

**APPARATUS AND METHOD FOR ESTIMATING TIMING CLOCK OFFSET IN
A WIRELESS COMMUNICATIONS SIGNAL**

5 The present invention relates to an apparatus and method for estimation of a timing clock offset component of a multiple input multiple output orthogonal frequency division multiplexing (MIMO-OFDM) wireless communications signal. In particular, the invention relates to providing an estimate of the timing clock offset component from an initial timing clock offset estimate.

10 MIMO-OFDM technology is extensively employed in IEEE802.11n based high-speed Wireless Local Access Networks (WLAN), mobile systems with Worldwide Interoperability for Microwave Access (WiMAX), and Digital Video Broadcasting (DVB) systems. It is well known that OFDM is robust in frequency selective fading channels with a relatively low implementation cost and high
15 bandwidth efficiency. Moreover, MIMO takes advantage of multipath propagation to increase throughput, range/coverage, and reliability. By transmitting multiple signals containing different information streams over the same frequency channel, MIMO provides a means of doubling or tripling spectral efficiency. The combination of MIMO and OFDM techniques provides
20 low-cost implementation particularly for high data rate communications.

However OFDM is known to be vulnerable to synchronisation errors, which can cause phase rotation, inter-carrier interference (ICI) and degrade system performance. Technical publications discussing this issue include, for example,
25 Michael Speth, Stefan A. Fechtel, Gunnar Fock, and Heinrich Meyr, "Optimum Receiver Design for Wireless Broadband Systems Using OFDM—Part I", *IEEE Trans. On Comm.* Vol. 47, No.11, November 1999, pp. 1668-1677, and Hlaing Minn, Vijay K. Bhargava, and Khaled Ben Letaief, "A Robust Timing and Frequency Synchronisation for OFDM Systems", *IEEE Trans. On Wireless
30 Comm.*, Vol.2, No.4, July 2003, pp. 822-839. In MIMO-OFDM transmission systems, the synchronisation tasks include carrier recovery, phase noise suppression and clock timing recovery.

- In MIMO-OFDM based WLAN systems, the processing of the MIMO-OFDM wireless communications signal preamble is sufficient for initial synchronisation of the MIMO-OFDM receiver as discussed in the Speth et al and Minn et al publications noted above. However, solely initial synchronisation may not be sufficient due to residual carrier frequency offset (CFO) and timing clock offset (TO) in the system. Though residual CFO/TO can be very small after coarse CFO compensation, accumulated phase rotation and timing drift in the signal can still deteriorate system performance. Consequently, there is a need for an efficient CFO/TO tracking scheme to compensate dynamically for such phase drift. One known method for this is to use signal pilot subcarriers, i.e., subcarriers containing known data, which are inserted into the signal data symbols.
- A few papers consider the timing drift recovery for MIMO-OFDM systems where CFO/TO estimation is considered at very high-level and only as a simple extension in OFDM systems. Examples of such works include Seok Ho Won, Deuk-Su Lyu, and Hyeong Jun Park, "Physical Layer Implementation and Evaluation of Multiple Input Multiple Output—Orthogonal Frequency Division Multiplexing (MIMO-OFDM) system", *IEEE Proc. Of International Conference on Communication Technology*, ICCT 2003, Vol. 2, April 9-11, pp. 1348-1352; Chi-Yeh Yu, Zih-Yin Ding, and Tzi-Dar Chiueh, "Design and Simulation of a MIMO OFDM Baseband Transceiver for High Throughput Wireless LAN", *IEEE proc. Of 2004 Asia-Pacific Conference on Circuit and Systems*, Dec 6-9, 2004, pp. 205-208; and Allert van Zelst, and Tim C.W.Schenk, "Implementation of a MIMO OFDM-Based Wireless LAN System", *IEEE Trans on Signal processing*, Vol. 52, No. 2, February 2004, pp. 483-494. A noncoherent delay-locked loop based sampling clock recovery scheme is proposed by Baoguo Yang, Khaled Ben Letaief, Roger S. Cheng, and Zhigang Cao, "Timing Recovery for OFDM Transmission", *IEEE Journal of Selected Areas in Communications*, Vol.18, No.11, Nov., 2000, pp. 2278-2291 for conventional OFDM systems. This method involves an early and late correlation of the received pilot subcarrier and the known pilots. Timing error is extracted from the noncoherent

combination of correlation outputs. This method provides some flavour of tracking the timing drift caused by clock offset. However, the acquisition of this method is slow and tracking performance is poor, particularly in low SNR environments and multipath fading channels due to the poor accuracy in its timing error estimation. A jointly weighted least squares (WLS) estimation of carrier frequency offset and sampling frequency offset in OFDM systems is proposed also for OFDM systems in Pei-yun Tsai, Hsin-Yu Kang and Tzi-Dar Chiueh, "Joint Weighted Least Squares Estimation of Frequency and Timing Offset for OFDM Systems over Fading Channels", *IEEE Trans. On Vehicular Technology*, Vol.54, Issue 1, Jan. 2005, pp. 211-223. The disclosed algorithm can achieve near the Cramer-Rao low-bound in the variance of estimation errors for conventional SISO (single input single output) OFDM systems. However, the closed-form expressions of the optimal weighting factors are difficult to derive for a MIMO-OFDM receiver due to complicated MIMO channel and spatial correlation. Moreover, its complexity is very high and it is not suitable for practical application.

