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Overloaded Minimum Total Squared Correlation Signatures Based Pilot Aided System for MC-CDMA and STBC MC-CDMA

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Abstract: This paper proposes multiple-access schemes based on Overloaded Minimum Total Squared Correlation (TSC) signatures, namely Pilot Aided Multi-Carrier Code-Division Multiple-Access (MC-CDMA) and Pilot Aided Space Time Block Codes (STBC) MC-CDMA. Since overloaded minimum TSC signatures were used as the spreading codes, a number of sub-channels in the MC-CDMA and STBC MC-CDMA schemes were not utilized for data transmission. These empty sub-channels can be exploited for comb-type pilot signaling. To maintain low system complexity, for the pilot sub-channels Least Square (LS) estimation was employed and for interpolating the characteristics of the data sub-channels linear interpolator was applied. The validity of the schemes is confirmed by comparing them with the original MC-CDMA method using Walsh-Hadamard orthogonal codes and also with Walsh-Hadamard based STBC MC-CDMA with block-type pilot. All systems use Equal Gain Combining (EGC) or Maximum Ratio Combining (MRC) in the MC-CDMA block at the receiver. The simulation result shows that although the spreading codes of interest are not fully orthogonal codes, for a low number of users the systems under investigation performed better than their Walsh-Hadamard based counterpart. This will be valuable for Wireless Personal Area Network (PAN) where the number of users is typically low.

Key words: Multi-carrier code-division multiple-access (MC-CDMA), Space time block codes (STBC), minimum total squared correlation (TSC)

INTRODUCTION

Multi-carrier CDMA is well-known as the name for hybrid transmission techniques based on code-division multiple-access (CDMA) and Multi-Carrier Modulation (MCM), particularly Orthogonal Frequency Division Multiplexing (OFDM). The hybrid schemes are intended to incorporate the benefits of OFDM, mainly its robustness against frequency selective channel, into CDMA. It can be divided into two groups, i.e. frequency domain spreading and time domain spreading. The spreading on the frequency domain was first introduced by Yee *et al.* (1993) and named Multi-Carrier CDMA (MC-CDMA), which is an intuitively very acceptable name. It was also the first published hybrid MCM and CDMA scheme using the name and since then, the commonly used name for the general idea overlaps with the name for the specific frequency domain spreading case. To differentiate the two, this paper uses multi-carrier CDMA for the general name of the hybrid schemes and MC-CDMA for the specific frequency domain spreading case. As for the time domain spreading method, it was introduced in Multi-Carrier DS-CDMA (MC-DS-CDMA) proposed by DaSilva and Sousa (1993) and also in Multi-Tone CDMA (MT-CDMA) by Vandendorpe (1993).

Later on, induced by the uncovering of the limits and capacity of Multiple Input Multiple Output (MIMO) systems (Foschini and Gans, 1998; Telatar, 1999), Space Time Coding (STC) came forward as a promising method for broadb and wireless communication system. STC schemes optimize channel efficiency in radio communication by effectively utilizing MIMO channel, where coding is performed in the spatial and temporal domain. It is basically employed in MIMO systems to take the benefits of the higher channel capacity. In general, variants of STC can be classified as Space Time Block

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Codes (STBC) (Alamouti, 1998; Tarokh *et al*., 1999a,b), Space Time Trellis Codes (STTC) (Tarokh *et al*., 1998), Space Time Turbo Codes (Liu and Fitz, 1999; Firmanto *et al*., 2002), Layered Space Time (Foschini, 1996; El Gamal and Hammons, 2001; Golden *et al*., 1999) and also concatenated versions of STC with outer channel codes.

In another development, in the area of information theory, Karystinos and Pados (2001, 2003) provided a tight lower bound for total squared correlation (TSC) of a binary signature set. They also established the optimum design of CDMA spreading codes with minimum TSC for almost any number of signatures K and almost any length of signatures L. This opens up possibilities of its application within multi-carrier CDMA schemes and more interestingly the combinations of multi-carrier CDMA and STC.

