A Novel Transmitting Diversity Scheme for Synchronization of OFDM Systems

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***Abstract*—Synchronization is important in order to correctly recover information for multi-antenna Orthogonal Frequency Division Multiplexing (OFDM) system. In this paper a novel transmitting diversity scheme named as Maximal Channel Power (MaxCP) is proposed. Specifically the channel state information (CSI) is feedback to transmitter firstly and then only one of transmit antennas with the highest channel power is selected. Thus synchronization sequence is only transmitted at the selected antenna. By simulation, it is found that the proposed MaxCP scheme has the better performance than conventional Maximal Ratio Combining (MRC) scheme, in both timing and frequency synchronization for OFDM systems.**

***Index Terms*—OFDM, Selection Transmitting, Timing Synchronization, Frequency Synchronization**

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is one of the most promising techniques for next generation mobile communication systems [1]. By inserting a cyclic prefix (CP) before each transmitted symbol, Inter-Symbol Interference (ISI) caused by multipath channel could be easily avoided. Furthermore, OFDM could be combined with antenna arrays at both transmitter and receiver to achieve the diversity gain and enhance the system capacity over the fading channel, resulting in a Multiple-Input Multiple-Output (MIMO) configuration [2].

Similar to Single-Input Single-Output (SISO) OFDM system, synchronization both in timing and frequency domain is also the first module of a multi-antenna OFDM receiver [3-5]. Timing synchronization deals with frame (coarse) and symbol (fine) timing synchronization while frequency synchronization is to estimate and compensate the carrier frequency offset (CFO) between the transmitter and receiver oscillators. As for the multi-antenna OFDM systems, the receiver diversity schemes have been extensively studied to improve the synchronization performance [6-9].

The receiver diversity schemes, including Selection Combining (SC), Maximal Ratio Combining (MRC) and Equal Gain Combining (EGC) are firstly proposed for synchronization in [6]. In [7] EGC and MRC schemes are compared for CFO estimation and packet detection. Especially, the orthogonal sequences at different transmit antennas are recommended in order to achieve MRC performance, like Golden sequences. In [8-9], the repeated Frank-Zadoff sequences are used at the transmitter in order to simplify maximal ratio combining (MRC) scheme for frequency synchronization of MIMO OFDM wireless LAN systems. Specifically, MRC scheme is designed at the receiver for CFO synchronization [8]. In [9], EGC for packet detection and CFO synchronizations are investigated.

From above summarization, we can find that previous studies mostly concentrate on the receiver diversity schemes. As for transmitting diversity schemes, orthogonal sequences are required in order to achieve MRC gain for CFO estimation. As for timing synchronization, it is seldom studied by previous researchers. So in this paper, we will analyze the timing and frequency synchronization metrics firstly. Then a novel transmitting diversity scheme for timing and frequency synchronization is proposed and compared with conventional MRC scheme for multi-antenna OFDM systems.

The structure of this paper is as follows. In section II the OFDM system model with synchronization is described and the proposed transmitting diversity schemes for timing and frequency synchronization are given in section III. In section IV the simulative results and analysis of diversity schemes are given. Finally the conclusions are achieved.

Notation: boldface letters are used for matrices and vectors. $(\cdot)^T$, $(\cdot)^*$ and $(\cdot)^H$ are transpose, complex conjugate, and Hermitian (conjugate) transpose, respectively. $|\cdot|$ is modulus. $\max(\cdot)$ denotes maximization, and finally, $j=\sqrt{-1}$ and $\delta(n)$ is unit sample function.

II. OFDM SYSTEM MODEL WITH SYNCHRONIZATION

In this section, an OFDM system with N_t transmitter antennas and one receiver antenna is plotted in Figure 1. The synchronization sequence structure proposed by Schimdl and Cox is adopted in this paper and two identical half OFDM symbols are utilized at the transmitter [4]. In order to produce such sequence of antenna m, its frequency domain sequence is defined as $\mathbf{C}_m = \{C_m(0), 0, C_m(1), 0, C_m(2), \ldots C_m(N/2-1), 0\}^T$, which has zeros at odd subcarriers and N is the IFFT size. After IFFT operation, we get the time domain sequence of antenna m as:

$$\begin{bmatrix} \mathbf{c}_m \\ \mathbf{c}_m \end{bmatrix} = \sqrt{2}\mathbf{W}\mathbf{C}_m \tag{1}$$

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Where $\sqrt{2}$ is used to normalize the sequence power for zeros padding and $\mathbf{W}$ is $N \times N$ IFFT transform matrix with element $e^{j\frac{2\pi}{N}nk}$ at nth row and kth column. The half of synchronization sequence is presented as a $N/2 \times 1$ column vector $\mathbf{c}_m$.