The invention is defined in the independent claims. Some optional features of the invention are defined in the dependent claims.

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Initial TO estimates may be seriously affected by coloured noise arriving from MIMO detection (eg, from the MIMO detection matrix $\mathbf{G}(m)$), and the noise power can vary as a function of channel. Therefore, performance can be greatly enhanced by utilising post-linear MIMO detection signal-to-noise ratio (SNR) characteristics.

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Two-dimensional post-linear MIMO detection SNR characteristics for a specific pilot subcarrier and a specific spatial stream may be used to weight an initial TO estimate for improved or enhanced estimation.

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Some apparatuses perform a weighted combination of a plurality of estimates, say for all spatial streams and all subcarriers of the MIMO-OFDM signals. Thus, the weighted combination of this plurality of estimates instead of a simple

averaging of estimates may be employed to provide enhanced accuracy in timing drift tracking.

5 Some apparatuses base the initial TO estimate on a multi-tier correlation. The use of a two-tier correlation has been found to be particularly advantageous. A two-tier correlation provides the advantage that the initial TO estimate is (at least substantially) independent of carrier frequency offset (CFO) and phase noise (PN). Thus, the effect of CFO/PN on TO estimation may be at least reduced or even eliminated and estimation accuracy may be significantly improved. Further, without the interplay of CFO and PN, the complexity of the TO estimator may be significantly reduced, when compared with the conventional joint CFO/TM estimation method disclosed in, for example, the Pei-yun Tsai et al paper noted above.

15 Some apparatuses generate the weighting factor from derived signal-to-noise ratio characteristics for a positive and negative pair of corresponding subcarriers. The derived weighting factor is based on the smaller or lesser value of the signal-to-noise ratio characteristics of the pair. This means that in the cross-correlation of two pilot subcarriers with different signal-to-noise ratio characteristics, the estimation reliability is dominated by the less reliable data. In other words, when one of pilot subcarriers of the pair has lower SNR, the pair should contribute less (i.e., smaller weighting factor) to the overall TO estimator.

25 Apparatuses implementing the invention can be used in conjunction with a carrier frequency offset/phase noise-independent timing offset tracking and compensation method for MIMO-OFDM systems implementing a third-order PLL (Phase Lock Loop) as disclosed in commonly-assigned Singapore Patent Application Number 200606234-3, the content of which is hereby incorporated by reference in its entirety. Such an implementation forms a timing recovery loop for MIMO-OFDM receivers which can achieve fast acquisition and stable tracking.

Thus, a method providing improved accuracy in MIMO-fading channels influenced by coloured noise is disclosed. Moreover, disclosed methods also have an attractive low complexity compared to conventional WLS methods for OFDM receivers.

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The present invention will now be described, by way of example only, and with reference to the accompanying drawings in which:

Figure 1 is a block diagram illustrating an apparatus for estimating a timing clock offset component of a MIMO-OFDM wireless communications signal;

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Figure 2 is a block diagram illustrating a more detailed view of the timing clock offset estimator of the apparatus of Figure 1;

Figure 3 is a block diagram illustrating a detailed view of an alternative arrangement for the estimator of Figures 1 and 2;

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Figure 4 illustrates process flow diagrams for the steps of an algorithm for estimating a timing clock offset component of a MIMO-OFDM wireless communication signal in the apparatus of Figures 1, 2 and 3;

Figure 5 is a graph illustrating the packet error rate (PER) comparison of the apparatuses of Figures 1, 2 and 3 and that of a conventional estimator in channel D; and

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Figure 6 is a graph illustrating the bit error rate (BER) comparison of the apparatuses of Figures 1, 2 and 3 and that of a conventional estimator in channel D.

25 Referring now to Figure 1, a first apparatus 10 for estimating a timing clock offset component of a MIMO-OFDM wireless communications signal will now be described. The apparatus 10 of Figure 1 comprises two receiver antennas (not shown), but the configuration of two antennas can easily be extended to other MIMO configurations employing higher numbers of antennas. Time-domain signals received at the receiver antennas are first input 11a, 11b to Fast Fourier Transform (FFT) modules 12a, 12b which convert the received time domain signals to the frequency domain. The converted frequency-domain signals comprise frequency-domain high throughput (HT) long preambles which

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are output by FFT modules 12a, 12b and are received at a channel estimation module 14 which generates a MIMO channel frequency response estimate matrix. The obtained channel frequency response estimate matrix is output both to signal-to-noise ratio (SNR) generator 16 and MIMO detector 18. SNR generator 16 operates to obtain a two-dimensional SNR characteristic – as will be described below – and a first output of SNR generator 16 is input as a first input 20a to timing clock offset (TO) estimator 20. An output of MIMO detector 18 is input as a second input 20b to TO estimator 20. TO estimator 20 obtains a TO estimate – as will be described in detail below – and the output of TO estimator 20 is supplied optionally to the third-order timing recovery loop made up of modules 22, 24, 26, phase rotation module 28 and FFT window controller module 30, described in detail in SG200606234-3, as noted above.

