Performance of Transmit Diversity Using Space-Time Block Codes in EDGE*

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Abstract— **Transmission diversity schemes have been emerging as an attractive solution in order to combine fading effect. Space-time block codes (STBC) with two antennas can provide similar order diversity as maximal-ratio receiver combining (MMRC). In this paper a transmit diversity scheme using STBC with two antennas is applied for EDGE/EGPRS system and its results evaluated in a interference-limited scenario.**

I. INTRODUCTION

THE enhanced general packet radio service of EDGE (EGPRS) combines multilevel modulation and an efficient link quality control in order to reach the high data rates demanded by third generation (3G) systems. With those characteristics EGPRS arises as a natural evolutionary path for two TDMA-based second generation (2G) systems, namely GSM and IS-136.

In the physical layer of EGPRS there are nine modulation and coding schemes (MCSs), MCS-1 through MCS-9. Four of them use GMSK modulation (MCS-1 through MCS-4) and five use the 8-PSK multilevel modulation (MCS-5 through MCS-9), see Table 1. As link quality control (LQC) strategies, EGPRS uses link adaptation (LA) and incremental redundancy (IR) separately or jointly. Through this dynamic adaptation in agreement with the link quality, one may choose between transmission rates and protection to maximize throughput.

The fading effect is one of the most important drawback factors of the maximum data rates reached by wireless communication systems. To mitigate fading some diversity strategies are usually provided, among which we can highlight: time, frequency and space diversity. Currently, in 2G networks, the most common strategies used for receive diversity include: space diversity - multiple antennas in the base stations are employed to provide receive diversity; time diversity - channel coding with interleaving; and frequency diversity - frequency hopping (FH) for TDMA systems and RAKE receiver for CDMA systems.

As internet traffic is expected to be asymmetric, with higher data rates on the forward link, the issue of transmit diversity becomes important. This importance arises because the link quality control of EGPRS will translate into throughput gain any gain perceived at the link-level, such as a diversity gain. Some possibilities of transmit diversity are then investigated in this work and their gains evaluated.

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In [1], Alamouti has proposed a simple transmit diversity scheme using space-time block codes (STBC) with two antennas. The obtained diversity order is similar to applying a maximal-ratio receiver combining (MMRC) with two antennas at the receiver. This scheme requires no bandwidth expansion, as redundancy is applied in space across multiple antennas. In [2], an extension to a scheme similar to Alamouti's STBC for more than two antennas in transmission is proposed using the *Theory of Orthogonal Design* [3]. Alamouti's scheme is indicated for flat fading channels, therefore without intersymbol interference (ISI). A generalization for channels with ISI is given in [4].

In this work we study the performance of transmit diversity techniques using STBC with two antennas applied in the context of the EDGE/EGPRS system in an interference-limited environment.

This work is structured as follows. First, space time codes are described, the Alamouti's scheme is presented and its extension to four antennas is reviewed. Next we describe the scheme for channels with ISI, which is the appropriate case of EDGE. Finally, the EDGE/EGPRS simulator model is presented and the results are discussed.

II. SPACE-TIME CODES

Space-time codes (STC) use channel coding techniques combined with multiple transmit antennas to increase data rates over wireless channels. STC introduces temporal and spatial correlation into signals transmitted from different antennas, in order to provide diversity at the receiver, and coding gain over an uncoded system without sacrificing bandwidth [1].

Two techniques widely used for STC are: space-time block codes (STBC) and space-time trellis codes (STTC). In this work the simulation results will only consider STBC. A block diagram of the transmit diversity scheme with N transmit antennas and one receive antenna is shown in Fig. 1.

A. Alamouti's Space Time Block Codes

Alamouti proposed a simple scheme of transmission diversity with two transmit antennas in which two symbols s_1 and s_2 are simultaneously transmitted by different antennas at a given symbol period, where s_1 is the signal transmitted by antenna one and s_2 is the signal transmitted by antenna two. In the next symbol period, antenna one transmits $-s_2^*$ and antenna two transmits s_1^*. It is assumed that the channel is constant

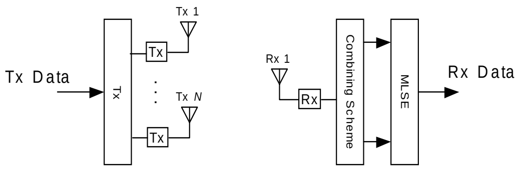

Fig. 1. Block diagram of transmit diversity scheme using one receive antenna.

during two periods of consecutive symbols. Considering this space-time coding, the received symbols in two consecutive symbol periods are:

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \cdot \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \quad (1)$$

where the channels samples h_1 and h_2 may be modelled by a complex multiplicative distortion and n_1 and n_2 are gaussian noise samples. This representation can be reorganized in a similar manner as:

$$\begin{bmatrix} r_1 \\ r_2^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \cdot \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix} \quad (2)$$

In a matricial equivalent form we have: $\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{n}$.

