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# On the Performance of Algebraic STBCs in WiMax Systems

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**Abstract:** WiMax is a wireless technology promising to deliver high data rates over large areas to a great number of users. In this paper, the performances of several algebraic space-time codes are investigated in a WiMax environment for different multi-antennae configurations, and by applying various detection methods. These performances are then compared against those of other space-time codes supported by the WiMax technology. The new results obtained here indicate that the algebraic space-time block codes, which are known to greatly outperform any other kind of space-time block codes in uncoded systems, perform slightly better than simple spatial multiplexing schemes in WiMax systems, but with a far greater decoding complexity. They also show that orthogonal space-time or spatial multiplexing codes are better adapted than algebraic space-time codes to multiple antennae transmission in WiMax systems, when performance and complexity are both taken into account.

**Keywords:** WiMax, OFDMA, MIMO, Space-Time codes, ML detection.

## 1. Introduction

Worldwide interoperability for Microwave access (WiMax) is a wireless communication technology designed to provide wireless transmission over long distances in a variety of ways, from point-to-point links to full mobile cellular types of accesses. This technology is based on the IEEE 802.16 standard [1], i.e., wireless Metropolitan Area Network (MAN) standard, and since its introduction in 2001 it has evolved into several versions, namely 'a', 'd' referred as the fixed WiMax, and 'e' referred as the mobile WiMax [2].

In the latest version of the IEEE 802.16e standard [2], four physical layer techniques have been developed for different uses and several frequency bands, namely the wireless MAN-Single-Carrier (SC), the wireless MAN-SCa, the wireless MAN-Orthogonal Frequency Division Multiplexing (OFDM), and the wireless MAN-Orthogonal Frequency Division Multiple Access (OFDMA). Moreover, the 802.16e standard defines several combinations of modulations, channel coding methods, and rates that enable a fine tuning of the data rate or the system robustness according to the propagation environment, for each physical layer technique. In this paper, we consider the wireless MAN-OFDMA air interface since it fully supports the use of spatial diversity coding schemes, e.g., Space-Time Block Codes (STBCs), in order to improve the transmission in mobility conditions.

In wireless communications, Multiple Input Multiple Output (MIMO) architectures generate spatial diversity to improve the spectral efficiency and to increase the transmission reliability, as shown in [3] and [4] for WiMax systems. STBCs are well-know codes that can take advantage of this diversity and some of them, i.e., Alamouti scheme [5], Orthogonal STBCs (OSTBCs) and Spatial Multiplexing (SM) codes, are already part of the IEEE 802.16 standard [1 Section 8.4.8]. On the one hand, OSTBCs provide full diversity, exhibit low decoding-complexity, but are not full-rate codes. On the other hand, SM codes are full-rate codes, but they provide no diversity. Recently, Algebraic STBCs (ASTBCs)

 

[6], [7] have been designed to combine both the advantages of OSTBC and SM codes and have proven to convincingly outperform these codes in uncoded systems, as shown in Figs. 2 and 3. In this paper, a performance comparison of these different STBCs is undertaken in order to establish if the use of advanced STBCs, i.e., ASTBCs, can be beneficial in WiMax systems. Furthermore, the computational complexity of the decoder is also considered here and several decoders are compared, namely, the Minimum Mean Square Error (MMSE) decoder [8], the Maximum Likelihood (ML) decoder [8], the Maximum A Posteriori (MAP) decoder [9], and the Soft-Input Soft-Output Sphere Decoder (SISO-SD) [9].

## 2. Wireless MAN-OFDMA Air Interface

This section provides a brief overview of the IEEE 802.16 physical layer, specifically the Wireless MAN-OFDMA air interface which is designed to support multi-antennae architectures, as explained in [1 Section 8.4] and [2 Section 8.4].