After radio channel, the received signal of the first half is written as:

$$\mathbf{y}_1(\Delta F, d) = \frac{1}{\sqrt{N_t}} \sum_{m=1}^{N_t} h_m \mathbf{\Lambda} \mathbf{c}_m(d) + \mathbf{w}_1 \tag{2}$$

Where $\frac{1}{\sqrt{N_t}}$ comes from the parallel transmitted sequences with the normalized power and h_m is the flat fading coefficient from transmit antenna m to the receiver antenna. d is the timing shift of the received signal and ΔF is the frequency offset which is normalized to subcarrier spacing. The target of synchronization is to estimate d and ΔF from the received signal. $\mathbf{\Lambda}$ is a $N/2 \times N/2$ diagonal matrix with element $e^{j\frac{2\pi}{N}\Delta F n}$, $0 \le n \le N/2-1$. $\mathbf{w}$ represents the complex AWGN in the time domain.

As for the second half of received signal, it can be expressed as:

$$\mathbf{y}_2(\Delta F, d) = \frac{e^{j\pi\Delta F}}{\sqrt{N_t}} \sum_{m=1}^{N_t} h_m \mathbf{\Lambda} \mathbf{c}_m(d) + \mathbf{w}_2 \tag{3}$$

So obviously, there is only a phase rotating factor $e^{j\pi\Delta F}$ between $\mathbf{y}_1$ and $\mathbf{y}_2$ and this property will be used to estimate ΔF.

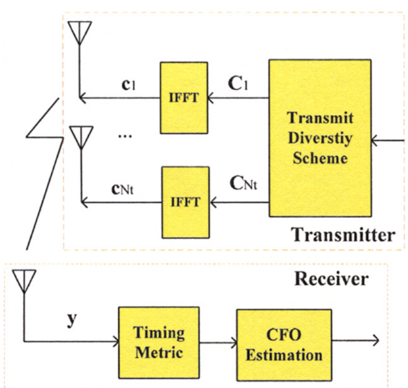

Figure 1 OFDM system model with transmitting diversity

By shifting and correlating the received signals of each antenna with the local reference sequence, we propose to achieve coarse and fine timing simultaneously. In [10], we propose the metric for timing synchronization as:

$$|\gamma_m(d)| = \left| \left(\mathbf{c}_m{}^H \mathbf{y}_1(\Delta F, d)\right)^* \times \left(\mathbf{c}_m{}^H \mathbf{y}_2(\Delta F, d)\right) \right| \tag{4}$$

Where shift value d varies from 0 to $N + L_{CP} - 1$ with CP length as L_{CP}. When the received sequence is matched with the reference sequence, the peak of the timing metric appears. So the frame and symbol start are simultaneously detected as:

$$\hat{d}_m = \arg \max_{0 \le d \le N + L_{CP} - 1} \left(|\gamma_m(d)| \right) \tag{5}$$

After timing synchronization, the exact start of synchronization sequence has been found and carrier frequency synchronization will be implemented. The auto-correlation function of the received training sequence could be used to accomplish CFO estimation as [4]:

$$\Phi(\Delta F, d) = \mathbf{y}_2^H(\Delta F, d)\mathbf{y}_1(\Delta F, d) \tag{6}$$

The timing estimate $\hat{d}$ is forwarded and CFO estimation metric is given as:

$$\Delta\tilde{F} = -\frac{angle\left\{\Phi(\Delta F, \hat{d})\right\}}{\pi} \tag{7}$$

After CFO estimation, CFO is compensated before the signal detection of each antenna, i.e., multiplying the received signal by $\exp\left(-j2\pi n \Delta\tilde{F}/N\right)$ in time domain.

