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Low Complexity Separate Network and Channel Coding Algorithm for Multiple Access Relay Channel

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Abstract: The employment of the network coding (NC) combined with distributed FEC, in cooperative transmission schemes leads to a more efficient use of the additional time-frequency resources required by cooperation, i.e. by allowing a single relay node to serve two or more user terminals (Multiple Access Relay Channel). This paper proposes a low complexity cooperation algorithm which employs network and distributed channel coding techniques in a two sources – one relay node cooperation scheme for the uplink connection of a cooperative cellular network. The performances of the proposed cooperation algorithm are evaluated in terms of BER, PER and spectral efficiency in several significant scenarios. The performances provided by this algorithm are compared with the performances of non-cooperative coded transmission and with the performances of the "mother" algorithm, the "complete"-SNCC algorithm.

1 Introduction

Relaying and cooperation between terminals are considered as some of the most promising approaches for the improvement of the wireless networks performances. The channel-coded (CC) cooperation included in schemes where a relay-node (RN) serves only one mobile or fix user terminal (UT) in its transmission to the base station (BS) is one of the techniques proposed in literature to accomplish those improvements [1] [2]. Though this approach is shown to bring performance improvements for the served UT in terms of bit error rate (BER), packet error rate (PER) and/or coverage, the additional time-frequency resources (TFR) required by the RN are used to serve only one UT leading to a loss of performances in terms of spectral efficiency. In order to decrease the effect of the additional TFR upon the spectral efficiency of the MS-BS transmission, Network Coding (NC) techniques [3] were included in coded cooperation algorithms. Since the NC techniques allow cooperation structures within which the RN serves more UTs, such an approach leads to a more efficient employment of the additional TFR of the RN. But, making these techniques effective raises new questions that have to be addressed.

The combined use of NC and channel coding was considered in several papers, e.g. [4] [5]. NC-based or joint NC-CC coding cooperation algorithms were proposed and their performances were studied in different scenarios, but some practical aspects are still not completely addressed. This paper considers the cooperative scheme within which one RN serves the uplink connections of two UTs, using combined NC and distributed CC (DCC) techniques. It proposes a low complexity cooperation algorithm which employs the NC and DCC techniques and compares the performances of the proposed algorithm with the ones of the "mother" algorithm (the SNCC algorithm) and the non-cooperative turbo coded (TC) transmission in terms of BER, PER and spectral efficiency.

The paper is organized as follows: section 2 presents the scenarios employed for the performance evaluation of the proposed scheme and some basic considerations about the transmission scheme that should be employed and about the functionalities of the relay node. Section 3 describes the proposed cooperative coding scheme. Section 4 presents and briefly discusses the performances, BER, PER and spectral efficiency vs. E_b/N_0, ensured by the proposed coding scheme in the scenarios and transmission schemes defined in section 2. Finally, section 5 concludes the paper.

2 Cooperation Scenarios Considered

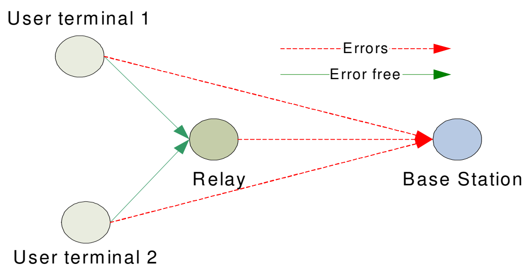
2.1 Scenarios

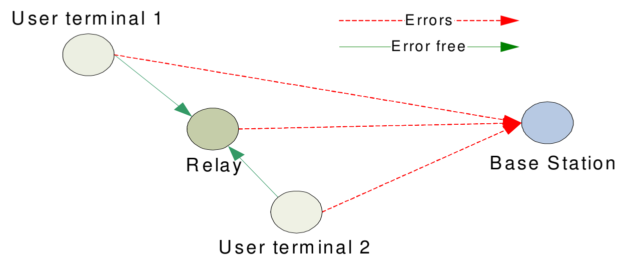
For the two sources-one relay cooperation algorithms three scenarios, schematically illustrated in Figure 1, are considered.