### *2.1 General Design*

This air interface is designed for Non-Line of Sight (NLOS) operation in the frequency bands between 2-5 and 11 GHz, and using bandwidth sizes from a minimum of 1.25 MHz up to 28 MHz. The OFDM modulation is accommodated over the bandwidth using four possible Fast Fourier Transform (FFT) sizes of 128, 512, 1024, and 2048 and four possible guard time overhead lengths. Moreover, the standard provides flexible mapping of users' data into sub-carriers of the OFDM signal. The two dimensional radio resources composed of OFDM sub-carriers, i.e., frequency domain, and their continuation along the time domain, are allocated to different users. The three main types of mapping are the Partial Usage of Sub-Carriers (PUSC), the Full Usage of Sub-Carriers (FUSC), and the Advanced Modulation and Coding (AMC) mapping. Furthermore, the sub-carriers can either be allocated in an adjacent or a distributed manner. The other main parameters of the Wireless MAN-OFDMA air interface, i.e., Forward Error Correction (FEC), interleaving, and modulation, are detailed in [1 Section 8.4], and the block diagram of the modulator and the FEC codec can be found at [1 Figure 252].

### *2.2 Multi-Antennae Architecture*

Three major multi-antennae transmission techniques have been adopted in the Wireless MAN-OFDMA physical layer standard, namely, STBC coding, uplink Collaborative Spatial Multiplexing (CSM), and MIMO pre-coding. STBC and CSM must be used along with distributed PUSC or FUSC sub-carrier mapping to take advantage of the diversity, and these mappings must be modified to accommodate MIMO channel estimation. For instance, a PUSC mapping structure modified to accommodate a 2x2 STBC scheme is presented in Figure 1, for both the DownLink (DL) and the UpLink (UL).

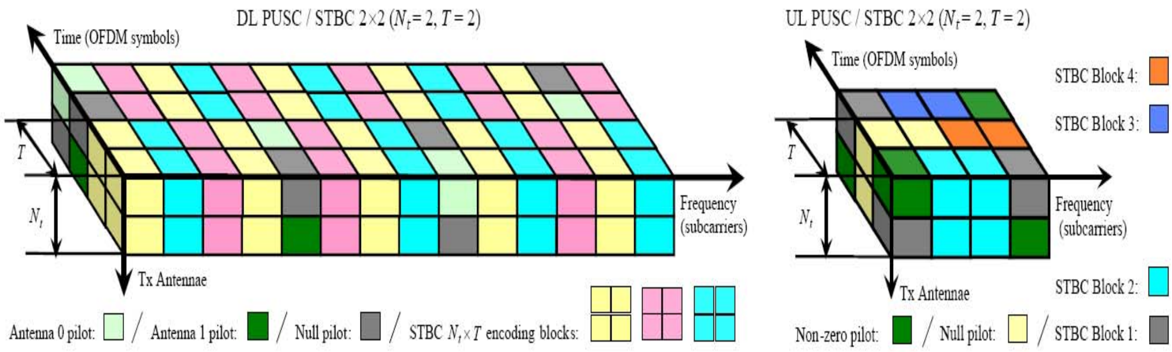


*Figure 1: DL(left) / UL(right) Modified PUSC Mapping Structure for a 2x2 WiMax STBC System*

Several STBCs are specified in the standard, specifically in the DL for a number of transmit antennae $N_t$= 2, 3, and 4. In the UL, CSM can be applied using the PUSC sub-carrier mapping. Practically, CSM allows two users to share the same time-frequency resource. The processing gain due to multiple receive-antennae enables the two users' signals to be dissociated by the receiver. The STBCs defined for the UL are similar to those defined for the DL, but where transmit data symbols are split amongst the users; hence, each user uses a different part of the STBC, as illustrated by $\boldsymbol{B_2}$ in (1), which is the counterpart of $\boldsymbol{B}$ for CSM in the UL. For $N_t$= 2, the Alamouti scheme (AL) and the SM scheme (SM2) can be applied in the DL, and the CSM scheme for (CSM2) can be applied in the UL, with respective transmission matrices as follows [1 Section 8.4.8.1.4]

$$\boldsymbol{A} = \begin{pmatrix} s_{u,i} & -s_{u,i+1}^{*} \\ s_{u,i+1} & s_{u,i}^{*} \end{pmatrix}, \boldsymbol{B} = \begin{pmatrix} s_{u,i} \\ s_{u,i+1} \end{pmatrix}, \boldsymbol{B_2} = \begin{pmatrix} s_{u,i} \\ s_{u+1,i} \end{pmatrix}, \quad (1)$$

where $s$ is a symbol, $i$ is the symbol number index, $u$ is the user number index, and (.)* denotes the complex conjugate operand. Also in [2 Section 8.4.8.3.3], a transmission matrix based on an ASTBC, i.e., the Golden Code (GC) [6], is defined for the optional zones of the DL as follows