III. The Proposed Transmitting Diversity Scheme for Synchronization of OFDM Systems

In section II, the synchronization metrics are given and we take advantage of transmitting diversity scheme to improve their performance further. In order to derive the new transmitting diversity scheme for synchronization, both the timing and CFO estimation metrics are further analyzed firstly. For simplification of analysis, the flat fading is assumed.

A. Transmitting diversity scheme for timing synchronization

Inserting equation (2) and (3) into equation (4), the timing metric is written as:

$$|\gamma_m(d)| = \left| \left\{R_m(d) + \eta_{m,1}(d)\right\}^* \times \left\{R_m(d) + \eta_{m,2}(d)\right\} \right| \tag{8}$$

Where $\eta_{m,i}(d)$ is the correlation between the ith part of noise and the reference sequence is defined as:

$$\eta_{m,i}(d) = \mathbf{c}_m^H(d)\mathbf{w}_i, \ i = 1, 2 \tag{9}$$

$R_m(d)$ is the signal that we are interested in and expressed as:

$$R_m(d) = \frac{1}{\sqrt{N_t}} \sum_{n=1}^{N_t} h_n \mathbf{c}_m^H(d) \mathbf{c}_n(d) \tag{10}$$

Here we omit frequency offset matrix $\mathbf{\Lambda}$ with the assumption that the normalized frequency offset ΔF is relative small and its effect on the analysis of timing metric could be negligible for simplicity. If the transmitted sequences are orthogonal, i.e. ideal auto-correlation and cross-correlation properties as:

$$\begin{cases} \mathbf{c}_n^H(d)\mathbf{c}_n(d) = N/2\delta(d), & m = n \\ \mathbf{c}_m^H(d)\mathbf{c}_n(d) = 0, & m \ne n \end{cases} \tag{11}$$

Then equation (10) is simplified as:

$$R_m(d) = \frac{N}{2\sqrt{N_t}} h_m \delta(d) \tag{12}$$

Replace equation (8) with equation (9) and (12), then the timing metric changes to:

$$|\gamma_m(d)| = \left| \frac{N}{2N_t} |h_m|^2 \delta(d) + \frac{1}{\sqrt{N_t}} h_m \delta(d) \eta_{m,1}^*(d) \right.$$

$$+\frac{1}{\sqrt{N_t}} h_m^* \delta(d)\eta_{m,2}(d) + \eta_{m,1}^*(d)\eta_{m,2}(d) \Big| \quad (13)$$

where the first term has a peak at both frame and symbol start point d with a coefficient of $\frac{|h_m|^2}{N_t}$, which is proportional to the channel gain from transmit antenna m to the receiver antenna. However, the parallel transmitting of synchronization sequences brings to a power decay coefficient $\frac{1}{N_t}$ at the timing metric.

Considering that timing metric $|\gamma_m(d)|$ is proportional to the channel power from transmit antenna m to the receiver antenna, we propose selection transmitting scheme to choose only one of transmit antennas in order to achieve the diversity gain. If the feedback fading channel coefficient from antenna m is assumed as h_m, the proposed selection scheme is expressed as:

$$M = \arg\left(\max_{1\le m\le N_t} |h_m|^2\right) \quad (14)$$

which is called as maximal channel power (MaxCP) and clearly only the antenna M with the maximal channel power is chosen to transmit the synchronization sequence. When multipath fading is assumed, the channel total power is equal to the power sum of all paths. Compared to equation (2), the transmitted signal is changed to:

$$\mathbf{y}_1(\Delta F, d) = h_M \mathbf{\Lambda c}(d) + \mathbf{w}_1 \quad (15)$$

Similar to the previous analysis, the timing metric of MaxCP is derived as:

$$|\gamma(d)|_{MaxCP} = \Big| \frac{N}{2} |h_M|^2 \delta(d) + h_M \delta(d)\eta_{M,1}^*(d)$$
$$+ h_M^* \delta(d)\eta_{M,2}(d) + \eta_{M,1}^*(d)\eta_{M,2}(d) \Big| \quad (16)$$

