SPACE-TIME CODED SATELLITE DIVERSITY IN S-UMTS

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ABSTRACT

The main goal of this paper is to analyze and compare the performance of some space-time codes applied to the forward link of a WCDMA multi-satellite UMTS environment. Space-Time Trellis Codes (STTrC) has been considered as a first comparison with already implemented transmit diversity schemes, as Maximal Ratio Combining (MRC), Space-Time Block Codes (STBC) and Selection Transmit Diversity (STD). Furthermore, in order to improve their performances, Convolutional Codes (CC) have been added as outer encoders to MRC, STBC and STD, while for STTrC, a CC plus an iterative decoding has been considered in order to perform a Space-Time Turbo Coded Modulation (STTuCM). All the aforementioned schemes have been implemented for a 2-satellite transmission. An intra and inter-cell interference model is presented in order to evaluate performances of these schemes for a loaded system. The effect of a feedback delay and errors in channel state identification have been introduced in order to have a real behavior of schemes which require a feedback communication channel.

INTRODUCTION

The standardization process of the third generation mobile systems made by 3GPP has already reached the standard approval by the Technical Specification Group (TSG) for what concerns the Terrestrial-UMTS (T-UMTS). On the other hand, the Satellite-UMTS (S-UMTS) has got the first technical specifications released at the end of year 2000 by the European Telecommunications Standards Institute (ETSI) [1].

The development of the satellite part of UMTS will be important in order to guarantee the anytime-anywhere services. Under this point of view, the capacity increase and a low complexity mobile terminal will be two of the main problems to be solved. The mobile radio channel in a wireless communication system involves deteriorating effects due to time-varying multipath fading. Apart from transmit power control, many different diversity techniques, e.g. temporal, frequency, polarization or spatial diversity, have been utilized in existing wireless communication systems bringing significant performance improvements. Due to their large coherence bandwidth, satellite channels do not offer high frequency diversity that is usually exploited in terrestrial WCDMA systems through maximal ratio combining (MRC) in a RAKE receiver. Therefore, spatial transmit diversity applied to Satellite-UMTS through simultaneous transmission from two or more satellites jointly covering the cell of interest has gained much interest in the literature recently.

In this paper we extend the previous study of uncoded transmit diversity methods applied to multi-satellite systems [2], where we had analyzed the performances of some simple diversity schemes, such as Maximal Ratio Combining (MRC) [3], Space-Time Block Codes (STBC) [4] and Selection Transmit Diversity (STD) [5]. Here, in order to improve the performances of diversity schemes, channel coding has been implemented to exploit an additional temporal diversity. Thus, in addition to MRC transmission (with artificial multipath), STBC and STD, Space-Time Trellis Codes (STTrC) [6] and Space-Time Turbo Coded Modulation (STTuCM) [7] have been considered.
The satellite scenario implemented is composed by one cell where the user of interest is placed, and two neighboring cells. In order to represent a realistic scenario, interfering users are present in the same cell of the user of interest (intra-cell interference) and in the two other cells (inter-cell interference).

Current standard proposes asynchronous transmission from neighboring satellites. In our study we have also considered a synchronous case, yielding a modification of the standard multi-satellite code allocation but also a requirement for the inter-satellite link to guarantee the synchronicity and proper scrambling code allocation.

The transmission schemes used can be classified in function of the requirement of a feedback channel, and whether the transmission from the two different satellites is synchronous or asynchronous. Asynchronous transmission is related to MRC and STD schemes. While the MRC simply coherently combines the signals from satellites, the STD scheme selects which satellite's signal is used for the decoding process. Asynchronous transmission is related to a synchronous case, yielding a modification of the standard multi-satellite code allocation but also a requirement for the inter-satellite link to guarantee the synchronicity and proper scrambling code allocation.

The feedback channel with no delay has always been supposed in the past [8]. In a realistic approach, the feedback channel will yield a not negligible delay and it could even carry some errors that could decrease the performances of STD schemes. In order to implement a space-time transmit diversity based on block codes (STBC), as well as STTrC and STTuCM, a synchronous transmission from the two satellites with the same scrambling code is here proposed. The improvements of this solution are mainly two: it can reach the same performance of a MRC scheme with two receiving antennas and it does not need any feedback channel, i.e., it doesn’t require any communication of the channel state between receiver and transmitter (open-loop transmit diversity). Moreover, its computational complexity is similar to MRC, but it doesn’t need a full power amplifier, yielding an easier implementation and a less complex mobile terminal. All these benefits are taken by supposing an inter-link between two satellite covering the same area. In order to get a more realistic scenario, we have assumed an imperfect feedback channel, i.e. non-zero delay and errors in the feedback channel.