Also shown in Figure 1 is a CFO/PN tracking estimator 32 and demapper 34, described in commonly-assigned Singapore Patent Application Number 200704494-4 (agent's reference SP7930), the content of which is hereby incorporated by reference in its entirety.

Figure 2 shows components in a more detailed view of the timing clock offset estimator of Figure 1. When compared with Figure 1, like components are denoted by like reference numerals. The apparatus 10 receives frequency-domain subcarrier signals from FFT stages 12a,...,12r for each of N_r receiver antennas. MIMO detector 18 receives the frequency-domain signals from FFT stages 12a, ..., 12r. Suppose that the transmitter has N_t antennas. The output of MIMO detector stage 18 comprises $2J \cdot N_t$ ($-J, \dots, -1, 1, \dots, J$) detected pilot subcarriers which are supplied to $J \cdot N_t$ cross-correlation stages 40a,...,40 $_{J \cdot N_t}$ where the detected pilot subcarriers are pairwise cross-correlated to obtain initial TO estimates.

The subcarriers of the MIMO-OFDM wireless communications signal may be defined by a set of indices, the set of indices having positive and negative values (the values $-J, \dots, -1, 1, \dots, J$ noted above) in the apparatus of Figure 2,

the multi-tier correlation is provided as a two-tier correlation by correlator 40, 44. The first-tier of the multi-tier correlation is a cross-correlation between a corresponding pair of subcarriers in first correlations stage 40. One example of the corresponding pair of subcarriers is a positive and negative pair of subcarriers with indices $m, -m$. That is the cross-correlation is carried out between a pair of received subcarriers of indices m and $-m$.

The outputs B_l of cross-correlation stage 40 are first fed to delay stages 42 and secondly fed directly to second correlation stage 44. Second correlation stage 44 provides the second tier or the two-tier correlation of Figure 2. The second tier is an auto-correlation of the output B_l of first-tier correlation stage 40 with a delayed version of itself B_{l-1} derived through delay stage 42. In the example of Figure 2, the delay length is set to be one OFDM symbol length l . The output of auto-correlation stage 44 is supplied to the timing clock offset estimator 20, which comprises weighted combination stage 46 and weighted TO estimate stage 48 as will be described in greater detail below. A second input to TO estimator 20 (or, for example, to weighted combination stage 46) is output from post-detection signal-to-noise ratio characteristic generator 16. The operation of signal-to-noise ratio characteristic generator 16 is also described in greater detail below. The output 50 of weighted TO estimator stage 48 comprises the TO component estimate.

Therefore, it can be seen that the timing clock offset estimator of Figure 2 is configured to generate a weighting factor from two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics and to apply the weighting factor to an initial timing clock offset estimate thereby to estimate the timing clock offset component. As a further alternative, a plurality of weighting factors can be derived for a plurality of subcarriers and a plurality of spatial streams of the MIMO-OFDM signal to be applied to a plurality of initial timing clock offset estimates, thereby to estimate the timing clock offset for the MIMO-OFDM signal. This is explained with respect to equation (9) below.

In the apparatus of Figure 2, the weighting factor(s) is/are applied to the initial

timing clock offset estimator at weighted combination stage 46 to derive the timing clock offset component as output 50 of stage 48. In the arrangement of Figure 2, the correlator is made up of stages 40 and 44. The timing clock offset estimator is made up of stages 46, 48. In the apparatus of Figure 2, the initial
5 timing clock offset estimate is derived from the output of the second-tier correlation stage 44 as described with respect to equation (8) below.

Figure 3 shows the components of a detailed view of an alternative arrangement for the timing clock offset estimator of Figure 1. Again, and when
10 compared with Figures 1 and 2, like components are denoted by like reference numerals. The apparatus 10 receives a frequency-domain subcarrier from FFT stages 12a,...,12r for each of N_r receiver antennas. MIMO detector 18 receives the frequency-domain signals from FFT stages 12a,...,12r. Again, MIMO detector stage 18 outputs $2J \cdot N_t$ pilot subcarriers which are supplied to $J \cdot N_t$
15 cross-correlation stages 40a, 40J·Nt where the detected pilot subcarriers are pairwise cross-correlated to obtain TO estimates.

Again, the subcarriers are defined by a set of indices having positive and negative values ($\pm 1 \dots \pm J$). In the apparatus of Figure 3, the multi-tier
20 correlation provided by correlator 40, 44 is also a two-tier correlation. A first-tier correlation is a cross-correlation between a corresponding pair of subcarriers and first correlation stage 40. An example of the corresponding pair of subcarriers is a positive and negative pair of subcarriers. That is, the cross-correlation is carried out between a received pilot subcarrier of index m and a
25 received pilot subcarrier with the index $-m$.

In the alternative arrangement of Figure 3, the order of the second-tier correlation and the weighted combination is changed. The output of cross-correlator 40 is first fed to weighted combination stage 46 where the weighting
30 factors derived from the two-dimensional post-linear MIMO detection signal-to-noise ratio characteristic generator 16 is applied. The output of weighted combination stage 46 is a weighted first-stage cross-correlation, comprising the initial TO offset B_i . B_i is fed both to delay stages 42 and directly to second

correlation stages 44. The second correlation stage 44 provides the second-tier of the two-tier correlation of Figure 3. The second tier is an auto-correlation of the output B_l of weighted combination stage 46 with a delayed version of itself B_{l-1} derived through delay stage 42. In the example of Figure 3, the delay
5 length is also said to be one OFDM symbol length, l . The output of auto-correlation stage 44 is fed to TO estimate stage 48, the output 50 of which comprises an estimate of the TO component.