PROPOSED SYSTEMS

First, based on the concepts of MC-CDMA and minimum TSC spreading codes a pilot aided scheme was designed. In this scheme, the MC-CDMA building block employs overloaded minimum TSC spreading codes based on Pados-Karystinos design. The term overloaded here means that the system capacity (number of available signatures K) is greater than the processing gain (signatures length L).

Naturally, the original MC-CDMA scheme (Yee *et al*., 1993) employs orthogonal codes such as Walsh-Hadamard codes, in which L = K equals to the number of sub-channels M. If the number of sub-channels M is maintained to be the same and the Walsh-Hadamard codes changed with the overloaded minimum TSC codes, which is shorter so that L < M, then there will be some sub-channels which are not occupied by data. Those unused sub-channels can be filled with pilot signals.

Furthermore, by using the concepts of STBC, MC-CDMA and minimum TSC spreading codes a second pilot aided scheme was designed. This scheme is a combination of the first scheme mentioned above with 2×2 STBC system (Alamouti, 1998). Studies on the basic forms of STBC combined with MC-CDMA can be found in (Auffray and Helard, 2002; Hu and Chew, 2003; Zhou *et al*., 2002; Deng *et al*., 2003; Arifianto *et al*., 2006).

In the overloaded minimum TSC based MC-CDMA, for low Multiple-Access Interference (MAI), i.e. low number of operating user K_0, it was expected that since the TSC value is maintained at the minimum, then the advantage of having pilot tones outweigh the drawback of having non-orthogonal codes. This is also expected for the second scheme, i.e. STBC MC-CDMA with overloaded minimum TSC. Note that low number of operating users is commonly found in wireless Personal Area Network (PAN). For example, in a Bluetooth pico-cell the maximum number of active slave is only seven.

MINIMUM TOTAL SQUARED CORRELATION OVERVIEW

Total Squared Correlation: Following descriptions by Karystinos and Pados (2001, 2003), the Total Squared Correlation (TSC) measures the cross-correlation properties of a signature set by taking the sum of the squared magnitudes of all inner products of the signatures. Suppose that S is a set of signatures (complex for generality), or spreading codes (typically binary), c_i, with chip length of L, allowing up to K users as follows:

$$\mathbf{S} = \{c_1, c_2, \ldots, c_K\}, \quad c_i \in \mathbf{C}^L \tag{1}$$

where $\|c_i\| = 1$ and I = 1,2,...,K then the TSC of set S is defined by:

$$\mathrm{TSC}(\mathbf{S}) \equiv \sum_{i=1}^{K} \sum_{j=1}^{K} \left| c_i^H c_j \right|^2 \tag{2}$$

where the superscript ^{H} denotes the hermitian operator.

Minimum TSC: The lower bound of TSC is defined by Welch (1974) as

$$\mathrm{TSC}(\mathbf{S}) \geq \frac{K^2}{L} \tag{3}$$

Although this classical Welch bound is tight for real-valued signatures, the bound is loose for binary signatures whose number is not a multiple of four. Hence, such binary signatures meeting Welch bound do not automatically mean that the binary signatures achieve the minimum TSC value.

The Pados-Karystinos bound is tight for binary signature sets with almost any number of signatures K and almost any length of signatures L. Any binary signatures or spreading codes meeting the bound have the minimum TSC value.

The summary chart of Pados-Karystinos bound for both underloaded and overloaded CDMA system is shown in Fig. 1. The design procedure for obtaining binary signature sets meeting the minimum TSC can be found in (Karystinos and Pados, 2001, 2003).

