Synchronisation Issues in Non-coherent MIMO Systems

SeungHwan Won and Lajos Hanzo
School of ECS, Univ. of Southampton, SO17 1BJ, UK.
Tel: +44-23-8059 3125, Fax: +44-23-8059 4508
E-mail:{shw04r, lh}@ecs.soton.ac.uk
http://www-mobile.ecs.soton.ac.uk

Abstract

In this article, we identify some of the key problems that may be encountered when designing Non-Coherent (NC) Multiple-Input Multiple-Output (MIMO) DownLink (DL) synchronisation schemes for communicating over multi-path fading channels. Our main objectives are to illustrate the information theoretic features and to provide design guidelines for the initial synchronisation of NC MIMO systems. We conclude by outlining the relationships between the beneficial and detrimental design factors.

I. INTRODUCTION

In wireless mobile networks, fading constitutes one of the main sources of channel-induced impairments and the impressive near-capacity performance predictions of coherently detected MIMO systems become unrealistic, because coherent MIMO detection requires both accurate channel estimation and synchronisation in the face of hostile channel conditions. The substantial appeal of MIMOs is that their capacity may be deemed to increase linearly with the Signal-to-Interference plus Noise Ratio (SINR), as opposed to the more modest logarithmic improvements of the classic Shannon-Hartley law, provided that we assign the associated increased transmit power to additional Transmit Antennas (TAs) which therefore linearly increases the achievable throughput.

The characteristics of NC MIMO scenarios have been analysed in [1]-[4]. The in-depth analysis of the initial synchronisation derived for NC MIMOs has been provided in [5]. However, the characteristics

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of NC MIMOs and the related initial synchronisation problems have not been well-documented in the literature, even though there are thousands of papers on quantifying the performance improvements of diverse MIMOs in perfect initial synchronisation scenarios. Therefore, our main objective is to outline the key factors affecting the initial synchronisation of NC MIMO systems.

In Section II of this article, we commence our discourse with a comparative discussion on the chip timing synchronisation issues of three typical NC MIMO-aided Spread Spectrum (SS) schemes, namely those of Single-Carrier Direct Sequence-Code Division Multiple Access (SC-DS-CDMA) [6], Multi-Carrier DS-CDMA (MC-DS-CDMA) [6] and Direct Sequence-UltraWideBand (DS-UWB) scenarios [7]. Furthermore, we also provide a comparative discussion on the frame-timing synchronisation and cell-search issues of NC MIMO aided Orthogonal Frequency Division Multiple Access using Time Division Duplexing (OFDMA/TDD) [8]. Then, a brief overview of both coherent and NC MIMO scenarios is provided in Section III. The numerical results associated with both Sections II and III are portrayed in Section IV. Based on both plausible information theoretic considerations and on the specific features of initial synchronisation schemes derived for NC MIMOs, we provide design guidelines for NC MIMO schemes in Section V. Finally, our conclusions are offered in Section VI.

II. NON-COHERENT MIMO SCENARIOS AND THEIR APPLICATIONS

In this section we provide a digest of OFDMA, MC-DS-CDMA, SC-DS-CDMA and DS-UWB solutions, with specific emphasis on the transmitted signals' structures. Fig. 1 illustrates the power spectra of the Frequency-Domain (FD) and Time-Domain (TD) signal waveforms associated with four representative systems, where T_S denotes the OFDM-symbol duration of OFDMA, whilst T_{Cm}, T_{Cs} and T_{Cu} are the chip duration of MC-DS-CDMA, of SC-DS-CDMA and of DS-UWB, respectively. Finally, T_f is defined as the pulse repetition period, i.e. the time between two consecutive signalling pulses of a DS-UWB system. As observed in Fig. 1, the symbol (or chip) duration of each system is inversely proportional to the BW assigned. In OFDM [8], a serial data stream is passed through Serial-to-Parallel (SP) conversion, which splits the data into U_o number of parallel streams. Each parallel stream modulates the corresponding subcarrier, which experiences frequency-flat fading. These U_o modulated carriers are then superimposed to create the OFDM signal.