**SYSTEM MODEL**

Let us assume that \( K \) users are present in the same cell which is in visibility to \( N_s \) satellites. Transmission towards the users is performed according to a QPSK DS-CDMA basis. The equivalent baseband received signal at the mobile terminal over a stream of \( N \) symbols is

\[
r(t) = \sum_{k=1}^{K} \sum_{l=1}^{N_s} A_{k,l} \sum_{n=0}^{N-1} b_{k,l}^{(n)} c_{k,l}^{(n)} s_{k,l}^{(n)} (t - nT - \tau_{k,l}) + n(t),
\]

where \( A_{k,l} \) is the received signal amplitude for the \( k \)-th user \( l \)-th satellite, \( b_{k,l}^{(n)} \) is the information in the \( n \)-th symbol interval, \( c_{k,l}^{(n)} \) are the channel complex coefficients including carrier phase, \( \tau_{k,l} \) is the \( k \)-th user transmission delay from \( l \)-th satellite and \( n(t) \) is the noise signal. The term \( s_{k,l}^{(n)} (t) = \sum_{g=1}^{G} s_{k,l}^{(n)} (g) p(t - gT_c) \) represents the spreading waveform for the \( n \)-th symbol where \( T \) is the symbol interval, \( T_c \) is the chip interval, \( p(t) \) represents the chip waveform due to pulse shaping filter and \( s_{k,l}^{(n)} (g) \) is the code referred to the \( n \)-th symbol interval. This code is a combination of channelization and scrambling codes \( s_{k,l}^{(n)} (g) = s_{k,l}^{[ch]} (g) s_{k,l}^{[sc]} (g + (n \mod (H/G))G) \), where \( G \) is the spreading factor and \( H \) is the length of the scrambling code. A single-path transmission has been here considered for both kinds of satellite channel; this is a good approximation since both near and far echoes (lower replicas of the transmitted signal) power is at least 15 dB below the first path, so that they can be considered negligible [9].

Several channel models have been proposed in the last years about the satellite channel and a comparison among them is presented in [10]. The results shown in this paper are obtained using the so called Corazza’s model presented in [11]. This model can be considered a good compromise between simulating the realistic behaviour of the satellite channel in several environments (from rural to urban) versus the computational complexity it requires. It is, in fact, a one-state model whose probability distribution of the received signal envelope \( p_r(r) \) is a combination of Rice and lognormal statistics, where shadowing is affecting both direct and diffuse component. Analytically, \( p_r(r) \) is

\[
p_r(r) = \int_0^\infty p(r|S)p_S(S) dS,
\]

where \( p(r|S) \) is a Rice distribution conditioned on a certain value of shadowing \( S \), whose distribution is lognormal, represented in (2) as \( p_S(S) \). As a matter of fact, the Rice process does not have a deterministic power anymore, but the effect of the shadowing \( S \) causes the Rice distribution to have a random power with lognormal statistic. For a detail analysis, see [11].
Three parameters characterize Corazza’s model: the Rice factor (direct-to-multipath power ratio) $c_{dB}$, the mean power level decrease $\mu_{dB}$ and the standard deviation of the power level due to shadowing $\sigma_{dB}$ [11], [12]. Their values are chosen in accordance to the characteristics of the terrestrial environment chosen and the elevation of the satellite. Empirical formulas used for their evaluation are the following ones

\begin{align}
K(\alpha) &= K_0 + K_1 \alpha + K_2 \alpha^2 \\
\mu(\alpha) &= \mu_0 + \mu_1 \alpha + \mu_2 \alpha^2 + \mu_3 \alpha^3 \\
\sigma(\alpha) &= \sigma_0 + \sigma_1 \alpha,
\end{align}

where $\alpha$ is the elevation of the satellite, and the other parameters are evaluated by empirical measurements [11]. The characteristics of this model are very suitable for non-geostationary satellites channels, as the one we have chosen in this paper and that is depicted next in this paper.

**TRANSMIT DIVERSITY SCHEMES**

Two schemes are presented for non-synchronous transmission: maximal-ratio combining (MRC) [3] and selective transmission diversity (STD). The basic idea of STD [5] is to make the transmitter choose the antenna that yields the highest received signal based on his SNR. To do that, the transmitter needs to know the state of the channel between the satellites and the mobile station (MS), indicating which antenna has the higher SNR. This is done using a one-bit antenna selection message (AS) that has to be sent from the mobile to the base station. In our simulations, this selection is made monitoring the power of the two channels so that the most powerful is used for the transmission. Thus, in this case there must be two pilot signals, one per each satellite. They can be common for all the users of one cell, so that there will be one pilot signal for each beam.