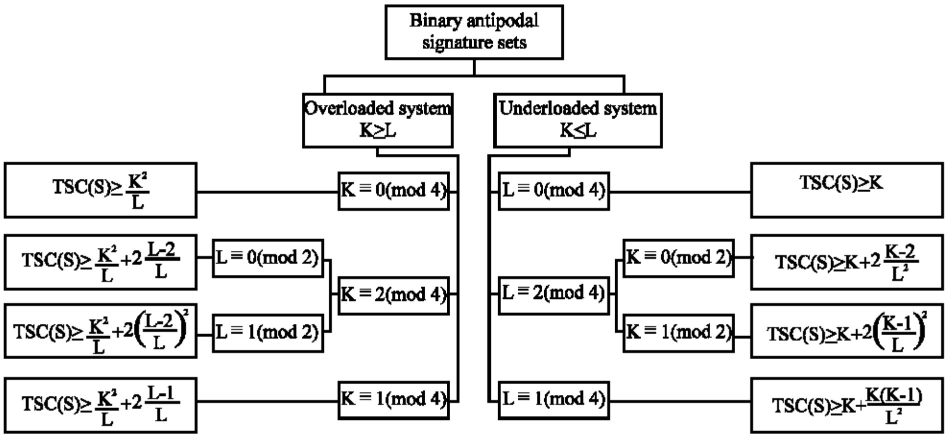

Fig. 1: Pados-Karystinos bound for underloaded and overloaded CDMA spreading codes

SYSTEM MODEL

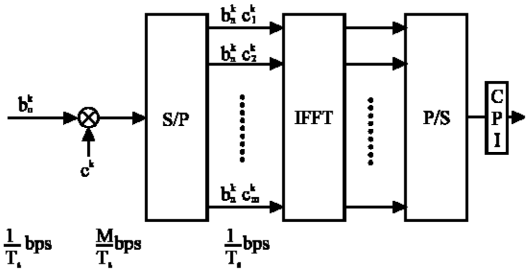

Fig. 2: MC-CDMA transmitter

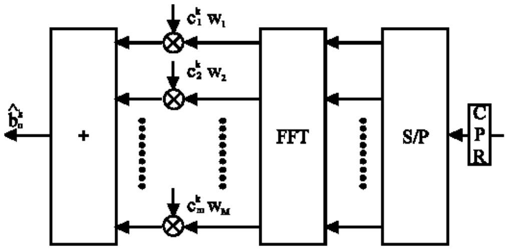

Fig. 3: MC-CDMA receiver

MC-CDMA Block Review: The diagram of the frequency domain spreading MC-CDMA transmitter is shown in Fig. 2. Here, the direct sequence CDMA spreading is still being used. Orthogonal frequency division multiplexing (OFDM), equipped with Cyclic Prefix Insertion (CPI), is performed after the spreading. The serial to parallel operation in the OFDM module operates at the chip level, which implies that each symbol is transmitted on all of the sub-channels, giving frequency diversity. The number of sub-channels M is actually represented by the size of the IFFT block.

Theoretically, in the frequency domain spreading there is no offset between the sequences. Hence, it is clear that orthogonal codes are the finest codes for MC-CDMA. Moreover, the chip length of Walsh-Hadamard codes L, where L, L/12 or L/20 must be a power of 2, fits well with the size of the IFFT block, which is typically a power of 2.

For the MC-CDMA receiver as shown in Fig. 3, after Cyclic Prefix Removal (CPR) and the FFT block, the combiner employs weighting vector w. The simplest case where the weighting vector only consists of '1' is known as Equal Gain Combining (EGC). If the weighting vector element values are the squared amplitudes of the received signal in the sub-channels then the combiner is called Maximum Ratio Combining (MRC). It is under assumption that the higher amplitude has the better SNR, hence given more weight.

Pilot Aided MC-CDMA Using Overloaded Minimum TSC: In an OFDM based system, pilot symbols can be inserted at certain interval at the transmitter so that the received pilot signals can be used for channel estimation at the receiver. There are two types of OFDM pilot arrangement, namely comb-type pilot and block-type pilot (Coleri *et al*., 2002; Hsieh and Wei, 1998).

In comb-type pilot signaling, some of the sub-carriers are always reserved and designated for the purpose of pilot signaling. The comb-type pilot symbols are inserted at fixed frequency interval. Block-type pilot signaling works by assigning all sub-carriers only in a specific period for pilot signaling. The block-type pilot symbols are inserted at fixed time interval.