For detection, Alamouti proposes the multiplication of the received signal vector $\mathbf{r}$ by matrix $\mathbf{H^H}$. Therefore $\hat{\mathbf{s}} = \mathbf{H^H} \cdot \mathbf{r} = \mathbf{H^H} \cdot \mathbf{H}\mathbf{s} + \mathbf{H^H} \cdot \mathbf{n}$. It can be noted that $\mathbf{H}$ is orthogonal and $\mathbf{H^H}$ is the matched filter, so: $\mathbf{H^H} \cdot \mathbf{H} = (|h_1|^2 + |h_2|^2) \cdot \mathbf{I}$ and $\hat{\mathbf{s}}$ is the vector of matched filter output. Those observations imply that the symbols s_1 and s_2 can be recovered from the matched filter output.

Tarokh in [2] achieved through orthogonal designs, simplicity similar to Alamoutis STBC for more than two antennas for transmission. Using four antennas the received symbols, modulated by real constellations, in four consecutive symbol periods are:

$$\begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \end{bmatrix} \cdot \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \end{bmatrix} \quad (3)$$

The same detection strategy used for two antennas can be used in this case.

This Alamouti's scheme is indicated for channels without intersymbol interference (ISI), but due to the nature of the mobile radio channel, transmitter, receiver, pulse shape and modulations present in the EDGE, the ISI is strongly present. In order to deal with this drawback some changes in the STBC rule were made, as it will be shown in the next section.

B. STBC for Channels with Intersymbol Interference

Lindskog and Paulraj in [4] extended the considerations made by Alamouti from symbol-wise to block-wise in order to treat channels with ISI. In this scheme a block of symbols $d[n]$ is divided in two sub-blocks $d_1[n]$ and $d_2[n]$ as well as the transmission frame. In the first half of the frame, $d_1[n]$ is transmitted by antenna one and $d_2[n]$ by antenna two. In the second half of the frame, $d_2[n]$ time reversed, complex conjugated[1] and negated is transmitted by antenna one and $d_1[n]$ time reversed and complex conjugated from antenna two. This can be represented by:

$$\begin{bmatrix} r_1 \\ r_2^R \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^R & -h_1^R \end{bmatrix} \cdot \begin{bmatrix} d_1 \\ d_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2^R \end{bmatrix} \quad (4)$$

In this case the ordinary multiplication is replaced by convolution. For detection, the same strategy used for the previous scheme can be applied here.

TABLE I
MODULATION AND CODING SCHEMES IN EGPRS.

MCS	User Rate [Kbps]	Code Rate	Header Code Rate	Blocks per 20ms
9(8-PSK)	59.2	1.0	0.36	2
8(8-PSK)	54.4	0.92	0.36	2
7(8-PSK)	44.8	0.76	0.36	2
6(8-PSK)	29.6	0.49	1/3	1
5(8-PSK)	22.4	0.37	1/3	1
4(GMSK)	17.6	1.0	0.51	1
3(GMSK)	14.8	0.85	0.51	1
2(GMSK)	11.2	0.66	0.51	1
1(GMSK)	8.8	0.53	0.51	1

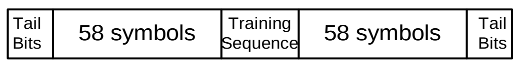

Fig. 2. Normal burst GSM.

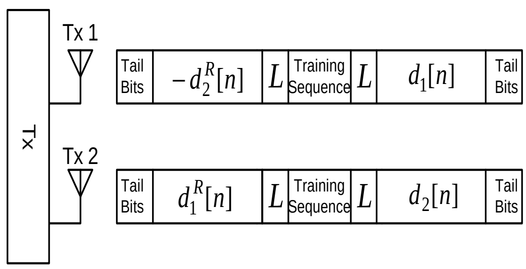

Fig. 3. New burst format.

In EDGE/EGPRS each user payload (RLC radio block) is interleaved over four bursts, and each burst contains 116 user data symbols (modulated with either GMSK or 8-PSK, see Table I), 26 training symbols in the middle and 3 tail bits in the extremities. In [5], a new burst format scheme using two transmit antennas compatible with the GSM burst format is proposed.

