

OPEN-LOOP TRANSMIT DIVERSITY IN IS-2000 SYSTEMS

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ABSTRACT

Recently, a new form of transmit diversity has been developed and included for Interim Standard 2000 (IS-2000) the third generation successor for IS-95 code division multiple access (CDMA) systems. This transmit diversity scheme which was developed by Bell Laboratories is similar in principle to space-time block coding methods developed for UMTS systems by Texas Instruments and TDMA Systems by Tarokh et al. This paper presents performance results of this new transmit diversity method, termed space-time spreading.

1. INTRODUCTION

Improving the performance of forward link of cellular systems even marginally can be difficult. Numerous practical constraints limit the ability of technical schemes which have merit but are often not feasible to implement. Operators are generally not inclined to add significant numbers of antennas to their towers as they face increasing resistance from communities to beautify or reduce the size of their antenna towers. Further, the systems themselves do not often readily lend themselves to enhancements without changing the standards themselves.

Recently, phase II of the IS-2000 standardization process has been completed where a review of forward link antenna techniques was completed. A few different schemes were proposed as possible enhancements for the system. The standard originally supported a method of transmit diversity known as orthogonal transmit diversity (OTD). This method offered significant performance gains for rate 1/4 convolutional codes at low speeds, but did not offer the same types of gains for rate 1/2 codes. Further, the scheme was open-loop, and made no use of user specific data such as location or condition of its channel, other than through user independent power control.

A scheme was proposed which attempted to close the loop by adaptively updating a set of user-dependent

complex weights. This scheme was really designed to mitigate fading rather than attempt to limit or reduce spatial interference. This method was met with significant resistance as numerous practical issues arose with closing the loop and feeding back the weights.

Through the efforts of Bell Laboratories [1], an additional open-loop scheme was developed which significantly improved performance of weaker convolutional codes or codes with higher rates. This scheme which we will term "Space-Time Spreading" can offer significant performance gains over the existing form of open-loop transmit diversity. This scheme is similar in concept and performance to the schemes proposed by Texas Instruments for the UMTS system (W-CDMA) [2], and by Tarokh et al. [3] for TDMA applications. This paper discusses the performance of this scheme, and shows some of the performance results which were used to win approval of this scheme in the IS-2000 standardization process.

2. AN IS-2000 SYSTEM MODEL

For a system with K mobiles receiving signals from a common base station, the transmitted signal on a single antenna can be modeled as:

$$x(t) = \left(\sum_{i=1}^K \sqrt{P_i} s_i(t) w_i(t) + \sqrt{P_p} w_0(t) \right) p(t) \quad (1)$$

where P_i is the power transmitted to the i^{th} mobile, $s_i(t)$ and $w_i(t)$ are the data signal and unique Walsh function intended for the i^{th} mobile respectively, P_p is the power of the pilot signal which uses Walsh function 0, and $p(t)$ is the covering code for the base station of interest. Further, the Walsh functions are orthogonal and repeat every symbol time T_s , i.e.

$$\frac{1}{T_s} \int_0^{T_s} w_i(t) w_j(t) dt = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases} \quad (2)$$

At the mobile the following signal is received on a single antenna

$$y(t) = h(t)x(t) + n(t) \quad (3)$$

where $h(t)$ is the scalar complex multiplicative distortion caused by the wireless channel and $n(t)$ is thermal noise and all other interference. Mobile i correlates the received signal with the i^{th} Walsh function during the k^{th} symbol interval after uncovering to achieve the decision statistic $z_i[k]$:

$$\begin{aligned} z_i[k] &= \int_{(k-1)T_s}^{kT_s} y(t)p^*(t)w_i(t)dt \\ &= \sqrt{P_i}h[k]s_i[k] + n[k] \end{aligned} \quad (4)$$

where $h[k]$ represents the cumulative effect of the channel $h(t)$ over the k^{th} symbol interval (assuming perfect sampling conditions), and $s_i[k]$ is the k^{th} transmitted symbol for the i^{th} mobile.

The transmitted symbol can be recovered by using an estimate of the channel distortion $\hat{h}[k]$ obtainable from the pilot channel, i.e.,

$$\hat{s}_i[k] = f\left(z_i[k]\hat{h}^*[k]\right) \quad (5)$$

where $f(\cdot)$ is an appropriate decision function. Alternatively, in a coded system $z_i[k]\hat{h}^*[k]$ may be used directly as a symbol metric. If the channel is a flat, slow Rayleigh faded channel, in the absence of fast, accurate power control, the resulting performance of the link will be rather poor due to the lack of diversity. As a result, it is desirable to have a second antenna at the receiver to allow diversity reception, improving performance considerably. However, mobile handsets do not easily allow a second antenna to be added.

