

An Introduction to PSTD for IS-95 and cdma2000

Alberto Gutierrez, Jun Li
Nortel Networks
Richardson TX, 75082, USA

Steven Baines, Damian Bevan
Nortel Networks, Harlow Laboratories
London Road, Harlow, Essex CM179NA, UK

Abstract – Of the feedforward transmitter diversity methods considered for 3rd generation PCS/Cellular systems one such method is known as Phase Sweeping Transmitter Diversity (PSTD). Since PSTD does not require a modification of the mobile station receiver, an important feature of this method is compatibility with 2nd generation as well as 3rd generation mobile stations. Furthermore, this method of transmitter diversity does not require specification in a standard. This paper provides an introduction to PSTD as it applies to IS-95 and cdma2000; the form of the received PSTD signal at the mobile station; compatibility issues between 2G and 3G; and link performance for AWGN, Rayleigh, and Ricean channel models.

I. Introduction

Recently, several methods for improving the spectral efficiency of the downlink (forward link) of 3rd generation CDMA PCS/Cellular radio systems have been considered. Although it is well known that receiver diversity yields at least a 3-dB improvement in link performance (e.g. for 2 antenna receiver diversity), it has the penalty of increased hardware complexity at the mobile station. Consequently, many forms of transmitter diversity have been considered, both feedforward and feedback. Of the feedforward methods, one such technique is known as Phase Sweeping Transmitter Diversity (PSTD) in which the base station signal is transmitted from two co-located antennas (i.e., both located at the same basestation site), where each antenna radiates the same signal, but the phase of one antenna is swept relative to the other. Of the many methods under consideration, PSTD does not require modification of the receiver design, nor does it require specification in the form of a standard. Therefore, a system with both 2nd and 3rd generation mobile stations can benefit from this form of transmitter diversity.

In [1], Hiroike et al. presented a system with PSTD including block coding and pilot symbol aided modulation. Reference [2] considers the performance of PSTD for a system with convolutional coding and with coherent and differentially coherent modulation. Block coded and Trellis coded modulation with PSTD diversity (presented in terms of an intentional frequency offset) are considered in [3].

In this paper, we evaluate the benefit of PSTD with respect to the cdma2000 spread spectrum mobile communication system [4-5]. This system includes several features for mitigation of fast fading; for example, block interleaving, convolutional coding, and fast power control with 800 updates per second. Therefore, this paper provides

an example of the benefits provided by PSTD in addition to, and in combination with, other diversity and fast fading mitigation techniques.

In Section II we describe the system including the transmitter details, the form of the PSTD signal, and receiver configuration. In Section III the performance of PSTD obtained from computer simulation is discussed. Some conclusions are summarized in Section IV.

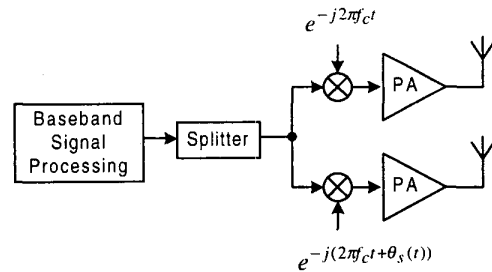


Figure 1. PSTD Transmitter

II. System Description

In Figure 1 is illustrated a PSTD transmitter. After baseband signal processing, the signal is split into two paths. In practice, this splitter may be implemented in baseband, IF, or RF. One path modulates a carrier at frequency f_c , and the other path modulates a carrier at frequency $f_c + d(\theta_s(t)/2\pi)/dt$. In other words, as indicated by [3], the phase swept path is really the carrier frequency f_c plus an intentional frequency offset. After carrier modulation, both the paths are amplified and radiated over two antennas. It is assumed that the two antennas are separated in space (typically by around 10-20 wavelengths) or in polarisation, such that the fields observed at the receiver antenna are independent at any instant, although statistically identical over the long term. An important practical consideration regarding the implementation of any transmitter diversity scheme is the need for two power amplifiers (PAs), antennas, and associated RF electronics. Thus, the system improvements with respect to link performance and capacity should justify any such complexity increase.