$$\boldsymbol{C} = \begin{pmatrix} s_{u,i} + j\phi s_{u,i+3} & \phi s_{u,i+1} + js_{u,i+2} \\ s_{u,i+1} - \phi js_{u,i+2} & j\phi s_{u,i} + s_{u,i+3} \end{pmatrix}, \quad (2)$$

where $\phi = \left(-1+\sqrt{5}\right)/2$. For $N_t$= 4, two OSTBC codes (OSTBC4A) and (OSTBC4B) along with the SM scheme (SM4) are defined for the DL, with respective transmission matrices as follows [1 Section 8.4.8.1.4]

$$\boldsymbol{A} = \begin{pmatrix} s_{u,i} & -s_{u,i+1}^{*} & 0 & 0 \\ s_{u,i+1} & s_{u,i}^{*} & 0 & 0 \\ 0 & 0 & s_{u,i+2} & -s_{u,i+3}^{*} \\ 0 & 0 & s_{u,i+3} & s_{u,i+2}^{*} \end{pmatrix}, \boldsymbol{B} = \begin{pmatrix} s_{u,i} & -s_{u,i+1}^{*} & s_{u,i+4} & -s_{u,i+5}^{*} \\ s_{u,i+1} & s_{u,i}^{*} & s_{u,i+5} & s_{u,i+4}^{*} \\ s_{u,i+2} & -s_{u,i+3}^{*} & s_{u,i+6} & -s_{u,i+7}^{*} \\ s_{u,i+3} & s_{u,i+2}^{*} & s_{u,i+7} & s_{u,i+6}^{*} \end{pmatrix}, \quad (3)$$

$$\boldsymbol{C} = \begin{pmatrix} s_{u,i} & s_{u,i+1} & s_{u,i+2} & s_{u,i+3} \end{pmatrix},$$

where $(.)^{T}$ is the transpose operand. In the UL, the counterpart codes based on matrices $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$, i.e., CSM4A, CSM4B, and CSM4C, respectively, are defined for two users as

$$\boldsymbol{A_4} = \begin{pmatrix} s_{u,i} & -s_{u,i+1}^{*} & 0 & 0 \\ s_{u,i+1} & s_{u,i}^{*} & 0 & 0 \\ 0 & 0 & s_{u+1,i} & -s_{u+1,i+1}^{*} \\ 0 & 0 & s_{u+1,i+1} & s_{u+1,i}^{*} \end{pmatrix}, \boldsymbol{B_4} = \begin{pmatrix} s_{u,i} & -s_{u,i+1}^{*} & s_{u,i+2} & -s_{u,i+3}^{*} \\ s_{u,i+1} & s_{u,i}^{*} & s_{u,i+3} & s_{u,i+2}^{*} \\ s_{u+1,i} & -s_{u+1,i+1}^{*} & s_{u+1,i+2} & -s_{u+1,i+3}^{*} \\ s_{u+1,i+1} & s_{u+1,i}^{*} & s_{u+1,i+3} & s_{u+1,i+2}^{*} \end{pmatrix}, \quad (4)$$

$$\boldsymbol{C_4} = \begin{pmatrix} s_{u,i} & s_{u,i+1} & s_{u+1,i} & s_{u+1,i+1} \end{pmatrix}.$$

## 3. STBC System Model and Parameters

In STBC coding, a block of $Q$ data symbols or chips are transmitted during a period $T$ over $N_t$ transmit antennae and received over $N_r$ receive antennae. The total transmitted power is constrained to unity, for any $N_t$. Moreover, any STBC codeword can be represented by an $N_t$x$T$ matrix that contains the $Q$ distinct data symbols. The rate of the STBC $R_c$ is given by $R_c$= $Q/T$ and its transmit diversity order $D_c$ depends on the rank criterion. STBCs with rates greater than one provide a multiplexing gain and increase the data rate by a factor of $R_c$. STBCs with high diversity order improve the bit or Packet-Error Rate (PER) performance.

Algebraic STBCs, e.g., the GC for $N_t= N_r= 2$ and the Perfect STBC (PSTBC4) for $N_t= N_r= 4$ [7], are based on linear dispersion codes where division algebras are used to construct efficient codes. A division algebra is an algebraic object that naturally yields a linear set of invertible matrices. Thus, algebraic STBCs are fully diverse, have a full-rate, a uniform average transmitted energy per antenna, and a non-vanishing constant minimum determinant for increasing spectral efficiency. They require SD or MAP decoding.