3. TRANSMIT DIVERSITY METHODS

One method of achieving diversity performance is to transmit the same signals on multiple carriers. However, this is wasteful of the one resource we cannot afford to waste in mobile communications, namely bandwidth.

As another alternative, re-transmitting the same waveform with a chip-level delay, also known as delay diversity, can help performance [4], but it can also degrade performance as it increases the amount of self-interference which degrades the performance of most typical Rake receivers.

Artificial Doppler distortion or phase switched transmit diversity (PSTD) has been suggested as a means to improve forward link performance [5]. It can help but it has been difficult to implement in practice and the gains are marginal.

Orthogonal transmit diversity (OTD) which is available in the standard as an option transmits half of the bits via one antenna, and half of the bits via a second antenna [6]. The received stream of coded bits will be

$$\{h_{i_0}[0]s_i[0], h_{i_1}[0]s_i[1], h_{i_0}(1)s_i[2], h_{i_1}(1)s_i[3], \dots\} \quad (6)$$

Using a Viterbi decoder, the link-level performance of the forward link becomes a function of the quality of both channels. Transmissions via channels with slow fading conditions benefit greatly from this method. However, this method offers less performance gain as the speed increases¹, and the code rate decreases.

A related concept introduced periodic switching of data between a two antenna system. It may achieve improvements in performance, but it also possesses similar performance degradation problems as OTD, and the transmitted signal has a higher peak to average ratio than OTD.

Finally, the primary topic of this paper, *Space-Time Spreading* was recently introduced as a possible method to improve performance. This scheme does not require additional bandwidth, introduce additional interference, or depend on code rate for diversity gain.

4. SPACE-TIME SPREADING

Based upon space-time block codes, attributed to Alamouti [7], a signal transmission scheme which utilized the multiple orthogonal code structure already available in the standard was developed. On the first antenna we transmit

$$x_1(t) = \left(\sqrt{\frac{P_1}{2}}s_e(t)w_1(t) - \sqrt{\frac{P_1}{2}}s_o^*(t)w_2(t) \right) p(t) \quad (7)$$

and on the second antenna we transmit,

$$x_2(t) = \left(\sqrt{\frac{P_1}{2}}s_e^*(t)w_2(t) + \sqrt{\frac{P_1}{2}}s_o(t)w_1(t) \right) p(t) \quad (8)$$

where P_i and w_i are the transmit power and Walsh code dedicated to the i^{th} transmit antenna respectively, and $s_e(t)$ and $s_o(t)$ represent the even and odd streams of bits, respectively. Note that a separate Walsh code is required for each transmit antenna to support a pilot on each antenna. Since the data rate has been reduced by a factor of two by this scheme for each stream of bits, it is possible to use double length Walsh codes and not utilize additional bandwidth or Walsh resources.

¹The interleaver helps compensate for loss of bits during bursty errors, because at high speeds, the duration of the errors tend to be shorter.

At the receiver, we again uncover and correlate with the two Walsh codes. At the output of the two Walsh correlations we obtain (dropping the dependence on symbol interval)

$$z_1 = \sqrt{\frac{P_1}{2}} h_1 s_e + \sqrt{\frac{P_1}{2}} h_2 s_o + n_1 \quad (9)$$

$$z_2 = \sqrt{\frac{P_1}{2}} h_2 s_e^* - \sqrt{\frac{P_1}{2}} h_1 s_o^* + n_2 \quad (10)$$

which obviously introduces interference terms in the decision statistics. However, if we have estimates of the channel distortions h_1 and h_2 from pilot signals 1 and 2, we can obtain a signal estimate for the even bits by

$$\begin{aligned} s_e &= f \left\{ h_1^* z_1 + h_2 z_2^* \right\} \\ &= f \left\{ h_1^* \left(\sqrt{\frac{P_1}{2}} h_1 s_e + \sqrt{\frac{P_1}{2}} h_2 s_o + n_1 \right) \right. \\ &\quad \left. + h_2 \left(\sqrt{\frac{P_1}{2}} h_2 s_e^* - \sqrt{\frac{P_1}{2}} h_1 s_o^* + n_2 \right)^* \right\} \\ &= f \left\{ \left(\sqrt{\frac{P_1}{2}} |h_1|^2 + \sqrt{\frac{P_1}{2}} |h_2|^2 \right) s_e + h_1^* n_1 + h_2 n_2^* \right\} \end{aligned} \quad (11)$$

where we've assumed that the channel estimation is exact, $h_1 = h_1$ and $h_2 = h_2$. Similarly, we can estimate the data for the odd stream of bits as

$$\begin{aligned} s_o &= f \left\{ h_2^* z_1 - h_1 z_2^* \right\} \\ &= f \left\{ \left(\sqrt{\frac{P_1}{2}} |h_1|^2 + \sqrt{\frac{P_1}{2}} |h_2|^2 \right) s_o + h_2^* n_1 - h_1 n_2^* \right\} \end{aligned} \quad (12)$$

It can be easily shown that this is identical to the decision statistic for two-antenna diversity reception (without the 3dB aperture gain)[8].