The transmitted signal is given by:

$$s(t) = \sum_{k=0}^{\infty} \sum_m x_m(k) \sum_{n=0}^{N_c-1} w_{m,n}(kN_c + n)p(kN_c + n) \\ h(t - kN_c T_c - nT_c) \cdot (e^{-j2\pi f_c t} + e^{-j(2\pi f_c t + \theta_s(t))}) / \sqrt{2}. \quad (1)$$

The transmitted signal, $s(t)$, is a sum of transmitted symbol, $x_m(k)$, over all time and each Walsh traffic channel m . Each Walsh traffic channel symbol, $x_m(k)$, is multiplied by the Walsh and PN chips $w_m(t)$ and $p(t)$, respectively, followed by pulse shaping with the filter $h(t)$ and finally multiplication of the main and diversity complex carriers $e^{-j2\pi f_c t} + e^{-j(2\pi f_c t + \theta_s(t))}$. cdma2000 may operate at various spreading bandwidths, [4-5], where the chip rates are $N \times 1.2288$ Mcps (millions of chips per second), where $N = 1, 3, 6, 9, 12$. The number of chips per symbol, N_c , depends on the symbol rate and chip rate, which is variable according to the data rate and spreading bandwidth.

The mobile station receiver, [7], is illustrated in Figure 2. The waveform presented to the receiver antenna consists of L copies (L paths) of the transmitted signal offset due to a Doppler frequency shift, f_d , scaled in magnitude according to a fading process, $\alpha_{l,i}(t)$, with addition of a random phase, $\phi_{l,i}(t)$, and addition of a noise term, $n(t)$, where i is 1 or 2 corresponding to the main or diversity antenna. First, the received waveform, $r(t)$, is down-converted in frequency by multiplying by the term to yield $r'(t)$, given by (after simplification) this is usually referred to as inter-path

$$r'(t) = \sum_{l \in L} s_l(t - \tau_l) \cdot (\alpha_{l,1}(t) e^{j\phi_{l,1}(t)} + \alpha_{l,2}(t) e^{-j(\theta_s(t) + \phi_{l,2}(t))}) + n(t). \quad (2)$$

The waveform $r'(t)$ is then processed by the Rake receiver where the PN and Walsh chips are aligned according to the delay of the l -th path. Also, a filter, $h_p(t)$, estimates the channel relative gains and phase. Note that the pilot is transmitted on Walsh channel 0 (unmodulated) so that effectively $h_p(t)$ estimates the channel from the pilot. The conjugate of the channel estimation filter multiplies the output of Walsh chip multiplication. Each Rake finger then performs a sum and dump operation after each N_c chips, where N_c corresponds to the length of each Walsh code. Note that for efficient implementation it may be desirable to perform the phase correction after the sum and dump operation; that is, the phase correction is made to each symbol rather than to each chip.

It is important to formulate the Rake finger outputs $y_l(t)$ in order to understand the effect of the phase sweeping diversity. For a 1-path model, then within each path, l' , and for user m' , the PN chips are effectively removed, and due to orthogonality of the Walsh codes, all channels, except m' , cancel. For the case of multipath channel models ($L > 1$), however, the PN chips for other paths, $l \neq l'$, are not aligned so that the respective traffic channels contribute interference to the l' -th path (i.e., inter-path interference or self-interference). Thus, after simplification, $y_l(t)$ can be put in the following form:

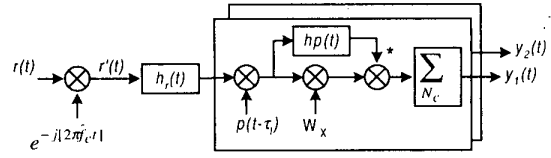


Figure 2. Mobile Station Receiver

$$y_l(t) = \hat{\alpha}_{l'}(t) e^{-j\hat{\phi}_{l'}(t)} N_c x_m(k) \cdot (\alpha_{l',1}(t) e^{j\phi_{l',1}(t)} + \alpha_{l',2}(t) e^{-j(\theta_s(t) + \phi_{l',2}(t))}) + \hat{\alpha}_{l'}(t) e^{-j\hat{\phi}_{l'}(t)} \sum_{l \in l'} \hat{\alpha}_l(t) s_L(t - \tau_l) \cdot (\alpha_{l,1}(t) e^{j\phi_{l,1}(t)} + \alpha_{l,2}(t) e^{-j(\theta_s(t) + \phi_{l,2}(t))}) + n'(t), \quad (3)$$

where $s_L(t)$ is the low-pass equivalent of (3), that is, without the exponential terms.