For comparison, MRC scheme for timing estimation is also given as [6]:

$$|\gamma(d)|_{MRC} = \sum_{m=1}^{N_t} |\gamma_m(d)| \quad (17)$$

So $|\gamma(d)|_{MRC}$ is a sum of timing metrics for all transmit sequences and its gain is approximately proportional to the channel power sum of all transmit antennas as:

$$|\gamma(d)|_{MRC} \propto \frac{1}{N_t} \sum_{m=1}^{N_t} |h_m|^2 \quad (18)$$

Compared equation (16) with equation (18), the gain of MaxCP is up to the maximal channel gain while MRC gain is decided by the average of channel gains. So theoretically, the timing synchronization with MaxCP scheme has the better performance than MRC scheme. Furthermore, the payment to achieve MRC diversity gain for timing synchronization is that we need to implement N_t metric calculations with correlation operations and this obviously leads to the increase of complexity. So in order to decrease the computation complexity, Frank-Zadoff sequence and its cyclic shifted sequences are used for CFO estimation [8]. The disadvantage of Frank-Zadoff sequence is that its timing range will decrease to $0 \le d \le (N/N_t) - 1$ and the extra sum operations for timing metric are also needed in order to combine the multiple timing peaks. However, the proposed MaxCP allows calculating timing metric one time and decreases the computational complexity.

As for the feedback channel information needed by MaxCP, channels of uplink and downlink are reciprocal for TDD system and the downlink channel state information (CSI) could be used to select antenna in terminal. Then only the index of chosen antenna is forwarded and synchronization sequence is transmitted on the selected antenna for uplink. So MaxCP is preferred for TDD systems with multiple transmit antennas.

B. Transmitting diversity scheme for CFO Estimation

Inserting equation (2) and (3) into equation (6), the CFO estimation metric is:

$$\Phi(\Delta F, d) = \Psi(\Delta F, d) + \varsigma(\Delta F, d) \quad (19)$$

Where $\varsigma(\Delta F, d)$ is the noise polluted useless signal and written as:

$$\varsigma(\Delta F, d) = \frac{e^{-j\pi\Delta F}}{\sqrt{N_t}} \sum_{m=1}^{N_t} h_m^* \mathbf{c}_m^H(d) \mathbf{\Lambda}^H \mathbf{w}_1$$
$$+ \frac{1}{\sqrt{N_t}} \sum_{n=1}^{N_t} h_n \mathbf{w}_2^H \mathbf{\Lambda c}_n(d) + \mathbf{w}_2^H \mathbf{w}_1 \quad (20)$$

$\Psi(\Delta F, d)$ is the useful signal for CFO estimation as:

$$\Psi(\Delta F, d) = \frac{e^{-j\pi\Delta F}}{N_t} \sum_{m=1}^{N_t} \sum_{n=1}^{N_t} h_m^* h_n \mathbf{c}_m^H(d) \mathbf{\Lambda}^H \mathbf{\Lambda c}_n(d) \quad (21)$$

Considering that $\mathbf{\Lambda}^H \mathbf{\Lambda} = \mathbf{I}_{N/2}$ and the orthogonality of the transmitted sequences given in equation (11), then equation (21) is gotten as:

$$\Psi(\Delta F, d) = \frac{e^{-j\pi\Delta F}}{N_t} \sum_{m=1}^{N_t} |h_m|^2 \delta(d) \quad (22)$$

So after accurate timing synchronization, the useful signal of CFO estimation metric contains a phase rotating factor $e^{-j\pi\Delta F}$ directly related to ΔF and this property is used to estimate CFO by equation (7). Another important fact in equation (22) is that when orthogonal synchronization sequences are employed at transmitter, the useful signal for CFO estimation is up to the average of channel powers. That means MRC diversity gain is achieved for CFO estimation and its performance is proportional to the average of channel powers.

The proposed MaxCP scheme is to choose one of transmit antennas with the highest channel gain. If only the antenna M with the maximal channel power is chosen to transmit the synchronization sequence, the diversity gain of MaxCP for CFO estimation is approximated as:

$$\Psi_{MaxCP}(\Delta F, \mu) \propto \max_{1\le m\le N_t} |h_m|^2 \quad (23)$$

So we can come to the same conclusion as timing synchronization that the gain of MaxCP for CFO estimation is up to the maximal channel gain while MRC gain is decided by the average of channel gains.