OSTBCs, as the Alamouti scheme, can generally achieve full diversity, i.e., $D_c= N_t$ but with a data rate lower or equal to one. They can also provide a multiplexing gain but with a lower diversity as $\boldsymbol{B}$ in (3). Moreover, these codes can be decoded in a ML fashion using low-complexity linear decoders such as MMSE decoders.

SM codes allow to transmit at full-rate, i.e., $R_c= N_t$, but without any diversity gain. They are useful to multiplex data on several antennae and can be decoded using a simple decoder such as VBLAST [10] if $N_t \geq N_r$, or using more complex decoders such as SD or MAP.

ASTBCs greatly outperform both SM codes and OSTBCs in an uncoded system over a Rayleigh fading channel, as it is shown in Figs. 2 and 3 for a 2x2 and 4x4 antennae configuration, respectively. Thus, in Figure 2, GC with a QPSK outperformed both AL with a 16-QAM and SM2 with a QPSK by 3dB and almost 6dB at a PER of $1.10^{-3}$, sequentially, for an equivalent STBC rate of $R_c= 2$. In Figure 3, the evaluation of 4x4 STBC systems show that the PSTBC4 outperformed the OSTBC4A, the OSTBC4B, and the SM4A schemes for the same STBC rate of $R_c= 4$ by 14 dB, 4.9 dB and 5.1 dB at a PER of $1.10^{-3}$, respectively. Moreover, the results confirm that PSTBC4 provides more diversity than the three other schemes. Thus, the ASTBC code design proves to be more efficient than the OSTBC and SM code designs in an uncoded system.

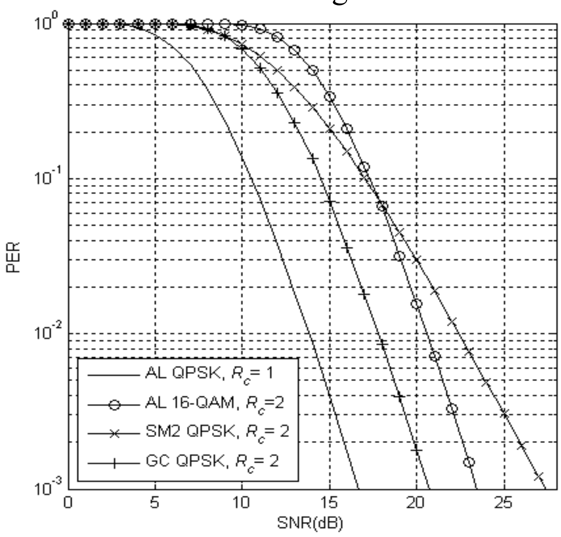


*Figure 2: PER Performance of SM2,AL, and GC Codes Over a Rayleigh Fading Channel*

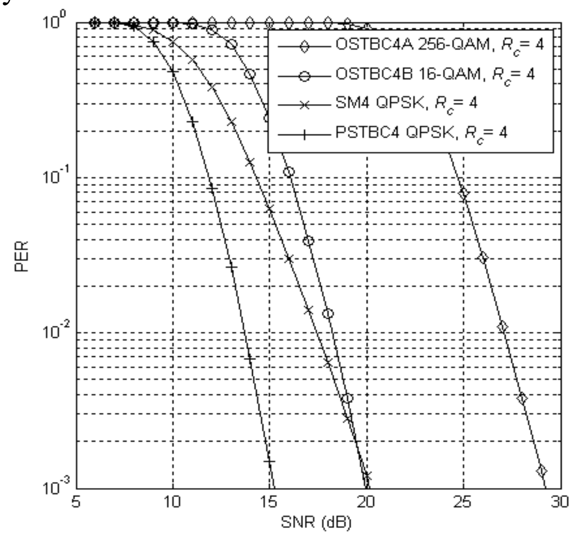


*Figure 3: PER Performance of SM4, OSTBC4A, OSTBC4B & PSTBC4 over Rayleigh Fading Channel*

The various STBCs considered in this paper and their respective parameters are summarised in Table 1. Diagrams of WiMax STBC coding systems for the DL and UL transmissions can be found in [1 Section 8.4.8.1].