[1] Time reversed and complex conjugate is represented for ^{R}.

Due to ISI in the downlink channels, some "edge effects" are introduced in the transmitted signals, and these effects need to be considered in the design of the new burst format. Let L denote the maximum delay of the two-downlink channels [5].

In Figs 2 and 3, two burst formats are described. In the Fig. 2 the normal GSM burst format is shown, while in Fig. 3 the new burst format is presented.

In the new format, the block contains 116 data symbols, $\{d[n]_{n=0}^{115}\}$, which are divided in two sub blocks and now transmitted in two bursts. The sub-blocks are defined as follow:

$$\begin{array}{ll} d_1[n] = d[n]; & n = 0, ..., 57 \\ d_2[n] = d[n]; & n = 58, ..., 115 \end{array} \quad (5)$$

III. EDGE/EGPRS LINK LEVEL SIMULATOR

A complete EDGE/EGPRS link level simulator has been constructed based on 3GPP specifications. The whole physical layer of EGPRS is simulated including: channel encoder, interleaving, burst mapping modulator, pulse shaping, channel modelling, equalizer, de-interleaving and decoder. The simulator is divided in two parts: inner core and outer core. The outer core encompasses the functions at the radio link control (RLC) block level, while the inner core is responsible for the burst level. In this work only the outer core part is considered for results.

The outer core is based on [6]. The Jakes' fading model is used for generating the channel response. Its time variation and correlation depends on the mobile velocity. For the FH case independent channel samples are generated for each burst. For NoFH, the degree of channel correlation, from burst to burst, depends on the velocity. For the interference-limited scenario, one time-aligned interferer is assumed. The same assumptions regarding fading, modulation and velocity made for the desired user are extended for the interferer. The severity of the Doppler spread is controlled according to the selected mobility conditions.

The basic unit of time in the simulator is an RLC radio block; each RLC radio block is referred to as iteration. As in EGPRS specifications, the header and data are coded separately. At each iteration the first task of the simulator is to separate the RLC radio block in two parts: header and data blocks. After that, each part is coded and punctured separately in agreement with [6] and the interleaving and mapping of burst is made for subsequent transmissions in the air interface.

IV. PERFORMANCE RESULTS

We compare the performance of a single antenna and STBC with two uncorrelated antennas for MCS-1 through MCS-4. Some simplifications on the inner physical layer are assumed. The BPSK modulation scheme replaces GMSK with perfect phase recovery in the receiver. Flat fading is also assumed and can be considered a good approximation for the typical urban (TU) channel [7]. We are also assuming perfect channel estimation in the receiver. When a more realistic channel estimation is considered, e.g. based on the training sequence (imperfect), a decrease in the performance is expected.

With perfect timing at the receiver and synchronized interference, no further considerations about pulse shaping are essential at this moment. We use the burst format displayed in Fig. 3 with $L = 0$. We assume that the scenario is interference-limited, hence block error rate (BLER) and throughput in Kbps is plotted versus C/I in dB, with the noise power assumed to be 3dB below the interference power. In this scenario the implementation of frequency hopping (FH) may be considered or not (NoFH). The throughput for each MCS can be found from the BLER values by using the following rule:

$$Throughput = (1 - BLER) \cdot R_{max} \quad (6)$$

where R_{max} is the user data rate for a given modulation and coding scheme, e.g. 8.8Kbps for MCS-1, see Table I.

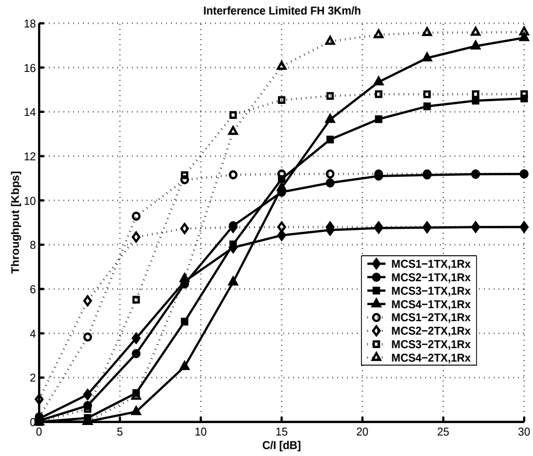

Fig. 4. Throughput performance using STBC with two transmit antennas.