IV. SIMULATION RESULTS AND ANALYSIS

The performance of the transmitting antenna diversity schemes is investigated by simulation. The carrier frequency is 2GHz; system bandwidth is 5MHz; sampling frequency is 7.68MHz, and the number of subcarrier is 512. Therefore, the subcarrier spacing, useful symbol duration, CP duration and OFDM symbol duration are 15kHz, 66.7us, 16.7us, and 83.4us, respectively. Assuming that a frame is composed of 4 OFDM symbols, of which the first symbol is synchronization sequence (Frank-Zadoff codes with a length of 256). Thus the time length of one frame is 0.33ms. The channel power delay profile is 3GPP Pedestrian B (PB) 3km/h and Vehicular A (VA) 120km/h [11] and the channel impulse response (CIR) is produced by spatial channel model (SCM) [12].

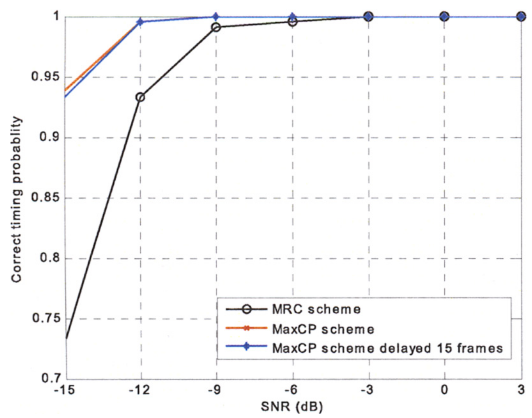

Figure 2 Correct timing probability with 2×1 antennas in PB 3km/h

In Figure 2, the correct timing probability is given and the antenna configuration is 2×1. For comparison, the performance of MRC scheme is also plotted. It can be found that MaxCP scheme achieves obvious performance gain compared to MRC scheme. The reason is that gain of selection scheme (MaxCP) is proportional to the maximal channel gain while MRC is decided by the average channel gains. So MaxCP has more performance gain compared to MRC, i.e. $\max_{1\le m\le N_t}|h_m|^2 \ge \frac{1}{N_t}\sum_{m=1}^{N_t}|h_m|^2$. Furthermore, the delay of CSI is introduced in simulation and the delay period is 5ms (15 frames). It can be observed that MaxCP scheme with delay has negligible performance degradation compared to that without delay. The reason is that the Doppler shift f_d of 3km/h is 6Hz and its coherence time is $\frac{9}{16\pi f_d} = 32ms$. So the feedback CSI with 5ms delay is smaller than coherence time and MaxCP scheme with 5ms delay works well.

After timing synchronization, the start of synchronization sequence is forwarded to CFO estimation. In Figure 3, the mean square error (MSE) of CFO estimation is given and the antenna configuration is 2×1. It can be observed that MaxCP scheme for CFO estimation achieves near 2dB gain compared to MRC scheme when MSE is equal to 10^{-4}.

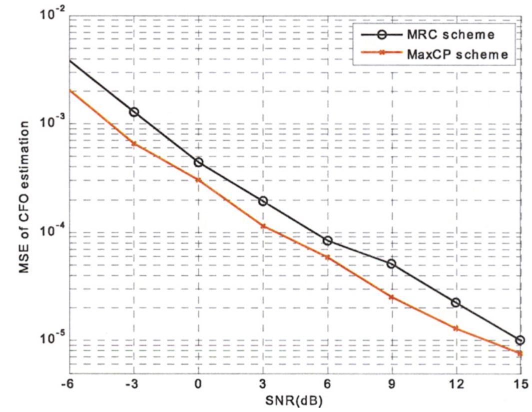

Figure 3 MSE of CFO estimation with 2×1 antennas in PB 3km/h

In Figure 4, correct timing probability with the different transmit antennas are compared in VA120km/h. When the transmit antenna number is increaseds to 4, the performance of MaxCP is further improved compared to that of two transmit antennas. The reason is that more transmit antennas, more chance that MaxCP scheme can choose the higher channel power gain. However, the antenna number is a tradeoff between the performance and complexity. Furthermore, the delay of CSI is introduced in simulation and the delay period increases from 2 frames to 3 frames. It can be observed that the performance of MaxCP scheme degrades obviously compared to that without delay. The reason is that the Doppler shift f_d of 120km/h is 222Hz and coherence time is $\frac{9}{16\pi f_d} = 0.806ms$, which is smaller than 3 frames. So when the feedback CSI is larger than coherence time, MaxCP scheme is not recommended for its performance degradation.

