 4 uncorrelated downlink channels, and we assume that the receiver knows these channels exactly.

The following transmission schemes have been evaluated:

1) TDRF scheme with perfect channel knowledge.
2) TDCF scheme with 1,2, and 3-tap pre-filters chosen based on MAX L-Tap approach.
3) Per-Antenna Rate Control (PARC) scheme [3].
4) Transmission scheme with 1 transmit antenna and 1 receive antenna (SISO).

In Fig. 2 the average achievable information rate is plotted versus SNR. From Fig. 2 we see that the information rate obtained by the TDCF scheme even with 2-tap pre-filters is very close to close-loop capacity obtained by the TDRF scheme. Furthermore, to achieve a data rate of 10 Mb/s the TDCF scheme with 4 transmit antennas and 2-tap pre-filters requires approximately 5 dB less SNR than the PARC scheme and 7 dB less SNR than SISO.

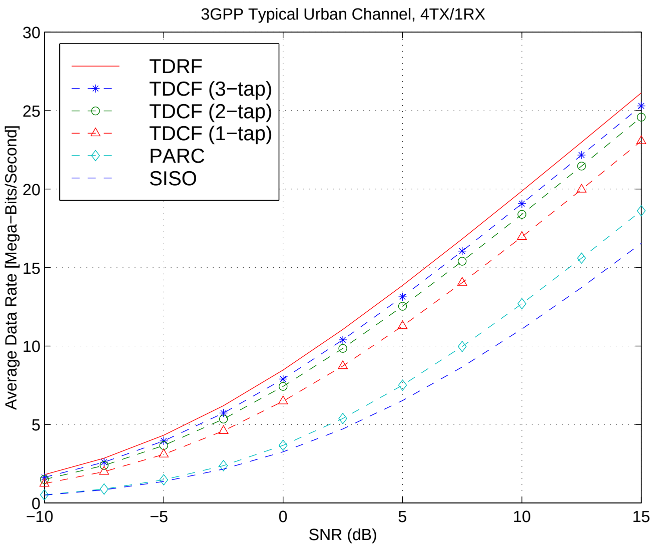

Fig. 2. Average Information Rate vs SNR for 3GPP Typical Urban channel (4 transmit antennas / 1 receive antenna)

V. Simulation Results

The channel capacity study in the previous section is only valid under the unrealistic assumption of employing infinite-length random coding at the transmitter and optimal Maximum Likelihood Sequence Estimator at the receiver. To verify the capacity analysis, a simple simulation is set up with parameters listed in Table I.

Since one of the primary goals of advanced antenna systems is to achieve higher data rate, the downlink traffic in our simulation is fully loaded with spreading factor one. Under such condition, the conventional RAKE receiver would perform poorly in the highly dispersive channel such as 3GPP Typical Urban channel, especially for the SISO case. Therefore, an MMSE receiver is used instead [6].

TABLE I
Simulation Parameters

Parameter	Value
# of TX antennas	4
Channel bandwidth	5 MHz
Channel model	3GPP Typical Urban
Turbo Decoder	Log_Map
Turbo Decoder Iterations	8
Spreading Factor	1, no spreading
# of Information Bits	1024
Turbo Code Rate	1/2
Modulation	QPSK
Block Length	1024 chips

The following transmission schemes have been evaluated:

1) TDRF scheme.
2) TDCF scheme with 1,2, and 3-tap pre-filters chosen based on MAX L-Taps approach.
3) TDCF scheme with 1,2, and 3-tap pre-filters chosen based on Fixed-Grid L-Taps approach.
4) Antenna Switching (AS).
   In this scheme, the base station transmits data using just "the best" transmit antenna where the selection of the best antenna is based on the SNR measured at the output of the terminal MMSE receiver.
5) Single-Tap Closed-Loop scheme.
   This scheme is a generalized version of the the existing closed-loop transmit diversity in WCDMA [7]. In this scheme, which we refer to as 3GPPTXD+, each $h(t,m)$ is a 1-tap, complex-valued filter (i.e. a single complex-valued weight):
   $$h(t,m) = \lambda \cdot h(m), \tag{8}$$
   where λ is a real, positive scaling factor used to ensure that the transmitted power is σ_X^2. In the 3GPPTXD+ scheme, the coefficients $h(m)$ are selected such that the power at the output of the channel
   $$P_{out} = \int_\omega \left| \sum_{m=1}^{M} h(m)\ G(\omega,m) \right|^2 d\omega, \tag{9}$$
   is maximized subject to a transmitted power constraint. It can be shown that the maximizing $h(m)$ is a scaled-version of the eigenvector corresponding to the largest eigenvalue of the matrix χ whose elements are defined as
   $$\chi_{i,j} = \int_\omega G(\omega,i)\ G^*(\omega,j) d\omega. \tag{10}$$
6) Transmission scheme with 1 transmit antenna and 1 receive antenna (SISO).

Fig. 3 compares the Frame Error Rate (FER) performance between the Fixed-Grid (FG) and the MAX L-Taps (MAX) approaches.