A space time transmit diversity using space-time block codes (STBC) is introduced here as a profitable way to implement a synchronous transmission by different satellites. The principle of this transmit diversity scheme is to perform a simultaneous transmission through two different antennas, encoding the signal in space and time [4]. This improves the signal quality at the receiver on one side of the link by simple processing across two transmit antennas placed on the opposite side. The obtained diversity order is equal to applying MRC with two antennas at the receiver. For instance, for one receiving antenna this scheme provides a diversity order of 2.

Space-time trellis codes are trellis coded modulation schemes that employ multiple transmitting antennas to obtain both spatial diversity and coding gain [6]. Simulation results of 4- and 32-states STTrC from two transmitting antennas, without outer convolutional encoder, are presented in this paper.

For the space time encoder in STTuCM, a non-recursive 4-state STTrC has been put after interleaving the output of the convolutional encoder [7].

Fig. 1 depicts the system model of an outer convolutional encoder (CC) concatenated with an inner space-time encoder (STC) after interleaving ($\pi$). STC represents, for instance, any of the diversity schemes described above. For the convolutional encoder, two different choices have been made:

- For STTuCM, a half rate, 4-state recursive systematic convolutional code (RSC) has been implemented. Its generators are $[5, 7]$ in octal basis.
- For all the other diversity scheme with outer encoder, a half rate, 64-state convolutional code has been used. Its generators are $[133, 171]$ in octal basis.

In all cases, overall bandwidth efficiency is therefore halved to 1bit/sec/Hz. Moreover, in STTuCM iterative decoding with 5 iterations has been performed in the decoder (for more details see [7]), while in all other cases STC and CC decoders are separated in a non-iterative fashion. The main characteristics of the transmit diversity schemes used in this paper are depicted in Table 1.

Since we are considering systems with and without an outer code, to make a fair comparison in terms of throughput, we have used different lengths for the channelization codes. For instance, Hadamard-Walsh channelization codes of length-16 have been used for coded systems, while length-32 codes have been applied to uncoded systems. Thus, the throughput is the same for all the systems. For what concerns the results shown in this paper, the percentage of load considered
Table 1. Main characteristics of the space-time codes performed in simulations.

<table>
<thead>
<tr>
<th>Transmit Diversity Model</th>
<th>Transmission from the two satellites</th>
<th>Feedback channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRC</td>
<td>Asynchronous</td>
<td>Not required</td>
</tr>
<tr>
<td>MRC + CC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STD</td>
<td>Asynchronous</td>
<td>Required</td>
</tr>
<tr>
<td>STD + CC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STBC</td>
<td>Synchronous</td>
<td>Not required</td>
</tr>
<tr>
<td>STBC + CC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STTC</td>
<td>Synchronous</td>
<td>Not required</td>
</tr>
<tr>
<td>STTuCM</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. System concept for multi-satellite transmission.

Fig. 3. Beams configuration and position of the user of interest and interfering users.

for simulations of coded systems is 12.5%, that means 2 users per cell for length 16 channelization codes, for a total amount of 6 users, the one of interest and 5 interfering one (see Fig. 3). For uncoded systems, the same number of users is considered, but, since the length of channelization codes is 32, the relative percentage of load is 6.25%.

MULTI-SATELLITE ENVIRONMENT

Scenario

The scenario considered for this analysis is represented in Fig. 2, and a complete description of it can be found in [9]. We will consider that each one of the $N_s$ satellite in visibility generates $N_b$ beams towards the earth surface and, as a general assumption, each group of spot beams from different satellites lights the same area on the ground. To provide soft handoff and to make diversity reception possible, every satellite spot beam reuses the same carrier frequency. As shown in Fig. 2, the forward link assumes the direct transmission from the satellites to the MS, while for the reverse link a gateway station (GS) is required, since the MS itself has not enough power to cover that huge distance. This will enhance the feedback delay and errors in STD schemes, as it will be explained later, since a multiple link is required to send back information from MS to two satellites.