Thus, it is seen from Figure 3 that the apparatus 10 of Figure 3 provides an
10 alternative method with similar performance of estimating the timing clock offset component. In the apparatus of Figure 3 the initial timing clock offset estimate is derived from the first tier in stage 40 of the multi-tier correlation as described with respect to equation (12) below. Weighting factor(s) are applied to the initial timing clock offset estimate output from first correlator stage 40 to derive the
15 timing clock offset estimate through correlator stage 44 and timing offset estimate stage 48.

The processing of the signals in the apparatuses of Figures 1, 2 and 3 are explained as follows:

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Matrix manipulation transform operators used in the following discussion are given as follows:

- $(\dots)^{-1}$ denotes matrix inverse transform operation
- $(\dots)^T$ denotes matrix transpose transform operation
- 25 • $(\dots)^H$ denotes matrix conjugate and transpose transform operation

In a MIMO-OFDM based WLAN system, the transceiver signals may be expressed in the frequency domain using relatively straightforward matrix algebra. Considering a $N_t \times N_r$ MIMO-OFDM system, where N_t and N_r are the
30 numbers of transmitter and receiver antennas respectively, the $N_r \times 1$ received signal vector on the k -th subcarrier may be written as:

$$\mathbf{y}(k) = \mathbf{H}(k)\mathbf{x}(k) + \mathbf{n}(k) \quad (1)$$

Here $\mathbf{y}(k) = (y_1(k), y_2(k), \dots, y_{N_r}(k))^T$, and $\mathbf{x}(k)$ is the $N_t \times 1$ signal vector transmitted from N_t transmitter antennas on the k -th subcarrier, which may be written as

$$\mathbf{x}(k) = (x_1(k), x_2(k), \dots, x_{N_t}(k))^T$$

- 5 The channel frequency response of the k -th subcarrier from the j -th transmitter antenna to the i -th receiver antenna may be denoted by $H_{i,j}(k)$, and

$$\mathbf{H}(k) = \begin{pmatrix} H_{1,1}(k) & H_{1,2}(k) & \dots & H_{1,N_t}(k) \\ H_{2,1}(k) & H_{2,2}(k) & \dots & H_{2,N_t}(k) \\ \vdots & \vdots & \dots & \vdots \\ H_{N_r,1}(k) & H_{N_r,2}(k) & \dots & H_{N_r,N_t}(k) \end{pmatrix}$$

and $\mathbf{n}(k) = (n_1(k), n_2(k), \dots, n_{N_r}(k))^T$, is a spatially independent Gaussian noise vector for all receiver chains.

- 10 In the above system model, ideal synchronisation in the OFDM receiver has been assumed. However, there is usually a carrier frequency offset and timing clock offset between the receiver and transmitter due to the mismatch between the transmitter and receiver oscillators or the channel Doppler frequency shift. This is true also for the receiver sampling clock. There is also usually a
15 sampling frequency offset between transmitter and receiver side.

- In practice, there are multiple radio chains in the MIMO-OFDM transmitter and receiver sides respectively, and these multiple radio chains share the same frequency synthesiser such that multiple radio chains in the transmitter or
20 receiver side are synchronised respectively. Denote the CFO as Δf , and the normalised TO as $\eta = (T' - T)/T$, where T and T' are the nominal sampling period and the actual sampling period at the receiver. Following the system analysis method in Pei-yun Tsai, Hsin-Yu Kang and Tzi-Dar Chiueh, "Joint Weighted Least Squares Estimation of Frequency and Timing Offset for OFDM

Systems over Fading Channels”, *IEEE Trans. On Vehicular Technology*, Vol.54, Issue 1, Jan. 2005, pp. 211-223, and “EWC HT PHY Specification”, *Enhanced Wireless Consortium Publication*. V1.27, December 23rd, 2005 (for the synchronisation model for MIMO-OFDM systems), the l -th received OFDM symbol suffering from the synchronisation error can be derived as shown in Equation (2) below.

It is assumed that the information signals are encoded and modulated to form an OFDM symbol $\mathbf{x}_l(k)$ in the frequency domain. After IFFT transformation and pass-band modulation, the time-domain transmitted signals pass through a MIMO fading channel. The l -th received baseband OFDM symbol after sampling with sampling clock T and removing the guard interval, may be represented by N samples. The demodulation of the received samples via an N -point FFT yields the received OFDM symbols in the frequency domain

$$\mathbf{y}_l(k) = \exp(j[2\pi\Delta f(IN_s + N_g)(1+\eta)T + \varphi_l]) \exp\left(j\frac{2\pi k(IN_s + N_g)\eta}{N}\right) \mathbf{H}(k)\mathbf{x}_l(k)s(\pi\phi_{kk}) + \mathbf{ICI}_l(k) + \mathbf{n}_l(k) \quad (2)$$

where φ_l is phase noise; N is the number of FFT points; N_g and N_s are samples in the guard interval and the whole OFDM symbol including guard interval respectively.