From (3), $y_l(t)$ consists of three major components: the desired signal with phase and magnitude corrections, $\hat{\alpha}_{l'}(t)$ and $e^{-j\hat{\phi}_{l'}(t)}$, respectively; inter-path interference; and additive noise. The latter two terms are present with or without PSTD and will have essentially the same impact on performance regardless of PSTD. It is evident that the terms due to antenna diversity, $(\alpha_{l',1}(t) e^{j\phi_{l',1}(t)} + \alpha_{l',2}(t) e^{-j(\theta_s(t) + \phi_{l',2}(t))})$, occur at the same chip timing so that they are not resolvable. Consequently, the desired signal is equivalently the sum of two phasors – one from each antenna and offset in phase by the phase sweeping plus random phase components.

PSTD Signal Properties

The received PSTD signal is equivalently the sum of two phasors. In the case that the two individual phasors each have a complex Gaussian amplitude distribution (i.e. are Rayleigh faded), then the resultant signal will also have a complex Gaussian distribution, since the sum of Gaussians is also a Gaussian. The resultant signal in effect fades at a faster rate than the non-PSTD signal due to the periodic alternation of constructive and destructive combining. The sweep rate of the second transmission is chosen such that the phase change over a symbol period is small (such that there is minimal energy loss in the 'sum and dump' operation), but the phase change over a period of a coded frame is large. For example, with a sweep rate of 50 Hz, the phasor rotation due to the phase sweeping goes through one cycle during one 20ms frame. The performance of coded systems with restricted interleaver span (often designed this way due to latency considerations) tends to be better at higher Doppler rates. This is because at these higher Doppler rates the interleaver has more opportunity to

disperse any errors widely over the coded frame. The result of applying PSTD in order to increase the 'effective' mobile Doppler is therefore to improve link performance (i.e. reduce downlink power requirement for the same frame error rate).

For a slow-moving mobile, if both the main and diversity path suffer a fade, then the resultant PSTD signal will be weak potentially over a longer period than would be the case for a fast moving mobile. This latter phenomenon is what makes the composite PSTD signal different in the frequency domain from a simple Rayleigh fading signal with a classical Doppler spectrum (as would be associated, for example, with a fast-moving mobile).

What if our underlying channel behavior is Ricean rather than Rayleigh? Figure 3 and Figure 4 illustrate the time evolution of channel taps without and with PSTD, respectively. The channel taps are Ricean, with various K factors, and exhibit the 'Classical' Doppler spectrum [8] with an 8 Hz maximum Doppler frequency. For the non-PSTD case the power variation against time reduces as the K factor increases. This is as we would expect because higher K factors result in channels which are closer to being static, having less and less energy in the fading component. For the PSTD case at high K-factor, the power variation against time is greater than for the non-PSTD case. Furthermore, for the PSTD case, the power variation against time increases as the K factor increases. Again, this is to be expected for PSTD. This is because higher K factors result in the two antennas transmitting increasingly similar signals (due to the reduced effect of the independent fading) which are phase swept relative to each other, resulting in very deep fades which occur at the PSTD frequency. For all K factors, the effect of PSTD is to increase the fading rate, as expected. These trends indicate that the application of PSTD is to be preferred for systems which typically operate in channels with low K factors.

IS-95 and cdma2000 Interoperability/Compatibility

The transmitted symbols, $x_m(k)$, are interleaved and may represent user information or power control commands, which have been punctured onto the data stream.¹ Therefore, prior to FEC (Forward Error Correction) decoding the received samples are deinterleaved and samples representing power control commands are removed (not shown) and replaced with zeros. Note that in cdma2000 the error correction code can either be a Convolutional or Turbo code.