Interference

The interference scenario considers the presence of three cells, the one where the user of interest is located, and two neighbor interfering ones (Fig. 3). As it can be seen from the figure, the user is placed at the intersection of the three cells, that can be considered the worst interference condition. In fact, its distance from the center of any cells is the same, and all the signals directed to them from the satellites arrive with the same average power level [9]. All the intra and inter-cell interfering users are considered asynchronous with the one of interest.
Two kinds of interference models are considered in this paper, depending on the transmit diversity model chosen. In diversity schemes already proposed, no time-synchronization is assumed, so that signals coming from different satellites generate interference after despreading at the demodulator site. This is the case of a simple maximal ratio combining (MRC) of the two signals using a RAKE receiver [9], or when an STD is applied [8]. In these conditions, each satellite has its personal scrambling code, and every beam has a different shifted version of that code. Furthermore, all of them can reuse the same set of spreading codes, since orthogonality is guaranteed by the scrambling ones.

The use of space-time diversity schemes like the one previous depicted (STBC, STTrC, STTuCM) needs the different signals to arrive at the same time to the MS. Thus, the inter-satellite link has to provide the synchronization of the two pilot signals related to the beams that are lighting the same area on the ground. As the most evident characteristic of these models, same channelization and scrambling codes have to be used by the two satellites. This could be done making the GS on the ground monitor the power of pilot channels, so that it can choose the two strongest ones. After that, thanks to the inter-satellite link, the satellites will exchange a unique scrambling code, so that the cell of interest will have one code, and the neighboring ones a shifted version of it. This searching for the best two satellites requires, of course, a feedback link; this can be considered a “long-term feedback” compared to the one required by STD for the choice of the most powerful satellite. For this reason, the errors done by this feedback link have been considered negligible in our simulations. Furthermore, the same family of channelization codes can be used for neighboring cells, but not in the same one.

**FEEDBACK ERRORS**

As told previously, for STD at least three links (MS-GS, GS-old satellite, old satellite-new satellite) are needed to let feedback information for the state of the channel to come back and to take decision about which satellite has to transmit to the MS. These errors can be divided in two different kinds, i.e. when

- feedback information hasn’t reached yet the satellites and the MS continues to receive signal from the satellite whose power has become lower than the other one,
- the AS signal is deteriorated by the channel so that selection is made in the wrong way.

For this purpose, we have introduce a parameter ($\varepsilon$) that expresses the percentage of time of the transmission in which, for a closed-loop diversity scheme, the MS is receiving from the wrong satellite. As we can see from Fig. 4, the STD, as a closed-loop scheme, worsens their performances as $\varepsilon$ increase. After the crossing point for $\varepsilon \approx 8\%$, STBC outperforms STD. In the simulation results shown below, two values for $\varepsilon$ have been chosen: $\varepsilon = 4\%$ is a common value used in terrestrial environment, and $\varepsilon = 10\%$ can be considered an extreme worst case.

**SIMULATION RESULTS**

A constellation with two available satellites has been considered; this is a realistic average case, even if in most recent satellite constellations like Globalstar [13], the contemporary presence of 3 or 4 satellites in visibility can be assumed, although in a smaller percentage of time.

Several simulations have been performed, all according to parameters shown in Table 2.

**A Load Capacity Study**

This kind of study has been performed for two satellite at the same elevation ($60^\circ$); Fig. 5 shows the performances of coded systems in a rural tree-shadowed environment whose channel parameters are shown in Table 3.

The results show that for a systems with more than 6 users transmitting at the same time, the performances of the communication system are quite low with any of the transmit diversity models used. Thus, for our simulations we have chosen that number of users for the loaded system, that corresponds to 12.5% of the full load, in order to have a clear comparison among the diversity schemes.

**Performance of uncoded systems**

The performances of uncoded systems are shown, for frame error rate (FER) and bit error rate (BER), respectively in Fig. 6(a) and 6(b). The percentage of load used in simulations of uncoded systems is 6.25%, that means 2 users per cell with length-32 channelization codes, having a total amount of 6 user, the one of interest and 5 interfering one. As it is clearly depicted in the performance curves, since the space-time trellis codes are designed to minimize the probability of
Table 2. Parameters of the system used in simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip rate</td>
<td></td>
<td>3.840 Mc/s</td>
</tr>
<tr>
<td>Symbol rate</td>
<td></td>
<td>230 ks/s</td>
</tr>
<tr>
<td>Modulation</td>
<td></td>
<td>QPSK</td>
</tr>
<tr>
<td>Spreading factor</td>
<td>G</td>
<td>16 (coded sys.) 32 (uncoded sys.)</td>
</tr>
<tr>
<td>Number of users for the loaded system in all the cells</td>
<td>N</td>
<td>6 (coded sys.) 12 (uncoded sys.)</td>
</tr>
<tr>
<td>Number of samples per chip</td>
<td>S</td>
<td>4</td>
</tr>
<tr>
<td>Pulse shape roll-off factor</td>
<td>β</td>
<td>0.22</td>
</tr>
<tr>
<td>Pulse length in chips</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>f_c</td>
<td>2 GHz</td>
</tr>
<tr>
<td>Channel fading model</td>
<td></td>
<td>Corazza</td>
</tr>
<tr>
<td>Doppler power spectrum</td>
<td></td>
<td>Classical</td>
</tr>
<tr>
<td>Speed of MS</td>
<td>v</td>
<td>2.7648 Km/h</td>
</tr>
<tr>
<td>Number of satellites</td>
<td>N_s</td>
<td>2</td>
</tr>
<tr>
<td>Number of spot beams per satellite</td>
<td>N_b</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3. Parameters of the Corazza’s models for the rural tree-shadowed environment used in simulation