5. PERFORMANCE OF SPACE-TIME SPREADING

The performance of STS was examined for voice and data channels associated with the forward link of the IS-2000 system². Fundamental channels, which are the basic dedicated traffic channel in IS-2000, are intended for voice rate data and communicate data at roughly 9.6kbps. Two different convolutional coders are supported for voice rate traffic. Radio configuration 3 (RC3) is a 1/4 rate convolutional coder with additional

²A superset of these results appeared in standards contributions [9] and [10]

Table 1: Fundamental Channel Parameters

Base Station Antennas:	1 (No Div.) & 2
Bit Rate:	9600bps
Chip Rate:	1.2288Mcps
Coding:	RC3 & RC4
Frame Duration:	20ms
Frequency:	1.9GHz
Mobile Geometry:	$I_{or}/I_{oc} = 6$ dB
Pilot E_c/I_{or} :	-7, -13 dB
Max/Min power allocation:	-3 dB/-40 dB
Inner-loop PC rate:	800Hz
PC command error rate:	4%
Inner loop PC step:	± 0.5 dB
Outer loop PC:	1% FER target
Channel:	Rayleigh fading

puncturing for overlay of reverse-link power control information at a rate of 4/48. RC4 is a 1/2 rate convolutional coder with the same type of overlay puncturing at a rate of 2/24.

In addition, we also studied dedicated traffic channels which can accommodate higher data rates. These channels are termed "supplemental channels" in the standards nomenclature. These channels are intended for high speed data applications. We examined a 76.8 kbps supplemental channel using a 1/2 rate convolutional coder. Note that there is no puncturing of supplemental channel data.

5.1. Fundamental Channels

The performance of STS was simulated for one and two path Rayleigh fading channel model for the fundamental channel. The transmit power fractions, E_c/I_{OR} , required to achieve a 1% frame error rate (FER) for full-rate voice using radio configurations RC3 and RC4 were derived from simulation. E_c represents the energy per chip, and I_{OR} represents the total transmit power spectral density. The quantity, I_{OR}/I_{OC} represents the ratio of the transmit power spectral density to the out of cell interference plus any additional thermal noise. It is commonly referred to as "mobile geometry" with low values associated with mobile locations close to the edge of the cell and high values associated with mobiles close to the base station. The geometry is related to the signal to noise ratio of the receiver.

The effects of power control, puncturing, and coding using the interleaver specified in the ballot version of the proposal [6] were included. The major simulation parameters are summarized in Table 1.

The simulation results for the fundamental channel are summarized in Figures 1 and 2. For both RC3 and

RC4, it is clear that STS offers significant performance advantage and makes the capacity of RC3 with OTD and the capacity of RC4 with STS approximately equal. Since RC3 uses 1/4 rate convolutional codes while RC4 uses 1/2 rate codes, RC3 uses length 64 Walsh codes while RC4 uses length 128 Walsh codes. Thus, RC4 is less likely to experience a capacity limit due to a Walsh code limitation and may be preferable in situations where the number of Walsh codes is a concern.

Shown in Figure 1 for a geometry of $I_{OR}/I_{OC} = 6\text{dB}$, STS offers up to 5 dB performance improvement over OTD at low speeds, and a minimum of 1.5 dB improvement at high speeds for RC4. For RC3, the gains are smaller, with STS offering a minimum of 0.5 dB improvement over OTD and up to 1dB at low speeds.

The two path results for both radio configurations are shown in Figure 2. Note that for RC4 with high geometry, $I_{OR}/I_{OC} = 6\text{dB}$, STS reduces transmit power requirements by 2.5 dB at low speeds, and a minimum of 1 dB at high speeds. For RC3, STS offers up to 0.75 dB improvement at high speeds and a minimum of 0.5 dB improvement at low speeds.

Note that the gains of STS over OTD are more substantial in RC4 since it uses a higher rate convolutional code. As mentioned previously, this is an expected result since OTD relies on the decoding process to obtain diversity gain whereas STS does not. Note also that STS and OTD (with 1/4 rate coding) both offer large improvements over no diversity, especially at low speeds.

5.2. Supplemental Channels

The performance of high data rate channels (*i.e.* supplemental channels) for STS and OTD was simulated in the one path Rayleigh environment at high geometry. The simulation environment for this supplemental channel is summarized in Table 2.