¹ Reference [5] specifies the power control command puncturing patterns for the chip rates of 1.2288 Mcps and 3.6864 Mcps. Puncturing patterns for the higher chip rates are yet to be specified.

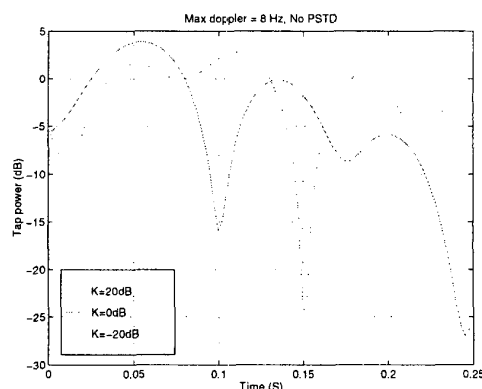


Figure 3. Time Evolution of Channel Taps without PSTD

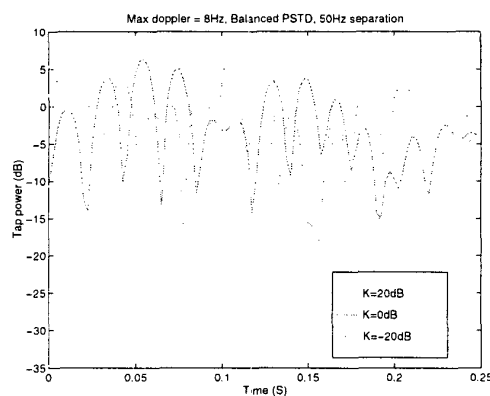


Figure 4. Time Evolution of Channel Taps with PSTD

Since IS-95 uses BPSK data modulation, then $x_m(k)$ is real; and since cdma2000 uses QPSK data modulation, then $x_m(k)$ is complex. This difference in modulation formats, $x_m(k)$ being real or complex does, not change the orthogonal properties of the Walsh channels. For example, for an IS-95 receiver all Walsh channels are orthogonal with the BPSK channels transmitted according to the IS-95 format as well as QPSK channels transmitted according to the cdma2000 format. A similar argument holds for a cdma2000 receiver. Then, (3) applies to an IS-95 receiver as well as cdma2000 receiver; and therefore, any benefits due to the received PSTD diversity paths benefit IS-95 mobile stations as well as cdma2000 mobile stations. The precise performance benefits, however, may vary due to differences in symbol rate, coding, and power control. Note that IS-95 does not include fast forward link power control, and so any diversity gains due to PSTD are particularly beneficial.

III. Performance

The simulation parameters used in this study are summarized in Table 1. We quantify the link performance improvements due to PSTD (100 Hz sweeping rate) for a 1.2288 Mcps system with respect to mean base station transmit power, since the base station per-user transmit power has a direct relationship to forward link capacity. It is noted, however, that detailed quantification of the benefit of PSTD on the forward link capacity requires also consideration of soft handoff regions, [6], which is beyond the scope of this study.

The power commands for the forward link power control are transmitted from the mobile station to the base station, at a rate of 800 bps. In this study, each power control command (i.e., power control bit) specifies a ± 0.5 dB step change in traffic channel power, where a 4% bit power control bit error rate is assumed. Some justification for this assumption comes from observing that with a 4% power control bit error rate there is insignificant link performance degradation. This implies that the reverse link power control commands should be sent at sufficient power to maintain at most this error rate.

The channel-tracking filter is a causal FIR filter of length 1/2 power control group and runs at the symbol level. Although the filter does not provide ideal performance it gives a reasonable tradeoff between computational complexity at the mobile station and performance.