An SC-DS-CDMA scheme transmits DS-spread signals using a single carrier [5], [6]. On the other hand, MC-DS-CDMA using no subcarrier overlapping may be deemed reminiscent of the CDMA-2000 3x arrangement, which has three 1.25 MHz-BW subcarriers. In the MC-DS-CDMA system of [5], [6], the input bit sequence is also SP converted and each of the parallel sequences is transmitted on a separate subcarrier. The Spreading Factor (SF) of the MC-DS-CDMA system's subcarriers is $SF_m = T_{Sm}/T_{Cm}$, whilst $SF_s = T_b/T_{Cs}$ denotes the SF of a corresponding SC-DS-CDMA system, where T_b represents the bit duration of the data sequence before SP conversion. Finally, T_{Sm} indicates the symbol duration after SP conversion. Accordingly, we have $T_{Sm} = U_m{\cdot}T_b$, where U_m is the number of subcarriers and hence the relationships of $T_{Cm} = U_m{\cdot}T_{Cs}$ and $SF_s = SF_m$ hold. According to the above arguments, both the MC- and the corresponding SC-DS-CDMA systems have the same BW. The fading magnitude and phase of the adjacent subcarriers of a typical MC-DS-CDMA system having a sufficiently wide BW may be considered to be uncorrelated, provided that the Channel Impulse Response (CIR) duration is high. DS-UWB techniques may be characterised by low-duty-cycle pulse trains having a very short impulse duration and hence a wide BW, as visualised in Fig. 1 [7]. Depending on the logical value to be conveyed, a signalling impulse of T_{Cu} duration and having the required polarity is allocated at multiples of the UWB pulse-repetition period T_f. In the four systems contrasted in Fig. 1, the total allocated power is equally shared by the M TAs in OFDMA, SC-DS-CDMA and DS-UWB. By contrast, the total allocated power is equally shared by both the M TAs and the U_m subcarriers in the TD-spread MC-DS-CDMA.

A. NON-COHERENT MIMO AIDED SPREAD SPECTRUM SCENARIOS

In inter-cell synchronous SC- and MC-DS-CDMA the MS's receiver must be capable of aligning a locally generated PseudoNoise (PN) sequence with the received composite multi-user signal containing the desired PN sequence within an allowable timing error [5], [6]. The initial timing synchronisation of the DS-CDMA DL aims for adjusting the coarse timing of the signals received. The so-called uncertainty region in the DL corresponds to the entire duration of the PN sequence, which tends to be quite wide, namely on the order of the code length, such as $(2^{15} - 1)$ chip intervals. In the DS-UWB DL, the main goal of the initial timing synchronisation is the same as that in the DS-CDMA DL. However, the grade of challenge is higher in the DS-UWB DL, because there is a higher number of resolvable multi-path components in the DS-UWB channel. The synchronisation stage has to be activated for both coarse timing and fine code phase alignment. Both of these constitute a challenging problem owing to the extremely short signalling chip-duration [7], because this leads to a huge search space size represented as the product of two factors, namely that of the number of legitimate code phases in the uncertainty region of the PN sequence and the number of legitimate signalling pulse positions. By contrast, the so-called post-initial synchronisation procedure extracts the accurate timing positions of the delayed paths following the Line-Of-Sight (LOS) component and identifies the highest-power delayed paths earmarked for processing by the maximum ratio combining scheme of the Rake receiver. Hence post-initial synchronisation also has a major impact on the performance of the Rake receiver [9]. Further details on the post-initial synchronisation procedure may be found in [9].

B. NON-COHERENT MIMO AIDED OFDMA FOR IEEE 802.16e

Recently, the OFDMA/TDD based IEEE 802.16e scheme has been proposed for standardisation. When considering a cellular system, the adjacent cells are typically distinguished by different cell-specific synchronisation preambles in order to ensure that a MS becomes capable of discriminating signals received from different cells. Owing to the duality of the FD and TD, it is technically feasible to design synchronisation schemes operating purely in either the FD or in the TD, or using hybrid schemes. In practice, it is often beneficial to consider all the design options and then to opt for the most efficient combination of FD and TD techniques. For example, it was suggested in [10], [11] that the initial synchronisation procedure of an OFDMA/TDD system may be carried out in the order of (1) Frame-Timing (FT) synchronisation in the TD, which identifies the beginning of a transmission frame of say P OFDM symbols (2) fine or coarse Carrier Frequency-Offset (CFO) estimation in the TD, (3) cell-search which is also often termed as cell-identification in the FD and finally, (4) coarse or fine CFO estimation carried out in the FD. Again, the specific order of the above-mentioned procedures may change, depending on the preferred construction of the synchronisation preamble structure [8]. In the DL frame of the OFDMA/TDD scheme, an appropriately designed single preamble may be used for establishing initial synchronisation [10], [11]. The FT synchronisation does not require the specific knowledge of the particular serving cell the MS is connected to and FT synchronisation is readily attained by classic correlation techniques using a unique preamble having a periodically repeated pattern in the TD [10], [11]. Both fine and coarse CFO estimation are also acquired by correlation techniques [10], [11], which may be carried out either in the FD or in the TD[1]. The role of cell-search or cell-identification is to ensure that the MSs are connected to that specific cell, which provides the highest-quality coverage. During the cell-search, each cell in a group of cells should be distinguished from the others with the aid of their unique FD preamble patterns, which may be generated for example by the XOR function of a Walsh-Hadamard code and a specific PN code. The quality of all the received preamble signals is monitored in order to ensure reliable initial cell-identification and to compile a list of potential handover target cells based on the cell-specific received signal strength indicator measurements, where the best serving cell is identified by finding the specific FD pattern having the maximum cross-correlation peak.