*Table 1: Various STBCs' Parameters*

| STBCs \ parameters | $N_t$ | $Q$ | $T$ | $R_c$ | $D_c$ |
|---|---|---|---|---|---|
| AL | 2 | 2 | 2 | 1 | 2 |
| SM2, CSM2 | 2 | 2 | 1 | 2 | 1 |
| GC | 2 | 4 | 2 | 2 | 2 |
| OSTBC4A, CSM4A | 4 | 4 | 4 | 1 | 2 |
| OSTBC4B, CSM4B | 4 | 8 | 4 | 2 | 2 |
| SM4, CSM4 | 4 | 4 | 1 | 4 | 1 |
| PSTBC4 | 4 | 16 | 4 | 4 | 4 |

# 4. Performance of STBCs in Wireless MAN-OFDMA Air Interface

## *4.1 Receiver model for WiMax systems*

The receiver waits for $Q$ symbols and combines these symbols on a sub-carrier basis using linear or non-linear detection methods. Four types of decoders supporting different levels of complexity and performance are compared here. MMSE is a linear detection technique that has been developed to reduce the computational complexity requirements of the ML receiver. Despite its lower complexity in comparison with ML-based detectors, it can achieve ML performance if the different transmit sub-channels are independent, i.e., orthogonals. It forms the case when OSTBCs are used at the transmitter side. In ML detection, the detector enumerates every possible combination of transmitted codewords on each sub-carrier and it then computes the pairwise error probability knowing the received codeword for each combination. Eventually, the transmitted codeword that minimises this probability is outputted. MAP detection [9] is a ML based technique, that uses all the pairwise error probability combinations, i.e., $N_L^{max}= M^Q$, to obtain the bit reliability information of any bit using the A Posteriori Probability (APP) technique. MAP detection is optimum from a statistical point of view, however its complexity may become excessive if $N_L^{max} >> 1$. In order to reduce the complexity and maintain the ML performance, SISO-SD was introduced in [9]. It is a low-complexity ML scheme, which is based on SD, that finds codewords minimising the pairwise error probability in a smaller sub-set of combinations $N_L \leq N_L^{max}$ compared to ML or MAP. This sub-set contains only the $N_L$ codewords with minimum pairwise error probability. As in MAP, the sub-set of pairwise error probability is used to determine the APP and then to extract the bit reliability information. MAP detection is equivalent to SISO-SD for $N_L= N_L^{max}$, and ML is equivalent to SISO-SD for $N_L= 1$.

## *4.2 Performance Evaluation*

In this section, the PER performance evaluation in WiMax systems of the various STBCs introduced in Sections *2.2* and *3* is presented and discussed using the following settings: the frequency band is 3.4 – 3.7 GHz, the bandwidth is 5 MHz, the FFT size is 512, the sampling factor is 28/25, the guard to useful time ratio is 1/8, the sub-carrier mappings are DL or UL PUSC with all sub-channels, the FEC code is a CCTB, and the Modulation Coding Schemes (MCSs) are 4-QAM½ or 16-QAM¾. The results are obtained for the car scenario of the Fireworks channel model [11]. More specifically, WiMax communications over an Urban Outdoor High-to-Low (UOHL) or over an Urban Outdoor Medium-to-Low (UOML) channel model for high mobility (0-120khm) are simulated, for a NLOS antenna configuration. Perfect channel estimation is assumed for all the simulations presented here.