The forward link (FL) power control loop is based on estimation of the received E_b/N_r at the mobile station receiver. The E_b estimate is derived from the reverse link (RL) power control bits received at the mobile (i.e., punctured onto the FL traffic channel for RL power control) and E_b is the energy per information bit of the FL traffic channel. N_r is the effective FL noise spectral density measured after Rake combining. Thus, N_r contains the effect of inter-path interference. A power control group is by definition 1/16 of the 20 ms frame (i.e. 1.25ms). The power control loop delay is measured from the end of the E_b/N_r estimation at the mobile to the time the power is changed at the base station transmitter. This form of power control, where we carry out estimation of E_b directly from power control bits, is valid for variable rate applications (i.e., such as for cdma2000 voice channels).

For an AWGN channel (or Ricean with a 'high' K factor) we expect to have some loss in performance when PSTD is employed compared to transmitting from one antenna. For an AWGN environment with fast forward power control disabled and channel tracking turned on we obtain an E_c/I_{or} requirement of -24.6 dB and -24 dB at a 1% FER for single antenna transmitter and PSTD transmitter, respectively. Thus there is a loss due to PSTD at very high K factors, but it is only around 0.6dB.

Reference [9] is a study of channel models for a non-line-of-sight urban radio environment for various spreading bandwidths. For a 1.25 MHz CDMA system it is found that most of the multipath are confined to 1 or 2 diversity paths with severe fading. For such radio environments it is found that the K factor (ratio of deterministic to scattered power) is small. Thus, in practice, for urban mobile deployments we find that a high-K Ricean channel (where PSTD might be expected to show a performance loss) is rare. The extreme of such a low-K channel is represented by the Rayleigh distribution (K = $-\infty$). We also provide performance results for the more optimistic Ricean radio environment with K = 3 dB.

In Figure 5 and Figure 6 we plot the performance for 1-path and 2-path, respectively, for Rayleigh and Ricean radio environments (where 'NTD' represents the 'No Transmit Diversity' case). The vertical axis represents E_c/I_{or} , where E_c is the mean transmitted energy per traffic channel chip and I_{or} is the total energy spectral density of the base station transmitter. Hence, this quantity indicates the fraction of total base station power required to support a given traffic channel for the given simulation parameters. The power control loop is set for a target frame error rate of 1%, and each data point in the graphs corresponds to 10,000 frames. An important quantity in evaluation of the link performance is I_{oc} , which specifies the power spectral density of other cell interference observed at the mobile station antenna. This is modeled as AWGN noise. Note that the ratio $I_{or}/(I_{oc}+N_o)$ is assumed to be 6 dB for these simulations, where N_o is the thermal noise at the mobile station receiver. We choose to evaluate a 1.2288 Mcps system with a rate 1/4 FEC code since this corresponds to a likely scenario for mixing both IS-95 and cdma2000 channels.

Table 1 . Simulation Parameters

Parameter	Value
Chip Rate	1.2288 Mcps
FEC Code	R 1/4 Convolution Code
Block Interleaving	As specified in [5]
PSTD Sweeping Rate	100 Hz
$I_{or}/(I_{oc}+N_o)$	6 dB
Power Control Command Error Rate	4 %
Power Control Loop Delay	625 μ s
Forward Link Pilot Power as a Fraction of Total Forward Link Power	-7 dB
Symbol Rate	9.6 kbps
Carrier Frequency	2,000 MHz