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Equation (2) shows that the distortion of the k -th subcarrier data caused by synchronisation error includes phase rotation and the magnitude scaling, $s(\pi\phi_{kk})$, respectively. Moreover, the synchronisation error destroys the orthogonality between subcarriers resulting in ICI, which is the function of $s(\pi\phi_{pk})$. As set out in Pei-yun Tsai, Hsin-Yu Kang and Tzi-Dar Chiueh, “Joint Weighted Least Squares Estimation of Frequency and Timing Offset for OFDM Systems over Fading Channels”, *IEEE Trans. On Vehicular Technology*, Vol.54, Issue 1, Jan. 2005, pp. 211-223, the definition of $s(\pi\phi_{pk})$ may be expressed as:

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$$s(\pi\phi_{pk}) = \frac{\sin(\pi\phi_{pk})}{N \sin(\frac{\pi\phi_{pk}}{N})}, \text{ and}$$

$$s(\pi\phi_{kk}) = s(\pi\phi_{pk}) \text{ in the case of } p = k,$$

where p and k are subcarrier indexes and $\phi_{pk} = (1 + \eta)(\varepsilon + p) - k$, $\varepsilon = \Delta f \cdot T$.

When η and ε are small, $s(\pi\phi_{kk})$ is close to 1 and $s(\pi\phi_{pk})$ is near zero, and the magnitude distortion and the ICI term may be ignored. Thus, a phase rotation occurs when the subcarrier sample $x_l(k)$ is transmitted. The rotated phase is such that

$$\theta_l(k) = 2\pi\Delta f(lN_s + N_g)(1 + \eta)T + \frac{2\pi k}{N}(lN_s + N_g)\eta + \varphi_l \quad (3)$$

The first component is the inter-play of carrier and sampling frequency offsets, and the second component is contributed by sampling frequency offset exclusively. In the case where only timing clock offset exists, the phase rotation is proportional to the subcarrier index as well as the symbol index.

In order to take advantage of its properties as one of the most efficient methods of implementing a spatial multiplexing receiver in practical MIMO systems, linear MIMO detection is employed. This is particularly true for those systems with a large number of transmitter and receiver antennas. Linear receivers utilise matrix multiplication to separate the data streams transmitted simultaneously, as given by:

$$\begin{aligned} \hat{\mathbf{x}}(k) &= \mathbf{G}(k)\mathbf{y}(k) \\ &= \mathbf{G}(k)\mathbf{H}(k)\mathbf{x}(k) + \mathbf{G}(k)\mathbf{n}(k) \end{aligned} \quad (4)$$

where $\hat{\mathbf{x}}(k)$ is an estimate of the transmitted symbol vector; and detection matrix $\mathbf{G}(k)$ can be computed according to a zero-forcing (ZF) or minimum mean square error (MMSE) criterion. In this example, the detection is performed assuming that $\mathbf{G}(k)\mathbf{H}(k) = \mathbf{I}$, where $\mathbf{I}$ is an identity matrix. When using MMSE, $\mathbf{G}(k)$ is calculated from, as discussed in Catherine Z.W. Hassell Sweatmean, John S. Thompson, Bernard Mulgrew and Peter M. Grant, "A

comparison of Detection algorithms including BLAST for wireless communication using multiple antennas", *Proc. of IEEE PIMRC 2000*, Vol.1. pp. 698-703:

$$\mathbf{G}(k) = (\mathbf{H}^H(k)\mathbf{H}(k) + N_0 \times \mathbf{I})^{-1} \mathbf{H}^H(k) \quad (5)$$

5 here N_0 is noise spectral density.

If, say, $2J$ pilots are inserted among N signal subcarriers, the pilot subcarrier indexes are given by $m = -1, \dots, -J+1, -J, 1, 2, \dots, J$. Here, all positive and negative pilot pairs $\{-m, m\}$ are assumed to have equal distance of K ; that is, the distance between the subcarrier pair having indices -1 and 1 is K and the distance between the subcarrier pair having indices $-J$ and J is K . When residual CFO/TO is small, $s(\pi\phi_{kk})$ is close to 1. In light of these considerations, the detected pilot subcarriers in the l -th OFDM symbol incorporating CFO/TO and phase noise can be represented as:

$$\hat{\mathbf{x}}_l(m) = \exp(j\theta_l(m))\mathbf{x}_l(m) + \mathbf{G}(m)\mathbf{n}_l(m) \quad (6)$$

The above equation can be rewritten as the following $2J \cdot N_l$ independent equations

$$\begin{cases} \hat{x}_{l,1}(m) = \exp(j\theta_l(m))x_{l,1}(m) + \xi_{l,1}(m) \\ \vdots \\ \hat{x}_{l,N_l}(m) = \exp(j\theta_l(m))x_{l,N_l}(m) + \xi_{l,N_l}(m) \end{cases} \quad m = -1, \dots, -J, 1, 2, \dots, J. \quad (7)$$

Here $\xi_{l,i}(m)$ defines coloured noise components of pilot subcarrier, m , due to AWGN noise and MIMO detection. This coloured noise component is a function of the MIMO channel.