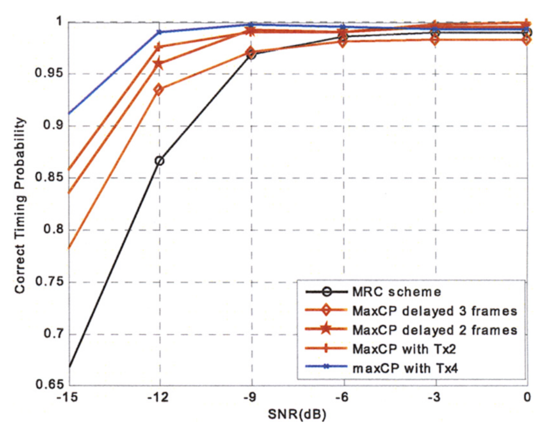

Figure 4 Correct timing probability with different transmitter antenna number and delay in VA 120km/h

V. THE CONCLUSIONS

In this paper, we analyze the timing and frequency synchronization metrics in fading channels firstly. Then we propose a novel selection transmitting scheme (MaxCP). By feedback CSI, only one of transmit antennas with the highest channel power is selected and synchronization sequence is transmitted at the selected antenna. Through theoretical analysis and simulation, it has been proved that MaxCP has the better performance than MRC. Furthermore, the multiple timing metric calculations is avoided by MaxCP while MRC scheme needs more computation complexity. However, MaxCP should work with the feedback CSI under coherence time. So MaxCP is recommended for TDD based OFDM systems in low mobile speed because of its better performance and low complexity.

REFERENCES

[1] R. D. J. Van Nee, and R. Prasad, "OFDM for wireless multimedia communications," Artech House, Incorporated, Jan. 2000

[2] G. L. Stuber, J. R. Barry, S. W. McLaughlin, Y. Li, M. A. Ingram, and T.G. Pratt, "Broadband MIMO-OFDM wireless communications," Proc. IEEE, vol. 92, issue. 2, Feb. 2004, pp: 271-294

[3] J.J. van de Beek, M. Sandell, and P. O. Borjesson, "ML estimation of time and frequency offset in OFDM systems," IEEE Trans. Signal Processing, vol. 45, Jul., 1997 , pp:1800 – 1805

[4] T.M. Schmidl, and D.C. Cox, "Robust frequency and timing synchronization for OFDM," IEEE Trans. on Communications, vol. 45, no. 12, Dec.1997, pp: 1616 -1621

[5] F. Tufvesson, O. Edfors, and M. Faulkner, "Time and frequency synchronization for OFDM using PN-sequence preambles," IEEE 50th Vehicular Technology Conference, vol.4, Sept. 1999, pp:2203 - 2207

[6] A. Czylwik, "Synchronisation for systems with antenna diversity," IEEE 50th Vehicular Technology Conference, vol. 2, Sept. 1999, pp. 728-732

[7] M. Schellmann, V. Jungnickel, and C.V.Helmolt, "On the value of spatial diversity for the synchronization in MIMO-OFDM systems," IEEE 16th Personal, Indoor and Mobile Radio Communications (PIMRC), 2005. vol.1,Sept. 2005, pp:201-205

[8] T.C.W. Schenk, and A. V Zelst, "Frequency synchronization for MIMO OFDM wireless LAN systems," IEEE 58th Vehicular Technology Conference. vol.2, Oct. 2003, pp:781-785

[9] T.J. Liang, X. Li, R. Irmer, and G. Fettweis, "Synchronization in OFDM-based WLAN with transmit and receive diversities", IEEE 16th. Personal, Indoor and Mobile Radio Commun. (PIMRC), vol.2, 2005, pp: 740-744

[10] H. Su, J. H. Zhang, and P. Zhang, "Cell search algorithms for the 3G long term evolution", Journal of Beijing University of Posts and Telecommunications, vol. 14, 2007, pp:33-36

[11] ITU-R Rec. M 1225, "Guidelines for Evaluation of Radio Transmission Technologies (RTTs) for IMT-2000", 1997.

[12] 3GPP TR 25.996: Spatial Channel Model for Multiple Input Multiple Output (MIMO) simulations, V6.1.0 (2003-09).