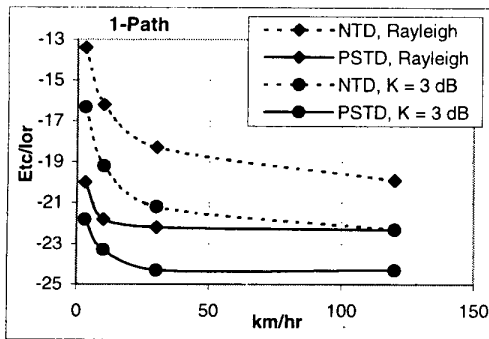


Figure 5. Performance for 1-Path Rayleigh and Ricean Radio Channel

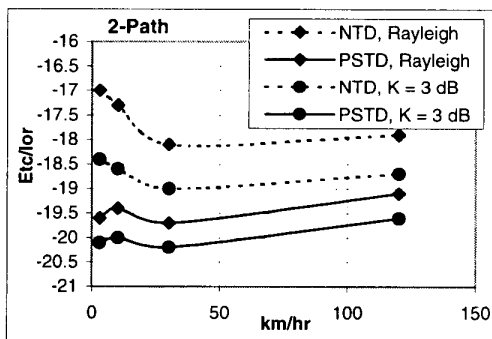


Figure 6. Performance for 2-Path Rayleigh and Ricean Radio Channel

As expected, without transmitter diversity, a larger degree of deterministic power always provides an improvement in link performance. The same also turns out to be true in these simulations for PSTD. For Rayleigh fading environment ($K = -\infty$) and slow mobile velocities (3 km/hr), we find a very large improvement in link performance with respect to a link without transmit diversity. At 3 km/hr we see approximately 6.5 dB and 2.5 dB benefit for 1-path and 2-path channels respectively. The gain lessens as the mobile velocity increases, but the gain is always positive even at high velocities.

For a K factor of 3 dB we observe the same trends as for the case of Rayleigh fading, albeit with smaller gains. In general, we see that the Etc/Ior requirement for a 1% FER is much less variable, with respect to mobile velocity, when PSTD is employed.

IV. Conclusions

This paper has introduced PSTD as it applies to IS-95 and cdma2000 CDMA PCS/Cellular systems. Expressions were developed illustrating the form of the transmitted signal at the base station, and received waveform at the mobile station before and after Rake combining. Some

background was given for performance modeling with respect to the parameters chosen for the computer simulations. The performance of PSTD over AWGN, 1-path and 2-path Rayleigh and Ricean fading channels was compared to transmission with a single basestation antenna. For an AWGN environment a 0.6 dB penalty due to PSTD is observed. However, it is noted that such a channel rarely occurs in practice in the mobile scenario. For all other radio environments considered, PSTD provides considerable performance enhancements, which includes mobile velocities from 3 km/hr to 120 km/hr.

We have summarized the signal processing at the mobile station for IS-95 and cdma2000. As a result of the signal properties, it was shown that PSTD provides benefits for systems which support either or both IS-95 and cdma2000 mobile stations. Furthermore, a cdma2000 system with PSTD can be deployed without a change in the specification of the cdma2000 or IS-95 standard, and is backward compatible with legacy IS-95 mobile terminals.

References

- [1] A. Hiroike, F. Adachi, N. Nkajima, "Combined Effects of Phase Sweeping Transmitter Diversity and Channel Coding," *IEEE Transactions on Vehicular Technology*, Vol. 41, No. 2, May 1992.
- [2] B. D. Su and S. G. Wilson. "Phase Sweeping Transmitter Diversity in Mobile Communications," Proc. VTC 96.
- [3] W-Y. Kuo and M.P. Fitz, "Design and Analysis of Transmitter Diversity Using Intentional Frequency Offset for Wireless Communications," *IEEE Transactions on Vehicular Technology*, Vol. 46, No. 4, Nov. 1997.
- [4] S. Dennett, *The cdma2000 ITU-R RTT Candidate Submission.*, Ver. 18, The Telecommunications Industry Association.
- [5] Telecommunications Industry Association, "Physical Layer Standard for cdma2000 Spread Spectrum Systems," TR45.5.3.1/99.06.17.01, June 1999.
- [6] A. J. Viterbi, A. M. Viterbi, K. S. Gilhousen, E. Zehavi, "Soft Handoff Extends CDMA Cell Coverage and Increases Reverse Link Capacity," *IEEE Journal on Selected Areas in Communication*, Vol. 12., No. 8, October 1994.
- [7] A. J. Viterbi, *CDMA: Principles of Spread Spectrum Communication*, Addison-Wesley, 1995.
- [8] W. C. Jakes, *Microwave Mobile Communications*, Wiley, New York, 1974.
- [9] S. Allpress, and M. A. Beach, "Measurement and Characterisation of the Wideband DS-CDMA Radio Channel," *Proceedings of ICAP '93*, Edinburgh, UK, 1993, IEE Conf. Publ. 370, Part 2, pp. 429-432.