The PER performance comparison of the SM2, AL and GC codes in a WiMax system is presented in Figure 4, considering a DL PUSC sub-carrier mapping (26 symbols), a QPSK ½ MCS, $N_r$ =2 receive antennae, and using either ML, MMSE, SISO-SD or MAP detection. In comparison with the results obtained for uncoded systems in Figure 2, the performance gap of 5 to 6 dB between AL and GC is unchanged while the large performance difference between SM2 and GC is almost reduced to 0.2 dB at a PER of $1.10^{-2}$ for MAP detection. As far as MMSE detection is concerned, it provides the optimum MAP performance when used to decode AL, and SM2 performs better than GC with this type of low-complexity detection. The performance of SM2 and GC improves as the decoding complexity increases. Thus, SM2 and GC decoded through MMSE performs 5.5 dB lower than if optimally decoded using MAP, at a PER of $1.10^{-2}$. Then, using ML or equivalently a $N_L$=1 SISO-SD detector improves the performance of SM2 and GC by 1 to 2 dB, respectively. The performance difference between SISO-SD and MAP detections decreases as the computational complexity, i.e., $N_L$, increases, and finally the performances of SM2 and GC are similar for MAP detection, i.e., a 0.2 dB difference at a PER of $1.10^{-2}$. The convergence of SM2 performance towards GC performance is mainly due to channel coding effect, and it has also been noticed in an IEEE 802.11n environment in [11]. In Figure 5, where $N_L^{max}$= 16 for SM2 and $N_L^{max}$= 256 for GC, it appears that SM2 with a $N_L$= 10 SISO-SD detector and GC with a $N_L$= 40 SISO-SD detector performs similarly to SM2 and GC with a MAP detector. Notice that GC with SISO-SD requires more complexity, i.e., a larger $N_L$ value, to reach the MAP performance than SM2. In addition, when a $N_L$= 10 SISO-SD detector is used SM2 performs better than GC, i.e., 0.5 dB at a PER of $1.10^{-2}$.

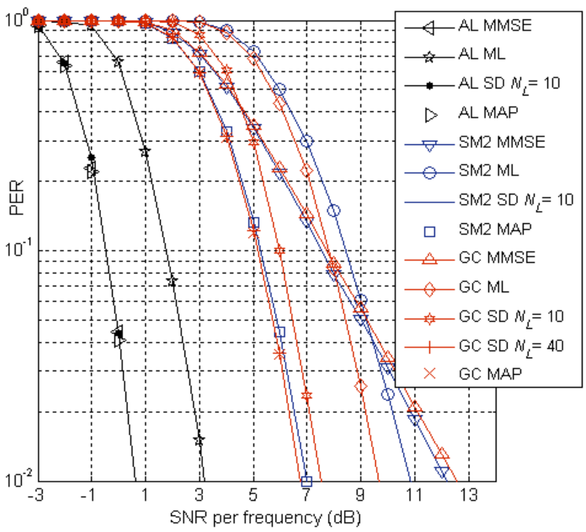


*Figure 4: PER Performance of AL, SM2, GC Codes Over the UOML Channel Model, DL PUSC, QPSK½ MCS, Various Detection Schemes*

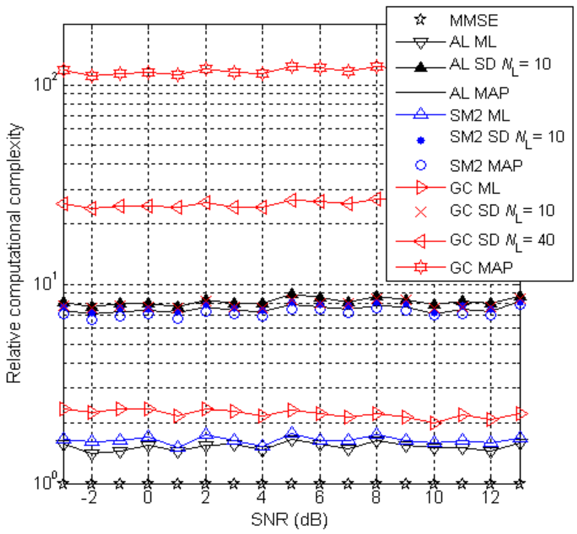


*Figure 5: Relative Computational Complexity of Various Detection Schemes, Using the Same WiMax Settings as in Figure 4*

In Figure 5, we provide a measurement of the relative computational complexity, i.e., the average decoding time per packet normalised to the average packet decoding time using MMSE detection. The results clearly show that MMSE is the less complex detection technique, then ML, SISO-SD and MAP. The complexity of SISO-SD increases with $N_L$. Also, the packet decoding time using GC with MAP is 100 times larger than with MMSE.

In Figure 6, the PER performance comparison of the CSM2, AL and GC is considered for the UL PUSC sub-carrier mapping (21 symbols), a QPSK½ MCS, $N_r$ = 2 receive antennae, and using all the detection schemes specified in Section *4.1*. The results provided here for the uplink are consistent with those obtained for the downlink in Figure 4. Moreover the optimum performance of CSM2 and GC codes with MAP detection are the same, and are equivalent to the performance of CSM2 with a $N_L$= 10 SISO-SD detector.