III. AN OVERVIEW OF NON-COHERENT MIMO SCENARIOS

Coherently detected MIMOs exhibit a high capacity, provided that the channel is known to the receiver, which may be hence termed as ’COH MIMOs’. On the other hand, when the channel is unknown at the receiver, we may refer to the resultant schemes as ’NC MIMOs’. When considering a COH MIMO system having M TAs and N Receive Antennas (RAs) as well as i.i.d. Rayleigh fading among all the antennas, the achievable MIMO capacity is increased linearly with $min(M, N)$ at high SINRs, hence incorporating more TAs is capable of increasing the attainable capacity [1]. In MIMO systems, the fading CIR taps may fluctuate quite rapidly and the reliable estimation of the CIR becomes challenging, because in an (M, N)-element MIMO system $(M \times N)$ CIRs have to be estimated [8]. In a frequency-selective scenario, this task may be further aggravated by estimating numerous CIR taps within a transmission frame duration. Moreover, the time and frequency resources dedicated to the transmission of pilot symbols required for estimating the $(M \times N)$ CIRs may become excessive, unless blind joint CIR and data estimation is employed. Accordingly, the tradeoff between the achievable capacity and the resources required is an important design consideration in MIMO systems. In wireless sensor networks low-power, low-complexity devices are required and hence only the employment of NC MIMOs may be feasible.

The plausible lessons of information theoretic considerations applied to NC MIMOs are as follows

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[1] The frequency difference between the local oscillator of the transmitter and receiver leads to the CFO to be compensated.

[1]-[4]. Naturally, a NC MIMO scheme, which does not rely on any CIR knowledge has a lower capacity than COH MIMOs. It was argued in [1] that at high SINRs there is no reason for using more than $(T_{sym}/2)$ number of TAs, where T_{sym} represents the space-time symbol duration expressed in terms of multiples of the coherence time duration[2], because the channel capacity gain[3] increases with $(T_{sym}/2)$, but only until M approaches $(T_{sym}/2)$.

Accordingly, the most attractive strategy is to activate only M^* of the M available TAs during the synchronisation process, where $M^* = min(M, N, \lfloor T_{sym}/2 \rfloor)$. Therefore, having more TAs than RAs does not provide any capacity increase, because neither the capacity gain nor the achievable diversity gain can be improved further, when employing more than N TAs. Increasing the number of TAs has a more beneficial impact at high SINRs than at low SINRs, because the total transmit power has to be shared by M TAs, which renders each of the M transmit signals having a factor-M reduced power seriously noise-contaminated. Hence, provided that T_{sym} is relatively short expressed in terms of multiples of the coherence time duration, the number of useful TAs M^* is limited by T_{sym}, rather than by the number of RAs N. When considering low SINRs, the NC and COH MIMO capacities become asymptotically equal [1], [2] provided that the BandWidth (BW) tends to infinity. More explicitly, at low SINRs the mutual information between the transmitter and receiver is maximised by using a single TA, because the mutual information bounds were shown to be decreasing functions of M owing to the plausible reason that upon dividing the total transmit power across M TAs results in noise-contaminated received signals [2]. This implies that using multiple TAs at low SINRs inflicts a performance degradation. Accordingly, at low SINRs the NC MIMO capacity is the same as the single TA-aided capacity.

As a further example, the characteristics of NC wideband MIMO-OFDM systems [8] as well as the wideband NC MIMO capacity trends may be summarised as follows [3], [4]. In SS schemes [4], the total transmit power assigned is spread over a large number of chips, hence the SS scheme operates at low chip-SINRs. In this scenario, the adjectives 'wideband' and 'low-SINR' may be used interchangeably. If white noise-like transmitted signals are employed, the mutual information is inversely proportional to both the total BW and the number of resolvable multi-path components, since the total energy is dispersed over

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[2] The duration is defined as the period in which both the amplitude and phase of the signal received may be considered near-constant.

[3] The achievable capacity gain is proportional to the number of degrees of freedom [1].

the entire BW and/or a high number of CIR taps. The employment of multiple TAs and RAs is capable of increasing the achievable capacity, but only to the finite capacity limit associated with a BW tending to infinity. The NC MIMO capacity approaches the COH MIMO capacity, as the channel's coherence time duration becomes sufficiently higher than the number of TAs and/or an SINR-dependent threshold[4].

This observation may be interpreted further by stating that the NC MIMO channel requires a higher BW in order to reliably support the same throughput as the COH MIMO channel. Provided that the coherence time duration is sufficiently high, the NC MIMO capacity approaches the COH MIMO capacity in the low-SINR region[5]. However, when the mutual information between the transmitted and received signals has to be maximised, the achievable capacity scales inverse-proportionally with the BW, because at a fixed total transmit power doubling the BW halves the power spectral density and hence the SINR per chip, for example. Hence, this NC MIMO capacity does not approach the wideband MIMO capacity limit and diverges from the COH MIMO capacity as the BW increases.