It is known that timing offset in the time domain results in phase rotation in the frequency domain and this phase rotation is proportional to both the sub-carrier index and the OFDM symbol index as shown in Equation (3). Thus the phase rotation of the known pilot symbol in the specific spatial stream, observed at the MIMO detector output, can be utilised to estimate the timing clock offset. In this algorithm, a two-tier correlation is performed on the pilot subcarrier output from MIMO detection stage 18. The first tier cross-correlation is performed in

frequency domain over the corresponding pairs of pilot subcarriers; e.g. pairs with positive and negative indices respectively. Subsequently, a second-tier auto-correlation is performed in the time domain over the first-tier correlation outputs with one OFDM symbol delay. For $m=1$ to J , the two-tier correlation can be expressed as:

$$\begin{aligned} z_{l,i}(m) &= [\hat{x}_{l,i}(m) \hat{x}_{l,i}^*(-m)] [\hat{x}_{l-1,i}(m) \hat{x}_{l-1,i}^*(-m)]^* \\ &= \exp\left(j \frac{2\pi K N_s \eta}{N}\right) + e_{l,i}(m) \end{aligned} \quad (8)$$

where the power of the known pilot symbol is assumed to be unity, $|x_{l,i}(m)|^2 = 1$, and $e_{l,i}(m)$ defines a noise component independent of the useful component. It can be seen that the output of this two-tier correlation is the exponential function of the initial TO estimate, disturbed by the coloured noise. Utilising this method, $J \cdot N_t$ TO estimates are obtained for each OFDM symbol. Some estimates may be seriously affected by coloured noise, so the weighted combination of all estimates instead of the simple average of these estimates is employed to attempt to obtain improved accuracy. Following from this, a weighted TO estimation method is proposed:

$$\hat{\eta}_l = \frac{N}{2\pi K N_s} \arg \left(\frac{\sum_{i=1}^{N_t} \sum_{m=1}^J z_{l,i}(m) w_{i,m}}{\sum_{i=1}^{N_t} \sum_{m=1}^J w_{i,m}} \right) \quad (9)$$

where $w_{i,m}$ is the weighting factor for the initial TO estimate $z_{l,i}(m)$.

It may be particularly onerous to derive the optimal weighting factor with minimum variance in estimation error for each spatial stream and subcarrier. This especially holds true for the considered MIMO-OFDM system, where a two-tier correlation, involving frequency domain cross-correlation and time domain autocorrelation, is performed.

However, it is known that noise is coloured by the MIMO detection matrix $\mathbf{G}(m)$, and the noise power can vary as a function of channel. Therefore for

linear MIMO detection, the post-processing SNR reliability measure is the parameter of interest. This reliability measure can be exploited in the TO estimator 20 to obtain the needed weighting factors.

- 5 When MMSE MIMO detection is employed, the two-dimensional (in the spatial and frequency dimensions) post-detection SNR reliability for the j -th sub-stream and m -th pilot subcarrier is given in the following equation as derived from Robert W. Heath Jr. and Arogyaswami Paulraj, "Antenna Selection for Spatial Multiplexing Systems based on Minimum Error Rate", IEEE International
10 Conderence on Communications, Vol.7, June 2001, pp. 2276-2280:

$$SNR_{j,m} = \frac{1}{N_0 [\mathbf{H}^H(m)\mathbf{H}(m) + N_0 \mathbf{I}]_{j,j}^{-1}} - 1 \quad (10)$$

where, $[\cdot]_{j,j}$ denotes the j -th element on the diagonal of the inverse matrix.

- 15 Since a WLAN channel is considered to be time invariant, the same SNR is applied continuously for all OFDM symbols in the time domain.

- Since there are $2J \cdot N_t$ SNR parameters (from Equation (7) above), in the TO estimation, $SNR_{i,m}$ $i = 1, \dots, N_t$, $m = -1, \dots, -J+1, -J, 1, 2, \dots, J$, but there are only $J \cdot N_t$ initial estimates of TO output by the first cross-correlation stage.
20 Therefore, the fact there are twice as many SNR estimates as initial TO estimates is catered for by implementation of the following equation:

$$w_{i,m} = \min\{SNR_{i,m}, SNR_{i,-m}\} \quad (11)$$

where $\min\{\cdot\}$ is the minimum value function.

- 25 Therefore, the timing clock offset estimator is configured to generate the weighting factor from two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics for a pair of corresponding subcarriers. And as an example, the pair of subcarriers is a positive and negative pair of corresponding subcarriers $m, -m$. The timing clock offset estimator derives respective values
30 for the two-dimensional post-linear MIMO detection signal-to-noise ratio

characteristics for the positive and negative pair of corresponding subcarriers and generates the weighting factor from the characteristic which has a lesser of the respective values.

- 5 This implementation means that in the cross-correlation of two pilot subcarriers with different SNR, the estimation reliability is dominated by the less reliable data.