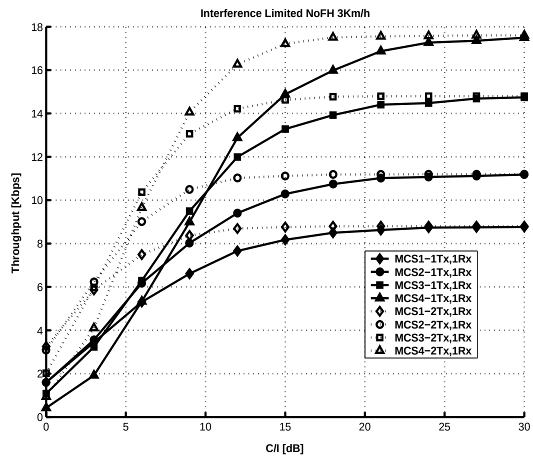

Fig. 5. Throughput performance using STBC with two transmit antennas.

The BLER is measured over 4000 blocks with one and two transmit antennas in the downlink, using link adaptation as link quality control. It is assumed that the total transmit power for STBC is the same as the one for a single antenna. A block is said to be erroneous, if one or more the following events occurs:

- Cyclic redundancy code fail for the header;
- Cyclic redundancy code fail for the data block.

Figs 4 to 7 shown comparative results using one and two transmit antennas, for low (3Km/h) and high (100Km/h)

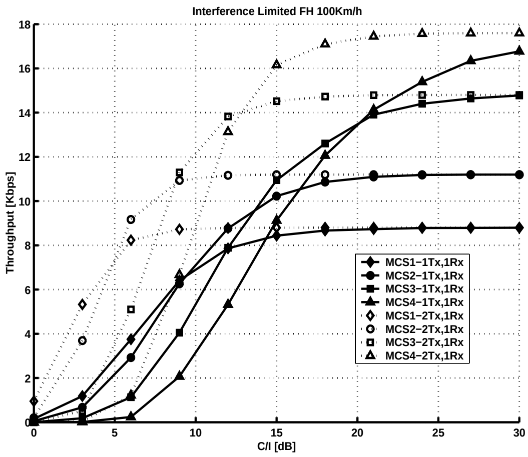

Fig. 6. Throughput performance using STBC with two transmit antennas.

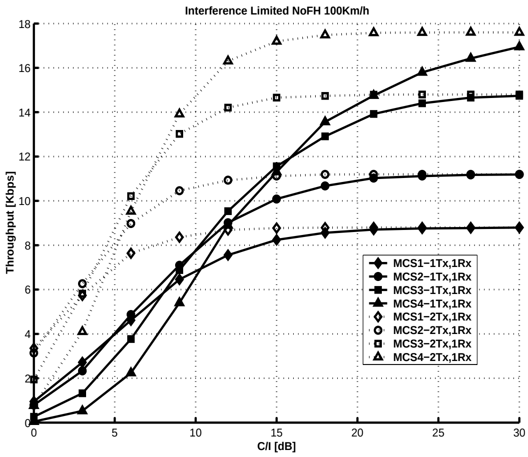

Fig. 7. Throughput performance using STBC with two transmit antennas.

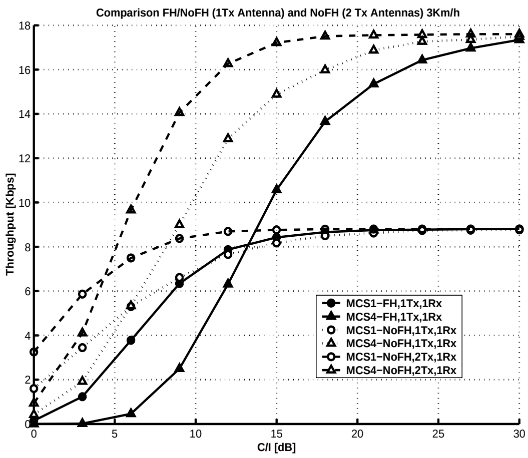

Fig. 8. Comparison between FH and NoFH with one and two transmit antennas.

mobility. Figs 8 and 9 show comparative results with FH and NoFH using one and two transmit antennas in two mobility conditions.

Tables II to V summarize the throughput gains relative to several reference scenarios, the highlight cells show the better

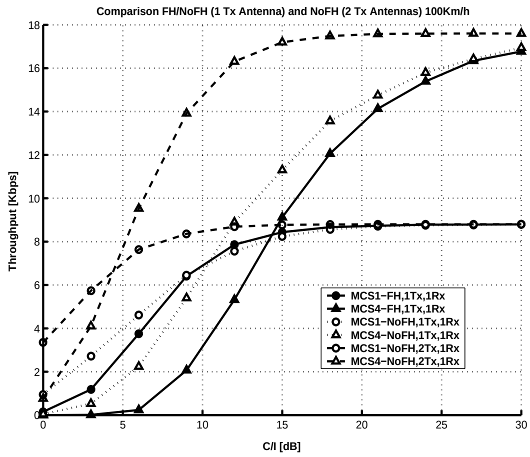

Fig. 9. Comparison between FH and NoFH with one and two transmit antennas.

performance achieved for each channel state. Some comments about these results follow below.