In NC MIMO-OFDM systems having a high BW [3], increasing the BW further may result in a NC MIMO capacity reduction, because the capacity of the NC MIMO-OFDM systems is constituted by that of the COH MIMO-OFDM system minus a penalty term, which results from the lack of channel knowledge. This phenomenon was termed as ’over-spreading’ in the FD [3], where the number of unknown CIR coefficients required for describing the wideband channel becomes excessive and owing to the lack of CIR knowledge the NC MIMO capacity may tend to zero. Moreover, increasing the number of TAs M may result in excessive over-spreading at a factor M reduced BW owing to the increased channel-related uncertainty of the NC MIMO system, when the number of CIRs ($M \times N$) is increased. Hence the employment of a high number of TAs M in addition to having a high BW, such as in a NC MIMO-OFDM based UWB system may lead to a further reduced channel capacity. In this article, the family of initial synchronisation schemes designed for both spatial division multiplexing and space-time coding aided MIMO schemes will be considered.

[4] More specifically, if we assume having a Gaussian input distribution, T_{sym} should be longer than $\frac{M^2}{(N+M)^2} \cdot \frac{1}{SINR^2}$ [4] and the total transmit power assigned should be proportional to both the BW and to the number of resolvable multi-path components.

[5] This may be made plausible simply considering that at a high coherence time the employment of the previous signal estimate as a reference for non-coherently detecting the current one may have a similar ’reliability’ as the explicit utilisation of the seriously noise-contaminated CIR estimate.

The summary of both COH and NC MIMO capacities is portrayed in Table I, which depend on M, N and T_{sym}, where 'c' represents the potential capacity gain related to the number of degrees of freedom, 'd' denotes the achievable diversity gain, 'L' is the number of resolvable multi-path components, $K = min(M, N)$ and $M^* = min(M,\ N,\ \lfloor T_{sym}/2 \rfloor)$. It is also worth noting that the key parameters regarding the wideband NC-MIMO capacity additionally encompass the BW.

IV. PERFORMANCE ANALYSIS

From the list of the four systems considered, we will focus our attention on two of them and investigate the initial code synchronisation performance of MIMO-aided SC- and MC-DS-CDMA systems, which will allow us to generalise the main characteristics of NC MIMOs. However, owing to lack of space we do not elaborate on OFDMA/TDD and DS-UWB systems any further. It is assumed that the time duration over which the correlator outputs are coherently accumulated is the same for both the scenarios considered. Details of the system parameters related to both Figs.2 and 3 can be found in [5].

Fig. 2 illustrates the Mean Acquisition Time (MAT) versus SINR per chip, i.e. E_c/I_0 performance of the SC-DS-CDMA initial timing synchronisation scheme parameterised with the number of TAs for M=1,2 and 4 as well as that of the number of RAs for the specific values of N=1 and 4[6]. In the curves of Figs 2 and 3, the solid lines represent the scenario of receiving a single-path signal (denoted as $L1$ in Figs.2 and 3), whilst the dotted lines represent a dispersive three-path scenario (denoted as $L3$ in Fig.2). It is worth noting that although not explicitly shown in Figs.2 and 3 for avoiding obfuscating details, the operating range of the scheme using N=2 RAs was found to be between those corresponding to the N=1 and N=4 RA scenarios. As the number of TAs was decreased, all the curves shown in Fig.2 illustrated a MAT performance improvement for the arrangements employing N=4 RAs in both the single-path and three-path propagation scenarios. Similar trends were observed also in the N=1 RA-assisted three-path scenario, except that a useful transmit diversity gain was experienced for N=1 in the specific E_c/I_0 range of the single-path system characterised in Fig.2. More explicitly, the $'M2N1'$ and $'M4N1'$ scheme communicating over a single-path channel reveals a better MAT performance compared to the $'M1N1'$

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[6] The aim of the initial timing synchronisation scheme is to minimise the mean acquisition time, which is directly related to both the correct detection probability as well as to the time required by the synchronisation scheme to notice after the elapse of the code phase verification period that a so-called false-locking event occurred and then to return to the search mode.

system across the specific E_c/I_0 range portrayed. More explicitly, this implies that the scheme using a single RA benefits from a higher diversity gain in the SC-DS-CDMA arrangement having a sufficiently wide BW. By contrast, although the number of successfully detected correlation peaks was increased by a factor of L=3, the MAT performance of the three-path scenario became worse than that of the single-path scenario. This is because given a fixed total power, a low ’per-path-power’ would result in a performance degradation in the three-path scenario. Similarly, the MAT performance degradation imposed by the ’low per-antenna-power’, when using multiple TAs becomes more drastic in the low E_c/I_0 range. In case of using both multiple TAs and multiple RAs, similar trends are observable, even though having two or four RAs has the potential of mitigating the MAT performance degradation imposed by the low per-branch E_c/I_0 values related to employing multiple TAs. More explicitly, in the N=4-receiver scenario the MAT performance degradation imposed by having three paths become substantially lower than those in the single RA arrangement, because the achievable receive diversity gain becomes sufficiently high for attaining a near-Gaussian MAT-performance, provided that an E_c/I_0 value in excess of -12 dB is maintained for both the single-path and three-path scenarios. The N=4 and N=1 scenarios might be interpreted as realistic upper and lower bounds for the attainable MAT performances.