In Figure 7, the performance evaluation of the system analysed in Figure 4 is carried out over the UOHL channel model. Consequently, similar observations can be made and therefore similar conclusions can be drawn. These conclusions are further supported by the results obtained in Figure 8, where the PER performance comparison of the AL, SM2, and

GC codes is illustrated for a 16-QAM¾ MCS and DL transmission. As indicated in Figure 4, a gain which is greater to 6 dB at a PER of $2.10^{-2}$ can be observed when SM2 or GC is combined with MAP instead of MMSE detection. SM2 with a SISO-SD decoder can reach the performance of SM2 with a MAP decoder for only $N_L$= 10 instead of $N_L^{max}$= 256. The complexity of GC with MAP detection being high, i.e., $N_L^{max}$= 65536, SISO-SD enables to obtain good performance with lower complexity, i.e., $N_L$= 10 or 40. Notice also, that if the FEC rate increases, i.e., 3/4 instead of 1/2 in Figure 5, the performance difference between GC and SM2 increases. Thus, GC outperforms SM2 for SISO-SD with $N_L$= 10 by about 0.4 dB at a PER of $1.10^{-2}$, and this gain is further increased by 0.3 dB when $N_L$= 40. However, this gain remains marginal compared to the uncoded system performance in Figure 2.

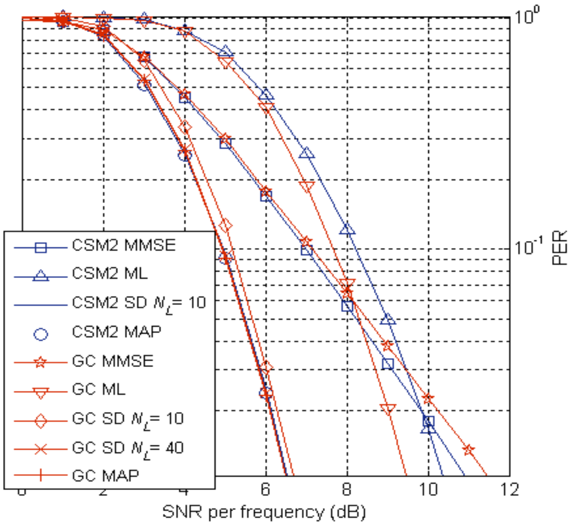


*Figure 6: PER Performance of CSM2, GC Codes Over the UOML Channel Model, UL PUSC, QPSK½ MCS, SISO-SD vs. MAP Detection*

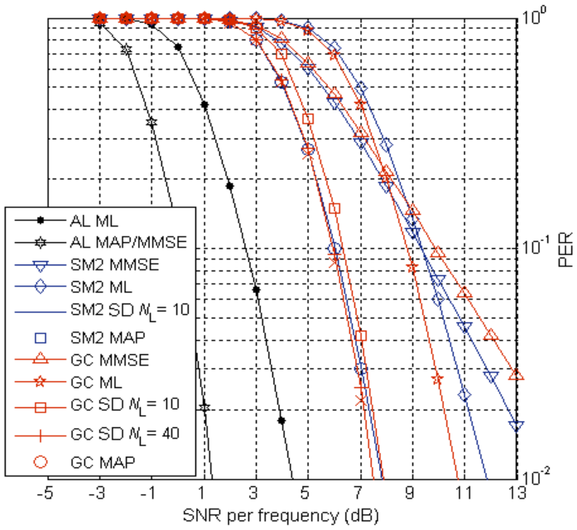


*Figure 7: PER Performance of AL, SM2, GC Codes Over the UOHL Channel Model, DL PUSC, QPSK½ MCS, Various Detection Schemes*

Figure 9 presents PER performance comparison of OSTBC4A, OSTBC4B, SM4 and PSTBC4 codes over the UOML channel model, considering a DL PUSC sub-carrier mapping (26 symbols), a QPSK½ MCS, $N_r$ = 4 receive antennae, and applying various detection schemes. The performance difference between PSTBC4 and SM4 is different from that observed in an uncoded system(Figure 3). As for 2x2 antenna configuration, MMSE detection is not efficient for non-OSTBCs. As in Figure 8, the complexity of the GC with MAP detection being very high, i.e., $N_L^{max}$ $=2^{32}$, SISO-SD is required to reach the best sub-optimal performance. If MMSE or $N_L$= 10 SISO-SD detections are applied, then SM4 outperforms PSTBC4, otherwise for SISO-SD with $N_L$= 1 or $N_L$= 40, PSTCB4 will improve system performance by 0.9 dB and 0.3 dB at a PER of $1.10^{-2}$, respectively.