Transmit diversity provides an important technique to mitigate the fading effects in almost all scenarios. This can be proved by observation of table results for low SIR (e.g. 9dB) where the fading effects are more pronounced. The better performance is achieved for less protected MCSs for most of scenarios, especially when the reference scenario consider is (1Tx, 1Rx FH 100Km/h), see Table V.

In this reference scenario, the higher gain is obtained using NoFH with two transmit antennas. This can be explained by not perceived temporal diversity for less protected MCSs when FH is used, with FH, one single burst experiencing a poor channel state may be enough to produce an erroneous block.

V. CONCLUSION AND FUTURE PERSPECTIVES

The achieved results states that STBC could combat the fading effects, thus offering increased throughput when two transmit antennas are employed. Frequency hopping may or may not be employed in conjunction (this affects the amount of relative gain). As a general rule, transmit diversity provides higher relative gains for less protected MCSs under bad channel conditions.

For the use of STBC some changes in EDGE/EGPRS standards are need. Between the changes we can highlight: two different training sequences transmitted by the two antennas for channel estimation in the receiver and STBC encoder.

For future results, STBC will be evaluated using four transmit antennas and with the inclusion of the EGPRS inner core link level simulator (where ISI is taken into account). Its performance with incremental redundancy (IR) LQC and in combination with sophisticated equalization strategies (such as DDFSE) is also a certain topic for investigation in the short term.

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TABLE II

THROUGHPUT GAINS [%] (RELATIVE TO 1TX-1RX, NOFH) AT 3KM/H WHEN EMPLOYING TRANSMIT DIVERSITY.

	FH 2Tx-1Rx			NoFH 2Tx-1Rx		
	SIR[dB]			SIR[dB]		
	9	15	21	9	15	21
MCS1	32.05	7.67	2.01	26.69	7.19	1.99
MCS2	**36.18**	8.79	1.65	30.77	8.06	1.58
MCS3	17.30	**9.42**	2.69	37.55	10.11	2.67
MCS4	-28.16	7.83	**3.57**	**56.24**	**15.64**	**4.04**

TABLE III

THROUGHPUT GAINS [%] (RELATIVE TO 1TX-1RX, NOFH) AT 100KM/H WHEN EMPLOYING TRANSMIT DIVERSITY.

	FH 2Tx-1Rx			NoFH 2Tx-1Rx		
	SIR[dB]			[dB]		
	9	15	21	9	15	21
MCS1	35.13	6.73	1.06	29.47	6.46	1.06
MCS2	54.04	10.99	1.57	47.66	10.21	1.55
MCS3	**64.23**	25.57	6.25	89.30	26.78	6.25
MCS4	23.55	**42.93**	**18.28**	**157.78**	**52.12**	**19.18**

TABLE IV

THROUGHPUT GAINS [%] (RELATIVE TO 1TX-1RX, FH) AT 3KM/H WHEN EMPLOYING TRANSMIT DIVERSITY.

	FH 2Tx-1Rx			NoFH 2Tx-1Rx		
	SIR[dB]			SIR[dB]		
	9	15	21	9	15	21
MCS1	37.68	4.47	0.55	32.10	4.00	0.53
MCS2	75.42	7.88	0.91	68.45	7.15	0.83
MCS3	146.20	32.52	8.26	188.72	33.47	8.23
MCS4	**159.08**	**51.81**	**13.88**	**463.49**	**62.80**	**14.39**

TABLE V

THROUGHPUT GAINS [%] (RELATIVE TO 1TX-1RX, FH) AT 100KM/H WHEN EMPLOYING TRANSMIT DIVERSITY.

	FH 2Tx-1Rx			NoFH 2Tx-1Rx		
	SIR[dB]			SIR[dB]		
	9	15	21	9	15	21
MCS1	36.10	4.22	0.81	30.40	3.96	0.81
MCS2	74.56	9.50	0.93	67.33	8.73	0.91
MCS3	178.81	32.61	6.33	221.37	33.90	6.33
MCS4	**222.55**	**77.05**	**23.51**	**572.98**	**88.43**	**24.45**

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