On the other hand, Fig.3 characterises the achievable MAT versus E_c/I_0 performance of the MC-DS-CDMA initial timing synchronisation arrangement as a function of the number of TAs/RAs, when using U_m=4 subcarriers. The MC-DS-CDMA system is expected to have a high diversity order, which is determined by the number of subcarriers employed, provided that they are sufficiently for apart to ensure their independent fading. We also assumed that the total transmitted energy per chip is the same in all the scenarios considered. Hence, the effect of the inherent frequency diversity is the same as that of the multiple TA-aided diversity, because they both simply provide the same number of independently fading components. This fact suggests that the employment of multi-carrier transmissions based on the DS-CDMA principle results in exactly the same detrimental effects inflicted upon the attainable MAT performance as that imposed by using multiple TAs. The results of Fig.3 are parameterised by both the number of TAs for M=1,2 and 4 as well as by the number of RAs for N=1 and 4. As the number of TAs is decreased, all the curves shown in Fig.3 illustrate a MAT performance improvement. This trend suggests that the performance of the MC-DS-CDMA initial timing synchronisation scheme becomes substantially worse than that of SC-DS-CDMA encountering a single-path. This is a consequence of having a low per-branch and/or per-subcarrier received signal strength, which results in a degraded performance, despite achieving a high transmit- and frequency-diversity gain. Based on comparing the results of Figs.2 and 3, the performance of the MC-DS-CDMA initial timing synchronisation scheme encountering a single-path is slightly better than that of the SC-DS-CDMA initial timing synchronisation scheme encountering three paths. This explicitly suggests that a low per-path received signal strength leads to an attainable performance degradation, despite having a four times higher number of accumulated chips over the same coherence time duration.

V. CHARACTERISTICS OF NON-COHERENT MIMO SCENARIOS

Based on both the information theoretic considerations derived for NC MIMO aided scenarios in [1]-[4] and on the initial synchronisation procedures outlined in [5], [9], the fundamental characteristics of NC MIMO aided initial synchronisation schemes are detailed in the forthcoming sections.

A. NON-COHERENT MIMO SCENARIOS

The resultant relationships between the beneficial and detrimental factors governing the best attainable performance of NC MIMO scenarios are characterised in Fig. 4, where 'S' denotes a factor relevant only for SS systems, 'O' presents a factor pertinent for OFDMA only, whilst 'C' represents a factor common to both 'S' and 'O'. Observe in Fig. 4 that the MIMO-assisted synchronisation performance degrades owing to the following five reasons/mechanisms: 1) If the clock-drift-induced frequency mismatch is increased, the higher clock-drift leads to a reduced coherence time duration, which is detrimental, because it limits the time-interval over which coherent summation can be carried out, hence degrading probability of correct synchronisation (C), 2) Increasing the number of TAs M reduces the per-antenna power (C), 3) Increasing the number of multi-path components decreases the per-path power (C), 4) Increasing the number of subcarriers reduces the per-subcarrier power (S) and 5) Using an excessive BW results in over-spreading, which occurs at a factor of approximately M lower BW, than for a single TA as quantified in Fig.2-(b) of [3]. (O).

On the other hand, also note in Fig. 4 that the attainable NC MIMO synchronisation performance may be improved by the following five measures: 1) If we use an increased coherent summation or correlator output integration duration, this results in a more reliable, but more complex synchronisation scheme (C), 2) Increasing the number of RAs N improves the achievable synchronisation performance (C), 3) Naturally, an increased transmit power improves the attainable MIMO-aided synchronisation performance (C), 4) As expected, the employment of more sophisticated receiver schemes improves the achievable MIMO-aided synchronisation performance[7] (C) and 5) If we increase the BW, this leads to an increased coherence time duration for the channel (S). By appropriately adjusting the corresponding system parameters, a near-Gaussian initial timing synchronisation performance may be achievable. However, the above-mentioned inherently detrimental factors nonetheless limit the best attainable performance. In Fig. 4 the term 'Gaussian performance' is used to refer to the best attainable performance, when communicating over an AWGN channel.

B. GUIDELINES FOR DESIGNING NC MIMO AIDED SCHEMES

Based on the results of [1]-[5], [9] the following conclusions may be inferred for the family of NC MIMOs:

1) Sharing the total transmit power across multiple TAs in NC MIMOs leads to detrimental effects. More specifically, in multi-path scenarios the family of MIMO-aided schemes typically fails to show a transmit diversity gain owing to the reduced per-transmit-antenna and per-path power. Therefore, during initial synchronisation activating only a single TA might be recommended in order to maximise the achievable initial timing synchronisation performance of the schemes investigated[8]. **2)** The employment of a power-boosted pilot or preamble signal is beneficial to the attainable performance[9]. **3)** Using a relatively low coherent correlator output summation duration imposes further limits on the attainable benefits of NC MIMOs, while a high duration increases the receiver complexity. **4)** Exploiting multiple RAs increases the achievable receiver diversity gain and hence has the potential of compensating for the

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[7] The family of more sophisticated schemes, such as for example differentially coherent rather than NC methods are capable of providing further performance improvements compared to using NC schemes.