10 In the alternative arrangement of Figure 3, a first-tier cross-correlation is generated in the correlator 40 on the pairs of the received positive and known negative pilot subcarriers, as given by:

$$z_{l,i}(m) = [\hat{x}_{l,i}(m)\hat{x}_{l,i}^*(-m)] = \exp\left(j\frac{2\pi K(IN_s + N_g)\eta}{N}\right) + e_{l,i}(m) \quad (12)$$

Secondly, the weighted combination is performed in weighted combination stage 46 on the output of first tier correlation stage 40. Here the weighting factor is derived from the post-linear MIMO detection two-dimensional SNR from characteristic SNR generator 16 as given by:

$$\chi_l = \frac{\sum_i \sum_m z_{l,i}(m)w_{i,m}}{\sum_i \sum_m w_{i,m}} \quad (13)$$

and $w_{i,m} = \min\{SNR_{i,m}, SNR_{i,-m}\}$

- 20 Finally, the second tier auto-correlation is performed on the combination output of weighted stage 40 with the delay of one OFDM symbol, and the estimated TO is extracted as given by:

$$\hat{\eta}_l = \frac{N}{2\pi KN_s} \arg(\chi_l \chi_{l-1}^*) \quad (14)$$

- 25 The processing of the signals as explained above may be better understood with reference to Figure 4. Referring first to Figure 4a, the process starts at step 100. At step 102, FFT stage 12 performs a Fast Fourier Transform on the

received time-domain signals. MIMO detection module 18 performs detection on the MIMO-OFDM signal at step 104. The resulting signals after detection at step 106 are frequency domain post-detection signals with residual TO. The subcarriers are represented by Equations (6) and (7) above. The $2J \cdot N_t$ subcarriers are output by MIMO detector 18 to cross-correlation stage 40. The output of auto correlation stage 44 is the two-tier correlation defined by equation (8) at step 108. At step 110, the post-detection SNR generator 16 derives the post-linear MIMO detection signal-to-noise ratio characteristics for a pair or pairs of corresponding subcarriers, as defined by equation 10.

At step 112, TO estimator 20 derives the weighting factor(s) in accordance with equation 11 given above. At step 114, TO estimator 20 applies the derived weighting factor(s) to the initial TO estimate in accordance with equation 9 above.

At step 116, TO estimator 20 derives an improved TO estimate defined by equation 9 given above. The algorithm ends at step 118.

Figure 4B illustrates the flow of the algorithm for the apparatus of Figure 3. The process of Figure 4B starts at step 130. As in Figure 4A, an FFT is performed on the received signals along with MIMO detection at steps 132 and 134 respectively. Again, at step 136, the frequency domain post detection signal with residual TO is achieved, the subcarriers of the signal being defined by equations (6) and (7) above.

In the alternative arrangement of Figure 3, a first-tier correlation, defined by equation (12), is performed at step 138 by correlator stage 40. At step 140, weighted combination stage 46 derives and applies weighting factor(s) in accordance with equation (13) above. Subsequently, the second-tier correlation is performed by stages 42 and 44 at step 142 leading to an improved TO estimate at stage 144 in accordance with equation (14) above. The algorithm ends at step 146.

The system performance may be considered in a 2×2 MIMO-OFDM based WLAN system platform. Two spatial streams are transmitted over a MIMO fading channel with 20MHz frequency band by utilising spatial division multiplexing (SDM) techniques. Convolutional codes with different puncturing rates are adopted. The detailed system specification is referred to the WLAN 802.11n standard draft "EWC HT PHY Specification", *Enhanced Wireless Consortium Publication*. V1.27, December 23rd, 2005. Type D MIMO fading channel model "IEEE P802.11 Wireless LANs TGn Channel Models", *doc.: IEEE 802.11-03/940r4*, May 2004 are employed in the system performance assessment. The antenna configuration is a linear array and the distance between adjacent antennas is a half carrier wavelength.

In the assessment, the residual CFO of 1000Hz and the TO of 40ppm is assumed. The least square MIMO channel estimation without smoothing and MMSE MIMO detection are adopted in the receiver. Moreover, the Viterbi decoding with trace-back length of 128 is employed. Two CPE (common phase error caused by residual CFO) compensation schemes are considered in combination with the disclosed methods. In a first CPE compensation scheme, CPE is estimated, averaged and compensated for on the basis of one OFDM symbol. In the second method, one OFDM symbol is divided into several segments with a pilot subcarrier as the center point, and the CPE is estimated and compensated for segment by segment.

The PER (packet error rate) and BER (bit error rate) comparison of the disclosed post-detection SNR weighted TO estimator(s) and the conventional un-weighted estimator are shown in Figures 5 and 6 respectively. Here BPSK and 64QAM modulations are considered. The curves for the disclosed method with the CPE compensation for the whole symbol are given in the figures along with curves for the method with CPE compensation for segment by segment within one OFDM symbol. The results clearly indicate that the disclosed estimator(s) out-perform the conventional un-weighted TO estimator when different CPE tracking schemes are applied.

- However, from these performance figures, it can be seen that the performance is much better when CPE is compensated for segment by segment than the CPE compensation for the whole OFDM symbol. This is due to the effect of the residual TO. Since the TO causes the phase rotation proportional to both the subcarrier index and OFDM symbol index, the phase rotation for all subcarriers in one OFDM symbol is not the same once the residual TO exists. Thus the CPE compensation segment by segment can successfully handle the residual TO effect for even better performance.
- 10 It will be appreciated that the invention has been described by way of example only and various modifications may be made to the invention without departing from the spirit and scope of the appended claims.