In our overloaded minimum TSC based MC-CDMA, the chip length is less than the IFFT block size, so that some sub-channels will be unused for data transmission. Thus, it is clear that the pilot to be applied is the comb-type pilot arrangement. The characteristics of the pilot sub-channels can be estimated by Least Square (LS), Minimum Mean Square Error (MMSE) or Least Mean Square (LMS), while characteristics of the data sub-channels can be made available by using interpolation methods (Coleri *et al*., 2002; Hsieh and Wei, 1998).

Pilot Aided STBC MC-CDMA Using Overloaded Minimum TSC: The model of STBC MC-CDMA is presented in Fig. 4. Here, the input to the Alamouti scheme encoder (Alamouti, 1998), of the k-th user, is two consecutive symbols represented as

$$X^k = [x_1^k, x_2^k] \tag{4}$$

and the encoder output matrix is

$$G^k = \begin{bmatrix} g_{11}^k & g_{12}^k \\ g_{21}^k & g_{22}^k \end{bmatrix} = \begin{bmatrix} x_1^k & -x_2^{k*} \\ x_2^k & x_1^{k*} \end{bmatrix} \tag{5}$$

For the orthogonality, the inner product of the output sequences is 0 and the output matrix G satisfies

$$G^k \cdot G^{kH} = pI \tag{6}$$

The first row of the output matrix belongs to the first transmitter Tx_1, while the second row belongs to the second transmitter Tx_2. The first column of the matrix occupies one time slot and the second column occupies the next time slot.

Symbols in each row are processed by MC-CDMA block in each transmitter. In the process, first the symbols are spread by using an L-chip signature. After that, the data streams enter a serial to parallel converter which operates on chip level, dividing one symbol such that each chip of one symbol occupies one sub-channel. Afterwards, inverse FFT of size M is applied to the parallel sub-channels consisting of data and inserted pilot sub-channels.

Let k be the k-th user, j be the j-th transmitter and n be the n-th time slot, then the output of the IFFT operation on each transmitter and time slot for the k-th user is

$$s_{jn}^k = \mathrm{IFFT}[f_p(g_{jn}^k c^k)] \tag{7}$$

where $c^k = [c_1^k \ c_2^k \ c_3^k \ \ldots \ c_L^k]^T$ is the spreading codes for the k-th user, function f_P is considered as the operation for inserting the pilot sub-channels into (M-L) unoccupied sub-channels, while $s_{jn}^k = [s_{jn,1}^k \ s_{jn,2}^k \ s_{jn,3}^k \ \ldots \ s_{jn,M}^k]^T$ is the vector output of the IFFT block. Note that for a synchronous downlink system, the combined output from all users is

$$s_{jn} = \sum_{k=1}^{K} s_{jn}^k \tag{8}$$

Next to that, parallel to serial operation is employed on the output of the IFFT, followed by CPI to provide the guard interval for inter symbol interference protection. The output signal of that step is ready to be transmitted using the RF components and antennas.

Consider that the system has i as the i-th receiver, m as the m-th sub-channel, $\varsigma_{i,n}$ as the noise at the i-th receiver in the n-th time slot and $h_{ij,n}$ is the impulse response of the channel between the j-th receiver and the i-th transmitter in the n-th time slot, then the received signal can be described as

$$r_{ij,n} = s_{jn} * h_{ij,n} + \eta_{i,n} \tag{9}$$

At the receiver, after the receiving antennas and RF components, the received signal in each receiver is processed first by guard interval remover, then serial to parallel operation, followed by FFT. The output of the FFT operation for the pilot sub-channel is

$$R_{i,n,mp}^P = \sum_{j=1}^{J} P_{jn} H_{ij,n,mp} + \eta_{i,n,mP} \tag{10}$$

where P_{jn} is the pilot signal transmitted by the j-th transmitter at the n-th time slot, while subscript m_P into