[8] In order to acquire the exact timing information of the received paths without any potential performance degradation that might be imposed on the NC MIMO aided scenarios, specifically designed preambles combined with time-switched transmit diversity or frequency-switched transmit diversity might be recommended, which is capable of achieving a diversity gain with the aid of a single TA.

[9] The preamble in IEEE 802.16e is transmitted at 9dB power boosting in each subcarrier compared to the data symbols and the power of the pilot channel is also several dBs higher than that of the data channels in the DS-CDMA DL.

performance degradation imposed by the low per-branch power of multiple TAs. **5)** Increasing the BW may be beneficial for single-carrier SS schemes when this is carried out by increasing the number of chips, since it increases the number of independently faded multi-path components according to the factor $\lfloor T_S/T_{Cs} \rfloor$, hence improving the diversity gain. However, increasing the BW becomes detrimental, when using an increased number of subcarriers, since it reduces the per-carrier power in a MC scheme[10].

VI. CONCLUSIONS

The systems of interest studied in this article are NC MIMO aided SS and OFDMA/TDD systems. Naturally, NC MIMOs are incapable of approaching the performance of COH MIMOs, regardless, whether the SS or the OFDMA/TDD DL is considered. Based on a variety of system considerations, we outlined five beneficial and five detrimental design factors predetermining the achievable performance of NC MIMOs. We concluded by suggesting practical guidelines for designing NC MIMO-aided synchronisation systems.

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[10] However, in SS scenarios, the tradeoff between an increased BW and an increased number of multi-path components should be considered.

REFERENCES

[1] L. Zheng and D.N.C. Tse, ”Communication on the Grassmann manifold: a geometric approach to the noncoherent multiple-antenna channel”, IEEE Transactions on Information Theory, vol. 48, no. 2, pp359–383, 2002.

[2] C. Rao and B. Hassibi, ”Analysis of multiple-antenna wireless links at low SNR”, IEEE Transactions on Information Theory, vol. 50, no. 9, pp2123–2130, 2004.

[3] M. Borgmann and H. Bolcskei, ”On the capacity of noncoherent wideband MIMO-OFDM systems”, International Symposium on Information Theory, pp651–655, 4-9 Sept. 2005.

[4] S. Ray, M. Medard and L. Zheng, ”On noncoherent MIMO channels in the wideband regime: capacity and reliability”, IEEE Transactions on Information Theory, vol. 53, no. 6, pp1983–2009, 2007.

[5] S.H. Won and L. Hanzo, ”Non-coherent code acquisition in the multiple transmit/multiple receive antenna aided single- and multi-carrier DS-CDMA downlink”, IEEE Transactions on Wireless Communications, vol. 6, no. 11, pp3864–3869, 2007.

[6] L. Hanzo, L-L Yang, E-L Kuan, K. Yen, Single- and Multi- Carrier DS-CDMA, Part IV Multi-Carrier CDMA, Chapter 21, Initial Synchronization of DS-CDMA and MC-CDMA Systems, Wiley, 2003.

[7] S.R. Aedudodla, S. Vijayakumaran and T.F. Wong, ”Timing acquisition in ultra-wideband communication systems”, IEEE Transactions on Vehicular Technology, vol. 54, no. 5, pp1570–1583, 2005.

[8] L. Hanzo, M.Münster, B.J. Choi and T.Keller, ”OFDM and MC-CDMA for Broadcasting Multi-User Communications, WLANs and Broadcasting”, John Wiley & Sons, 2003.

[9] S.H. Won and L. Hanzo, ”Initial and Post-Initial Code Acquisition in the Non-Coherent Multiple Input/Multiple Output Aided DS-CDMA Downlink”, To appear in the IEEE Transactions on Vehicular Technology, 2008 (http://eprints.ecs.soton.ac.uk/16021/).

[10] H. Lim and D. Kwon, ”Initial synchronization for WiBro”, Asia-Pacific Conference on Communications, pp284–288, 2005.

[11] T. Sun, K. Kim, S. Kang and K. Chang, ”Optimization of link-level performance and complexity for the floating-point and fixed-point design of IEEE 82.16e OFDMA/TDD mobile modem”, IEEE Mobile WiMAX Symposium, pp1–6, 2007.