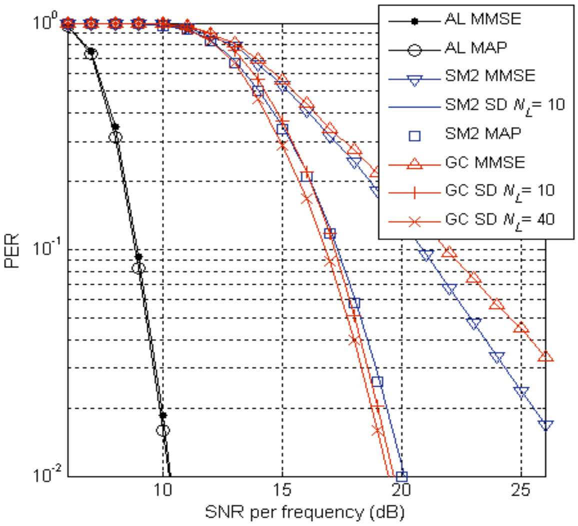


*Figure 8: PER Performance of AL, SM2, GC Codes Over the UOML Channel Model, DL PUSC, 16-QAM¾ MCS, MMSE vs. ML/MAP Detection*

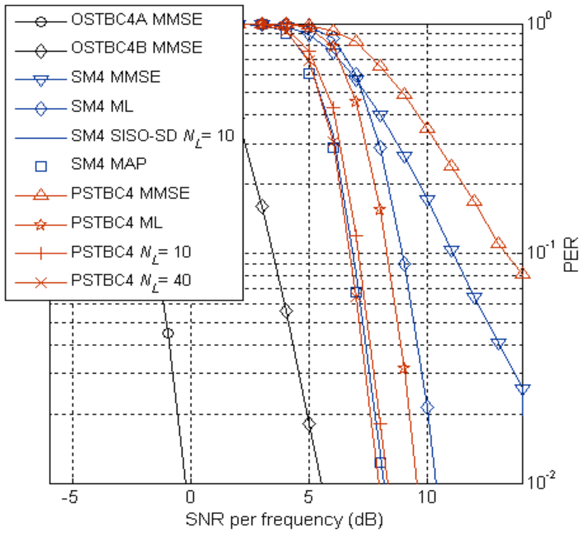


*Figure 9: PER Performance of OSTBC4A/B, SM4 and PSTBC4 Codes Over the UOML Channel Model, DL PUSC, QPSK½ MCS, MMSE vs. ML/MAP Detection*

## 5. Conclusions

In this paper, the performance of ASTBCs and other STBCs supported by the Wireless MAN-OFDMA air interface have been investigated and compared in a WiMax environment. The new performance evaluation results presented in this paper for different STBCs in a WiMax system, different multi-antennae configurations, and applying various detection methods indicate that ASTBCs provides only a marginal performance gain in WiMax systems in comparison with other simpler STBCs despite their higher decoding complexity. The main results of our analysis can be summarised as follows:

- OSTBCs perform similarly with MAP or MMSE detectors due to the orthogonally of these codes. OSTBCs provide lower performances than other STBCs for a given data rate, i.e., 3dB. However, OSTBCs with MMSE detection exhibit a very-low complexity.
- SM codes with SISO-SD detection always require a lower computational complexity, i.e., a lower $N_L$ value, than ASTBCs to reach the optimal MAP performance.
- SM and ASTBC MAP performances are similar for low FEC rate, i.e. ≤1/2. For higher rate, ASTBCs perform better than SM codes, and the performances difference increases as the FEC rate increases. However, ASTBC MAP decoding requires more complexity.
- From an implementation point of view, the complexity of the STBC encoder is roughly similar for any STBCs. MMSE and ML detectors are easy to implement in comparison with MAP or SISO-SD detector that requires more logic complexity.
- SM codes provide near-optimal performance for a lower computational complexity than ASTBCs in WiMax systems, thus they can be regarded as a good trade-off. However, in order to achieve a better trade-off it could be interesting to develop full-rate full-diversity OSTBCs that can be decoded using MMSE, as proposed in [12].

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