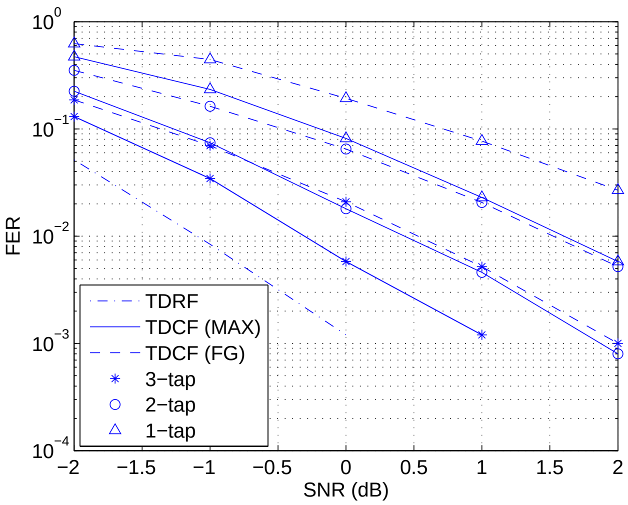

Fig. 3. Fixed-Grid vs MAX L-Tap in 3GPP Typical Urban channel

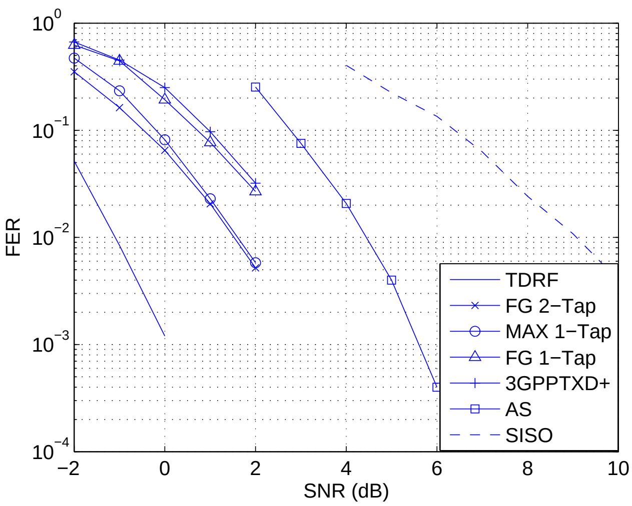

Fig. 4. Performance comparison of the MISO transmission schemes in 3GPP Typical Urban channel

As expected, MAX performs better than FG for the same number of taps. It is interesting to note that MAX 1-Tap and FG 2-Tap have roughly the same performance which is less than 3 dB away from the TDRF case. The amounts of feedback for the two are about the same as well. For each transmit antenna, MAX 1-Tap needs to send one complex coefficient and one delay whereas FG 2-Tap needs to send two complex coefficients.

Fig. 4 shows the performance for some selected cases in Fig. 3 along with the rest of the schemes listed above. Comparing with the SISO case, schemes that feed back only 4 coefficients (one for each antenna) has at least a 6 dB gain at 1 % FER. Even the simplest antenna switching method has a gain of 4 dB. A somewhat unexpected outcome of the experiment is the fact that FG 1-Tap performs slightly better than the 3GPPTXD+, which is the optimal solution in terms of maximizing channel output SNR given one coefficient for each transmit antenna. However, by probing into the simulation, it turns out that the SNR at the output of the MMSE receiver is higher for the FG 1-Tap method.

VI. Conclusions

To reduce the amount of feedback overhead for closed-loop MISO systems, we propose a family of sub-optimal approaches that feed back only partial channel information. They are referred to as Transmit Diversity with Constrained Feedback (TDCF) and include such methods as sending only the first few strongest taps or a short block of taps on a fixed grid. Both capacity analysis and simulation show that although the loss in performance is not insignificant, these methods still achieve considerable gain with respect to open-loop (or near-open loop) solutions in MISO systems. Specifically, TDCF with MAX 1-tap feedback performs 3 dB better than the transmit antenna switching method in a system with 4 transmit and 1 receive antennas—a respectable gain at a modest cost of reverse link overhead. Comparing with PARC, which requires roughly the same order of feedback overhead, TDCF has at least a 4 dB advantage.

References

[1] R.Choi, K.Letaief, and R.Murch, "MISO CDMA transmissions with simplified receiver for wireless handsets," *IEEE Trans. Commun.*, Vol.49, pp.888-898, May 2001.

[2] Kambiz Zangi and Leonid Krasny, "Capacity-Achieving Transmitter and Receiver Pairs for Dispersive MISO Channels," *IEEE Transactions on Wireless Communications* Vol.2, pp.1204-1216, November 2003.

[3] S. T. Chung, A. Lozano, H. C. Huang, A. Sutivong and J. M. Cioffi, "Approaching the MIMO Capacity with V-BLAST: Theory and Practice," *Proc. IEEE WCNC 2002*, March 2002.

[4] M.K.Varanasi and T.Guess, "Optimum detection feedback multiuser equalization with successive decoding achieves the total capacity of the Gaussian multiple-access channel," *Proc. Asilomar Conf. on Signals,Systems, and Computers*, Monteray, CA, November 1977.

[5] Carmela Cozzo, Gregory E. Bottomley, and Ali Khayrallah, "RAKE Receiver Finger Placement for Realistic Channels," *IEEE Proc. WCNC*, Atlanta, GA, March 2004.

[6] K. L.Baum, T. A. Thomas, F. W. Vook, and V. Nangia, "Cyclic-Prefix CDMA: An Improved Transmission Method for Broadband DS-CDMA Cellular Systems," *Proc. IEEE WCNC 2002*, pp.183-188, March 2002.

[7] E. Dahlman, P. Beming, J. Knutsson, F. Ovesjo, M. Persson, and C. Roobol, "WCDMA–The radio interface for future mobile multimedia communications," *IEEE Veh. Technology*, Vol.47, pp.1105-1118, Nov. 1998.