Claims

1. Apparatus for estimating a timing clock offset component of a MIMO-OFDM wireless communications signal, the apparatus comprising:
 - 5 a signal-to-noise ratio generator configured to generate a plurality of two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics of the MIMO-OFDM wireless communications signal; and
 - a multi-tier correlator configured to generate a plurality of multi-tier correlations, the apparatus being configured to derive an initial timing clock
 - 10 offset estimate from an output of a tier of the multi-tier correlations;
 - a timing clock offset estimator configured to generate a weighting factor from the plurality of two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics and to apply the weighting factor to the initial timing clock offset estimate thereby to estimate the timing clock offset component.
- 15 2. Apparatus according to claim 1, wherein the MIMO-OFDM wireless communications signal comprises a plurality of subcarriers, and the timing clock offset estimator is configured to generate the weighting factor from two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics for
- 20 a pair of corresponding subcarriers.
3. Apparatus according to claim 2, wherein the plurality of subcarriers is indexed by a set of indices, the set of indices having positive and negative values, and wherein the timing clock offset estimator is configured to generate
- 25 the weighting factor from two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics for a positive and negative pair of corresponding subcarriers.
4. Apparatus according to claim 3, wherein the timing clock offset estimator
- 30 is configured to derive respective values for each of the two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics for the positive and negative pair of corresponding subcarriers, and to generate the weighting factor from the characteristic which has a lesser of the respective values.

5. Apparatus according to any preceding claim, wherein the timing clock offset estimator is configured to generate a plurality of weighting factors for a plurality of subcarriers and a plurality of spatial streams of the MIMO-OFDM signal and to apply the plurality of weighting factors to a plurality of initial timing clock offset estimates thereby to estimate the timing clock offset of the MIMO-OFDM signal.
6. Apparatus according to claim 1, wherein the multi-tier correlator is configured to generate the multi-tier correlation by generating a first-tier cross-correlation of a received subcarrier pair having corresponding indices.
7. Apparatus according to claim 6, wherein the multi-tier correlator is configured to generate the multi-tier correlation result by generating a second-tier auto-correlation of the first-tier cross-correlation.
8. Apparatus according to claim 6, wherein the multi-tier correlator is configured to generate the multi-tier correlation result by generating a second-tier auto-correlation of a weighted first-tier cross-correlation.
9. Apparatus for estimating a timing clock offset component of a MIMO-OFDM wireless communications signal, the apparatus being configured to:
- generate a plurality of two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics of the MIMO-OFDM wireless communications signal;
 - generate a weighting factor from the plurality of two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics;
 - generate a plurality of multi-tier correlations;
 - derive an initial timing clock offset estimate from an output of a tier of the multi-tier correlations; and
 - apply the weighting factor to the initial timing clock offset estimate thereby to estimate the timing clock offset component.

10. A method for estimating a timing clock offset component of a MIMO-OFDM wireless communications signal, the method comprising:
- generating, with a signal-to-noise ratio generator, a plurality of two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics of the MIMO-OFDM wireless communications signal;
 - generating, with a multi-tier correlator, a plurality of multi-tier correlations;
 - deriving an initial timing clock offset estimate from an output of a tier of the multi-tier correlations;
 - controlling a timing clock offset estimator to generate a weighting factor from the plurality of two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics and to apply the weighting factor to the initial timing clock offset estimate thereby to estimate the timing clock offset component.
11. The method of claim 10, the method comprising receiving a MIMO-OFDM wireless communications signal comprising a plurality of subcarriers, the method further comprising generating, with the timing clock offset estimator, the weighting factor from two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics for a pair of corresponding subcarriers.
12. The method of claim 11, the MIMO-OFDM wireless communications signal comprising subcarriers indexed by a set of indices, the set of indices having positive and negative values, the method further comprising generating, with the timing clock offset estimator, the weighting factor from two-dimensional post-detection signal-to-noise ratio characteristics for a positive and negative pair of corresponding subcarriers.
13. The method of claim 12, further comprising deriving, with the timing clock offset estimator, respective values for each of the two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics for the positive and negative pair of corresponding subcarriers, and generating the weighting factor from the characteristic which has a lesser of the respective values.

14. The method of any of claims 10 to 13, the method comprising generating, with the timing clock offset estimator, a plurality of weighting factors for a plurality of subcarriers and a plurality of spatial streams of the MIMO-OFDM signal and applying the plurality of weighting factors to a plurality of initial timing clock offset estimates thereby to estimate the timing clock offset of the MIMO-OFDM signal.

15. The method of claim 10, the method comprising generating the multi-tier correlation result by generating a first-tier cross-correlation of a received subcarrier pair having corresponding indices.

16. The method of claim 15, the method comprising generating the multi-tier correlation result by generating a second-tier auto-correlation of the first-tier cross-correlation.

17. The method of claim 15, the method comprising generating the multi-tier correlations result by generating a second-tier auto-correlation of a weighted first-tier cross correlation.

18. A method for estimating a timing clock offset component of a MIMO-OFDM wireless communications signal, the method comprising:

generating a plurality of two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics of the MIMO-OFDM wireless communications signal;

generating a plurality of multi-tier correlations;

deriving an initial timing clock offset estimate from an output of a tier of the multi-tier correlations;

generating a weighting factor from the plurality of two-dimensional post-linear MIMO detection signal-to-noise ratio characteristics and;

applying the weighting factor to the initial timing clock offset estimate thereby to estimate the timing clock offset component.