<table>
<thead>
<tr>
<th>Elevation</th>
<th>Rice factor</th>
<th>Mean of lognormal component µ_dB</th>
<th>Power level decrease σ_dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>60°</td>
<td>6.27</td>
<td>-0.096</td>
<td>1.5</td>
</tr>
<tr>
<td>50°</td>
<td>4.30</td>
<td>-0.101</td>
<td>2</td>
</tr>
<tr>
<td>40°</td>
<td>2.87</td>
<td>-0.165</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Fig. 4. Comparison of frame error rate for closed and open-loop coded schemes as a function of the percentage of feedback error. Satellites at the same elevation (60°), system at 12.5% of load, $E_b/N_0 = 8$ dB.

Fig. 5. Frame error rate of coded systems as a function of the percentage of the system load. Satellites at the same elevation (60°), $E_b/N_0 = 8$ dB.

code word error, the FER decreases as more powerful code with larger number of states in the trellis is used. However, the situation is the opposite for BER at low SNR values. In fact, while STD outperforms all the systems for BER, in FER it is overtaken by STTrC with 32-state. Anyway, since all the systems show quite poor performances, it is straightforward to consider the introduction of an outer encoder.

Performance of coded systems

The performances of coded systems are shown, for frame error rate (FER) and bit error rate (BER), respectively in Fig. 7(a) and 7(b). The percentage of load used for the simulation of coded systems is 12.5%, that means 2 users per cell with length-16 channelization codes, having, like in the uncoded case, a total amount of 6 user. As it is shown in pictures, in this case STD outperforms the closed loop schemes only for low values of SNR (< 7 dB in BER and < 10 in FER). For higher SNR, while STBC is the best one in terms of BER, in terms of FER, due to the optimization of STTrC for codeword errors, STTuC gives the best performances for values of SNR > 10 dB.
Fig. 6. Performance results of space-time codes without outer encoder. The percentage of load is 6.25%. The two satellites are at the same elevation (60°).

Satellites with different elevation

Fig. 8 shows the performances of transmit diversity schemes for the urban environment considered with an SNR of 8 dB, when one satellite is hold at 60°, and the other one arises, going from 40° to 60°. Of course, performances are worsening while the elevation of one satellite is diminishing, since the probability to encounter obstacles along the air link gets higher. The STD scheme, anyway, shows more horizontally shaped curves than the other ones. This fact can have the following explanation: since this closed-loop scheme chooses only one satellite at time for the transmission, for instance the one that performs the higher SNR measured, if only one is setting, performances are not going to be much lower since the mobile terminal is going to establish connection with the one that remains at the same elevation.
Fig. 8. Frame Error Rate of coded schemes for satellites at different elevations. The first one is kept at 60°, while the second is rising from 40° to 60°. System at 12.5% of load.

CONCLUSIONS

In this paper, performances of several space-time codes have been presented for a multi-satellite transmission. These schemes have been implemented with and without the use of an outer encoder. Simulation results show that STD (as a closed-loop scheme) outperforms all the other schemes in terms of BER and FER for lower values of SNR. While the SNR is increasing, STTrC (for uncoded systems) and STTuCM (for coded systems) have shown the best performances in terms of FER. Furthermore, since closed-loop schemes need a reverse link for transmission about channel conditions, a performance evaluation has been carried out to exploit how the errors made by this link worsen the performances of closed-loop schemes versus open-loop ones. Finally, we have presented simulation results for satellites at different elevation in order to show the performances of space-time codes in a realistic multi-satellite scenario.

REFERENCES