TABLE I

SUMMARY OF COH- AND NC-MIMO CAPACITY BEHAVIOURS DEPENDING ON M,N AND T_{sym}

Classification of MIMOs	Key Parameters	Features	Classification of MIMOs	Key Parameters	Features
COH-MIMO (high SINR)	$M \geq N$	c : $min(M, N)$ $d = M - N$	COH-MIMO (high SINR)	$M < N$	c : $min(M, N)$ $d = N - M$
NC-MIMO (high SINR)	$T_{sym} \geq K + N$	$c : K(1 - K/T_{sym})$	NC-MIMO (high SINR)	$T_{sym} < K + N$	$c : M^*(1 - M^*/T_{sym})$
NC-MIMO (low SINR)	T_{sym}, M, N	c : N, $T_{sym} = 1$, $M = 1$	Wideband NC-MIMO	T_{sym}, M, N, BW, L	c : N and M, $T_{sym} >> 1$, BW $\propto L$

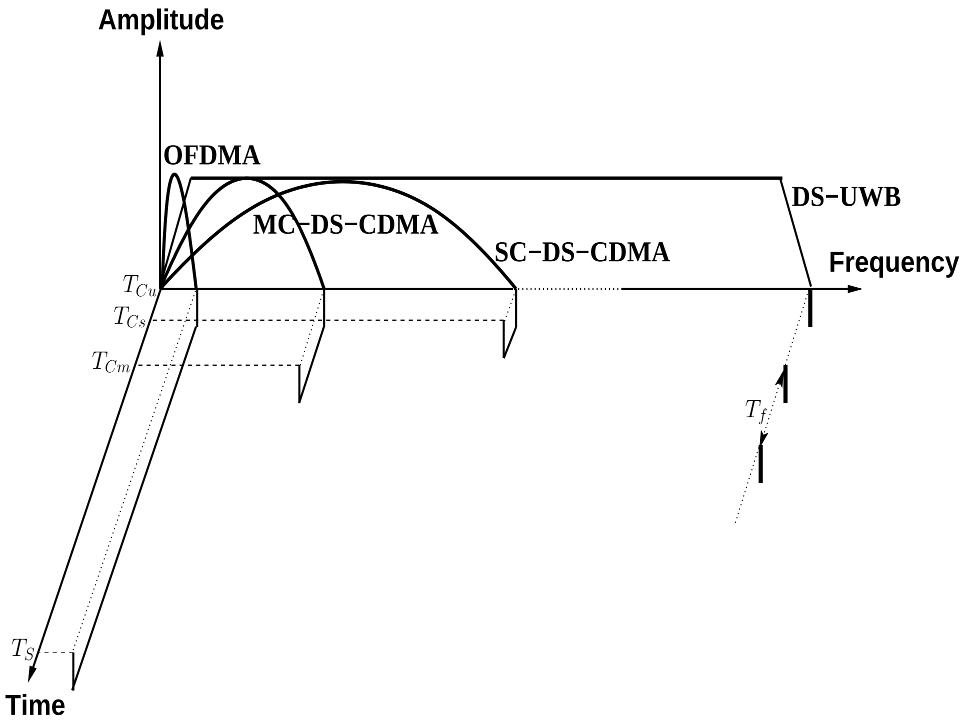

Fig. 1. Power spectra and time-domain chip (or symbol) duration of OFDMA, MC-DS-CDMA, SC-DS-CDMA and DS-UWB.

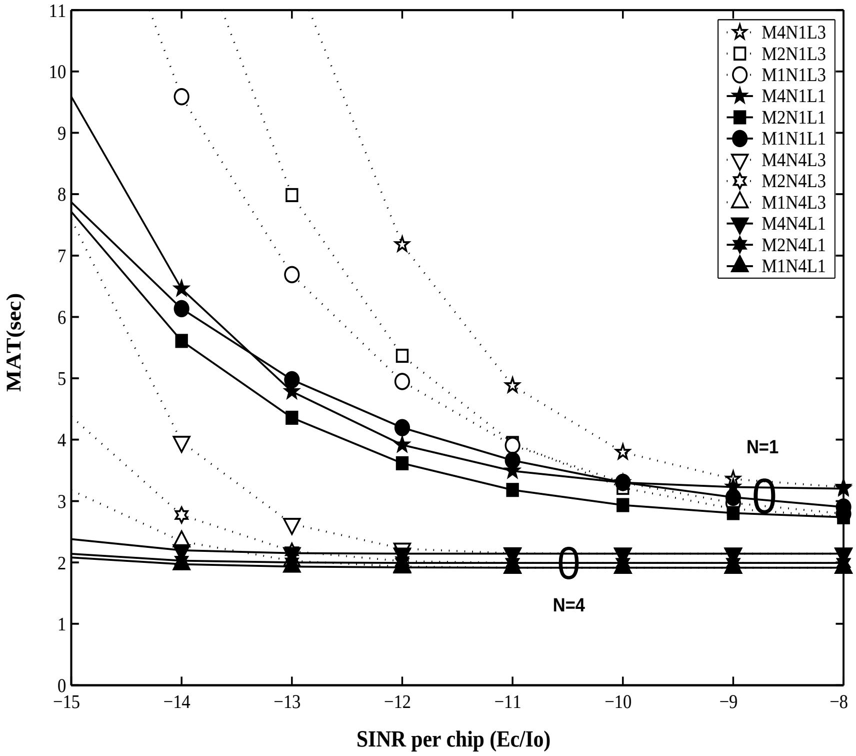

Fig. 2. MAT versus E_c/I_0 performance of the SC-DS-CDMA initial timing synchronisation scheme parameterised with both the number of TAs and RAs (Copyright of IEEE Transactions on Wireless Communications).