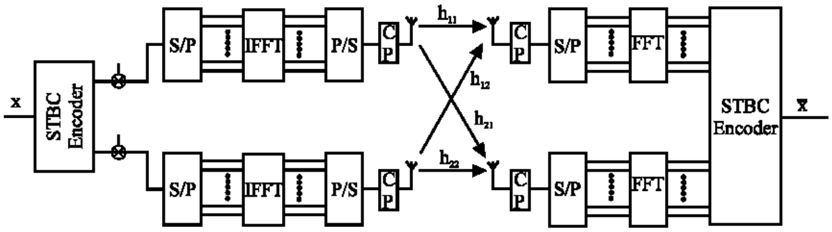

Fig. 4: STBC MC-CDMA diagram

represents the m-th sub-channel being occupied by the pilot. P_{jn} is set such that in a time slot its value is 1 for one transmitter and 0 for the other transmitters. The assignment of 1 should also be rotated from one transmitter to another as the time slot changes. Hence, for the 2 transmitter STBC MC-CDMA, (10) can be converted

$$R^{p}_{i,1,mp} = H_{i1,1,mp} + \eta_{i,1,mP} \tag{11}$$

$$R^{p}_{i,2,mp} = H_{i2,2,mp} + \eta_{i,2,mP} \tag{12}$$

The channel is considered to be unvarying across two consecutive symbol durations. Hence, (11) and (12) may be simplified further by using $H_{ij,mp} = H_{ij,1,mp} = H_{ij,2,mp}$.

The channel estimation methods mentioned in the previous sub-section, namely LS, MMSE and LMS can be applied to the pilot sub-channel output so that $H_{ij,mp}$ can be estimated. Based on the estimation result, $H_{ij,m}$ representing the complete channel response can be approximated by using the interpolation methods.

As for the FFT output for the data sub-channel the expression is

$$R_{i,n,m_\ell} = \sum_{j=1}^{J}\left[H_{ij,n,m_\ell}\sum_{k=1}^{K} c^{k}_{m_\ell} g^{k}_{jn}\right] + \eta_{i,n,m_\ell} \tag{13}$$

where subscript m_ℓ denotes the m-th sub-channel only and only if that sub-channel is being occupied by the ℓ-th chip. The signal in the data sub-channels can be expressed as

$$R_{i,n} = \begin{bmatrix} \sum_{k=1}^{K} c^{k}_{1} \sum_{j=1}^{J} g^{k}_{jn} H_{ij,n,m_1} + \eta_{i,n,m_1} \\ \sum_{k=1}^{K} c^{k}_{2} \sum_{j=1}^{J} g^{k}_{jn} H_{ij,n,m_2} + \eta_{i,n,m_2} \\ \vdots \\ \sum_{k=1}^{K} c^{k}_{L} \sum_{j=1}^{J} g^{k}_{jn} H_{ij,n,m_L} + \eta_{i,n,m_L} \end{bmatrix} \tag{14}$$

The matrix based STBC MC-CDMA decoder block in this model consists of weighting variables given by

$$W_{ij,n,m_\ell} = w_\ell c^{u}_{\ell} H_{ij,n,m_\ell} \tag{15}$$

where c^{u}_{ℓ} is the ℓ-th chip of the spreading codes of the user of interest (single user). In the vector notation, it is written as

$$W_{ij,n} = [w_1 c^{u}_{1} H_{ij,n,1} \quad w_2 c^{u}_{2} H_{ij,n,2} \quad \dots \quad w_L c^{u}_{L} H_{ij,n,m_L}]^{T} \tag{16}$$

On the assumption that $H_{ij,m} = H_{ij,1,m} = H_{ij,2,m}$, consequently $W_{ij,m} = W_{ij,1,m} = W_{ij,2,m}$ and $W_{ij} = W_{ij,1} = W_{ij,2}$ also hold. By using (14) and (16), as well as holding that assumption, the decision statistics for the 2×2 STBC MC-CDMA for the first symbol and the second symbol can be written as

$$\tilde{x}^{u}_{1} = W^{H}_{11} R_{1,1} + R^{H}_{1,2} W_{12} + W^{H}_{21} R_{2,1} + R^{H}_{2,2} W_{22} \tag{17}$$

$$\tilde{x}^{u}_{2} = W^{H}_{12} R_{1,1} - R^{H}_{1,2} W_{11} + W^{H}_{22} R_{2,1} - R^{H}_{2,2} W_{21} \tag{18}$$

If all values of w_l are 1 then (17) and (18) will maintain the classical definition of EGC in MC-CDMA. Where as to maintain the one for MRC, $w_m = [\sum_i \sum_j |H_{ij,m}|^2]$.