The simulated transmit power requirements to achieve the 1% target frame error rate (FER) are shown in Figure 3. As shown in the figure, STS outperforms OTD at all speeds of interest, offering over 2 dB in performance gain at low speeds, and a minimum of 1dB performance gain at high speeds.

6. CONCLUSIONS

Space-time spreading techniques offer the best overall performance that is obtainable by open-loop techniques. Space-time spreading offers performance gains which are robust to code rate changes and further puncturing of the code due to signaling commands. Further enhancements to the system must consider adaptive techniques with low rates or potentially no feedback.

Systems which require high rates of feedback obtain capacity gains at the expense of capacity of the reverse link.

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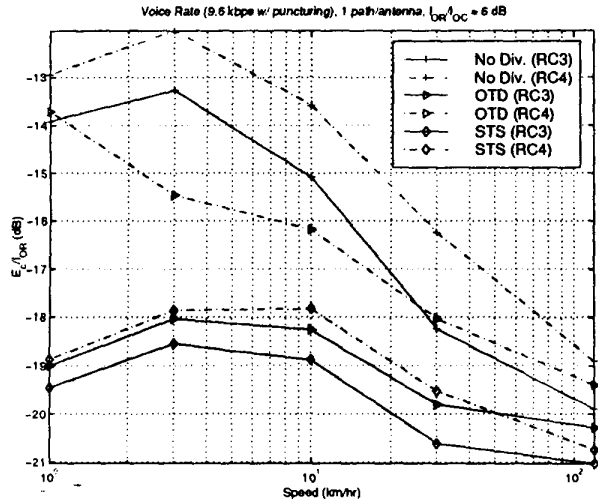


Figure 1: Fundamental Channel (9.6 kbps) Transmit Power, RC3 & RC4, One Path, $I_{OR}/I_{OC} = 6dB$

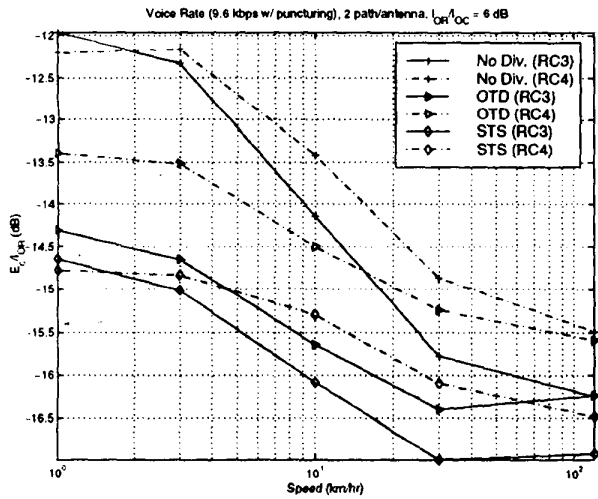


Figure 2: Fundamental Channel (9.6 kbps) Transmit Power, RC3 & RC4, Two Equal Power Paths, $I_{OR}/I_{OC} = 6dB$

Table 2: Supplemental Channel Parameters

Base Station Antennas:	1 (No Div.) & 2
Bit Rate:	76.8 kbps
Chip Rate:	1.2288 Mcps
Coding:	$R = 1/2$
Puncturing:	None
Frame Duration:	20ms
Frequency:	1.9GHz
Mobile Geometry:	$I_{OR}/I_{OC} = 6$ dB
Pilot E_c/I_{OR} :	-10, -10 dB
Max/Min power allocation:	-3 dB/-40 dB
Inner-loop PC rate:	800Hz
PC command error rate:	4%
Inner loop PC step:	$\pm 0.5dB$
Outer loop PC:	1% FER target
Channel:	flat Rayleigh fading

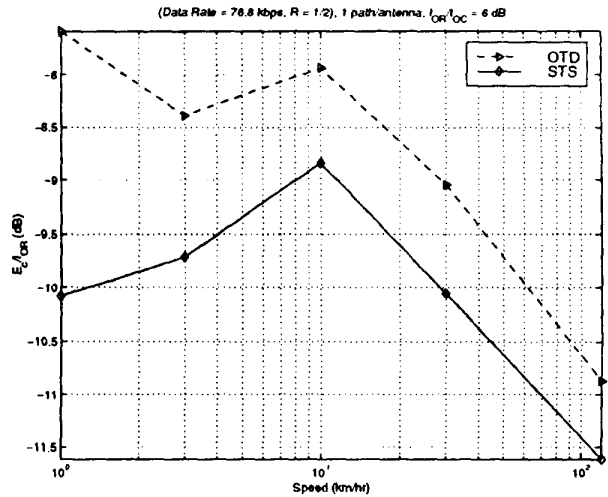


Figure 3: Supplemental Channel (76.8 kbps) Transmit Power, RC4, One Path, $I_{OR}/I_{OC} = 6dB$