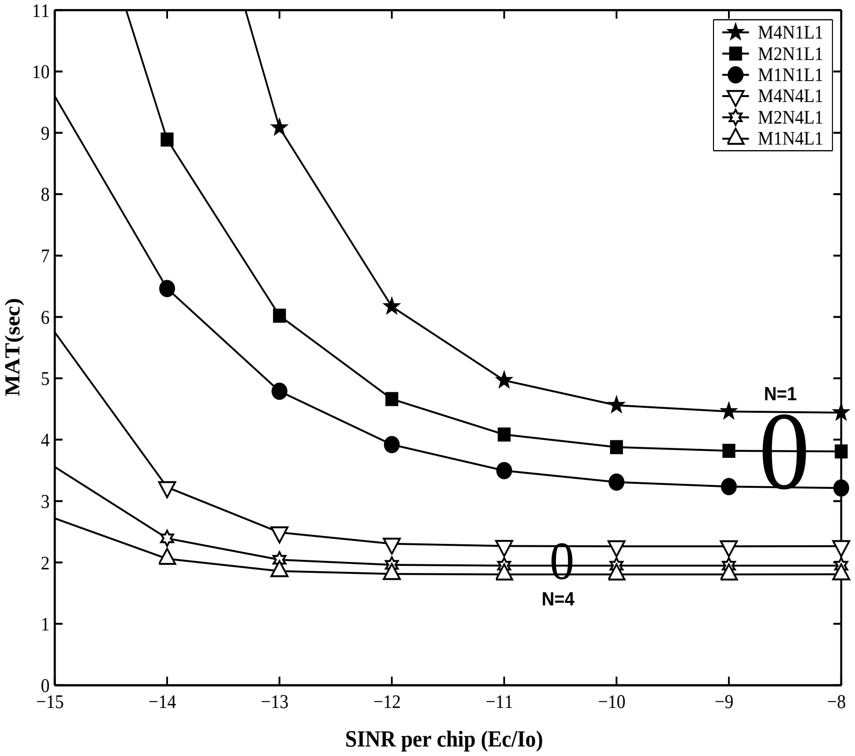

Fig. 3. MAT versus E_c/I_0 performance of the MC-DS-CDMA initial timing synchronisation scheme parameterised with both the number of TAs and RAs for $U = 4$ subcarriers (Copyright of IEEE Transactions on Wireless Communications).

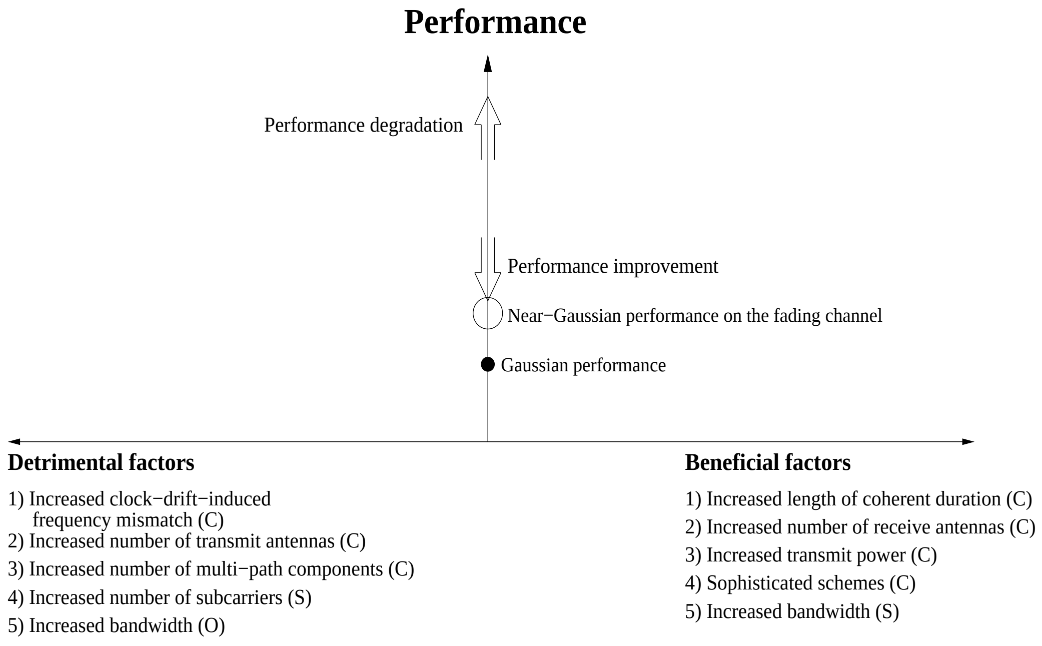

Fig. 4. Relationships between the beneficial and detrimental effects of using TAs and RAs in NC MIMO-aided synchronisation scenarios.