SIMULATIONS

The simulated schemes were pilot-aided minimum TSC based MC-CDMA and STBC MC-CDMA with comb-type pilot arrangement, original Walsh-Hadamard based MC-CDMA without pilot and STBC MC-CDMA using block-type pilot arrangement. All have implementations using the EGC and MRC combining. For fair comparison, all the systems were given equal IFFT block size of 32. Each of them used the same cyclic prefix guard interval of 12.5%. All were fed by r andom BPSK data symbols of 10 Mbps.

For the STBC MC-CDMA, all schemes were subjected to identical uncorrelated 2×2 MIMO channel model. Each MIMO entries is simulated by the 3-tap model of JTC 94 Indoor Channel Model-Residential A (Pahlavan and Levesque, 1995) as shown in Table 1. Each tap undergoes rayleigh fading with the assumption of maximum users velocity 1.5 m/s and 17 GHz carrier frequency, which creates maximum Doppler frequency of 85Hz. The same channel model was also implemented for the MC-CDMA schemes, which are single input single output (SISO) in nature with single channel entry.

All the pilot-aided minimum TSC based schemes employed the overloaded minimum TSC spreading codes with L = 18 and K = 32 generated according to (Karystinos and Pados, 2003). Hence, out of the M = 32 sub-channels, 14 of them were not being utilized for data transmission. Then, those 14 sub-channels, that were arranged to be located evenly within the 32 sub-channels, were filled by the comb-type pilot symbols. The pilot sub-channels characteristics were estimated by LS

Table 1: JTC 94 Indoor Channel Model-Residential A

Tap	Delay (ns)	Loss (dB)
1	0	0.0
2	50	-9.4
3	100	-18.9

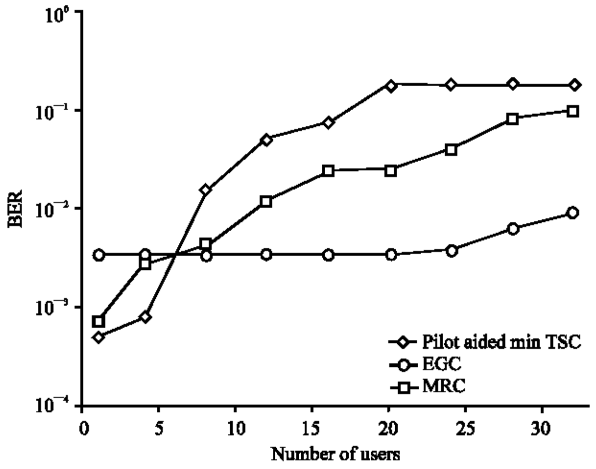

Fig. 5: BER vs Number of Operating Users for MC-CDMA using EGC, MRC and pilot-aided minimum TSC (E_b/N_0 =15 dB)

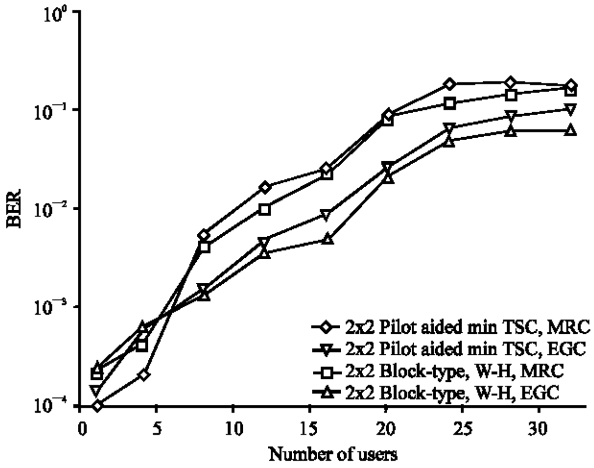

Fig. 6: BER vs Number of Operating Users for STBC MC- CDMA using the block-type pilot Walsh-Hadamard (W-H) and using the comb-type pilot-aided minimum TSC (E_b/N_0 =15 dB)

method. Then, the channel characteristics available from the pilot signaling system were exploited to interpolate the channel transfer function in all sub-channels. Here, the interpolation mechanism worked by means of linear interpolation method. The LS method and linear interpolation were selected for their relatively low complexity and fast processing time. As for the Walsh-Hadamard based schemes system, L = K = 32 equaling the size of the IFFT block M = 32 were being used.

The simulation result in terms of BER vs. number of operating users K_0 is shown in Fig. 5 and Fig. 6 for MC-CDMA and STBC MC-CDMA respectively. Obviously, as the number of operating users K_0 increases, MAI increases as well, instigating BER to become worse. In Fig. 5, it can be observed that although the overloaded Minimum TSC codes are not orthogonal, for low number of users (less than seven users) the MC-CDMA system under test outperformed EGC and MRC based MC-CDMA. Here, the benefit of having minimum TSC property and channel information is indeed more than the drawbacks of having shorter and non orthogonal codes. Here, the EGC and MRC based MC-CDMA does not make use of channel information.

Similarly, in Fig. 6, it is shown that the comb-type pilot aided STBC MC-CDMA with non-orthogonal overloaded Minimum TSC codes outperformed the Walsh-Hadamard based STBC MC-CDMA with block-type pilot for both cases EGC and MRC frequency combining, for lower number of operating users. The proposed system performed better than the original one when it was less than eight users when both utilized MRC and less than seven users for EGC. Overall, less than seven users should be maintained for the system of interest to outperform the original one. In this case, the benefit of having the minimum TSC property and continuously having updated channel information is indeed more than the drawbacks of having shorter and non orthogonal codes. Note that the Walsh-Hadamard based STBC MC-CDMA schemes here take the benefits of the availability of channel information required in the STBC processing.

For the larger number of operating users, the systems under test performed worse than the benchmark system, i.e the Walsh-Hadamard based systems. For the same number of operating users the overloaded minimum TSC schemes have higher level of MAI compared to that of the benchmark system. Higher level of MAI is the consequence of using shorter codes (L = 18 compared to L = 32). Not only that, they are also having more burdens from the non zero cross correlation property of the overloaded minimum TSC.

For the MC-CDMA scheme of interest, for the larger number of operating users, this higher level of MAI is negatively affecting it more than the positive effect of using the channel information given by the pilot signaling. Similarly for the STBC MC-CDMA with overloaded minimum TSC codes, for the larger number of operating users, this higher level of MAI is negatively affecting the system of interest more than the positive effect of having the continuously updated channel information given by the comb-type pilot signaling.

It is also noted that when the systems of interest, both pilot aided MC-CDMA and STBC MC-CDMA with overloaded minimum TSC codes, are "operationally overloaded", i.e. when the number of operating users $K_0 > L$, the performance begins to deteriorate faster.

CONCLUSIONS

This work has shown that for a low number of users, for the same size of IFFT block and the same system capacity, STBC MC-CDMA with overloaded minimum TSC spreading codes combined with a very simple and low complexity linearly interpolated comb-type pilot and LS channel estimation performed better than STBC MC-CDMA with Walsh-Hadamard orthogonal codes using block-type arrangement. For MC-CDMA, the pilot aided system with overloaded minimum TSC codes is also found to be superior compared to the original Walsh-Hadamard based MC-CDMA for low number of users, i.e. less than seven users. These results make the schemes of interest attractive for Wireless PAN where the typical number of operating users is low.

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