These scenarios are intended to point out two major elements of a cooperation cluster, namely:

- The symmetry of the two sources UT^j, j = 1, 2, with respect to the base station BS; the UT^j are placed either symmetrically compared to the BS (Figure 1.a and c - SS) or asymmetrically (Figure 1.b - AS). In all scenarios, the UT^j are placed symmetrically with respect to the RN.
- The quality of the channels between the relay node (RN) and the mobile stations (UT^j), i.e. they are considered to be quasi error-free (EF) or they are supposed to be affected by errors (WE).

In all scenarios, the UT^j-RN channels are considered AWGN channels, while the UT^j-BS and RN-BS channels are considered to be AWGN channels affected by block Rayleigh fading. The modulation used on all UT^j-RN, UT^j-BS and RN-BS links is 2PSK.





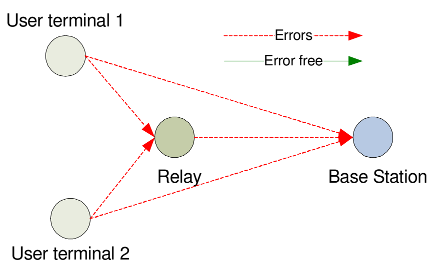


Figure 1. Two source, one relay test scenarios

a. left – Symmetric Scenario Error Free (SS-EF);

b. right – Asymmetric Scenario Error Free (AS-EF);

c. down – Symmetric Scenario With Errors (SS-WE);

The first scenario, SS-EF (Figure 1.a), consists of quasi error-free UT^j-RN channels and identical UT^j-BS channels. The E_b/N_0 of the UT^j-RN channels is set to 20 dB, so that the BER of the modulation scheme considered would be small enough to validate the quasi error-free assumption. The RN-BS channel is considered better than the UT^j-BS channels, i.e. the E_b/N_0 of the RN-BS channel is higher with 6dB than the ones of the UT^j-BS channels:

$$(E_b / N_0)_{RN->BS} = (E_b / N_0)_{UT^j->BS} + 6dB \qquad (1)$$

The second scenario, AS-EF (Figure 1.b), considers that the UT^1-BS channel is “worse” than UT^2-BS and the RN-BS channels and that UT^2-BS channel is “better” than RN-BS. The relations between the E_b/N_0 values of the involved channels are:

$$(E_b / N_0)_{RN->BS} = (E_b / N_0)_{UT^1->BS} + 6dB \;;\; (E_b / N_0)_{UT^2->BS} = (E_b / N_0)_{UT^1->BS} + 12dB \qquad (2)$$

The asymmetrical positions of the two UTs were chosen to point out the influence of a „well positioned” UT upon the cooperative gain ensured for a „badly positioned” UT.

The third scenario, SS-WE (Figure 1.c) is identical with the first one but assumes that UT^j-RN channels are affected by errors. Two simulations were performed for this scenario, for two different values of E_b/N_0 on UT^j-RN channels, namely E_b/N_0 was set to 6 dB (simulation 1) and to 4.5 dB (simulation 2), generating BER values of about $3 \cdot 10^{-3}$ and 10^{-2}, respectively.

All these scenarios are for the uplink transmission. The channels configurations for all three scenarios are summarized in Table 1.

These scenarios were chosen in a manner that would allow pointing out the effects of two important factors of a cooperative approach, namely the effects of the errors that might occur on the UT^j-RN channel and the influence of the quality of the UT^2-BS channel, upon the performances of the UT^1-BS, which has a poorer channel.

Channel/Channel type	SS-EF	AS-EF	SS-WE	
	E_b/N_0 domain	E_b/N_0 domain	E_b/N_0 domain - simulation 1	E_b/N_0 domain - simulation 2
UT^1-RN AWGN	20 dB	20 dB	6 dB	4.5 dB
UT^2-RN AWGN	20 dB	20 dB	6 dB	4.5 dB
UT^1-BS AWGN, Block fading	[0dB; 15dB]	[0dB; 15dB]	[0dB; 15dB]	[0dB; 15dB]
UT^2-BS AWGN, Block fading	[0dB; 15dB]	[12dB; 27dB]	[0dB; 15dB]	[0dB; 15dB]
RN-BS AWGN, Block fading	[6dB; 21dB]	[6dB; 21dB]	[6dB; 21dB]	[6dB; 21dB]

Table 1. Channel parameters for the considered scenarios

2.2 Principle of the Transmission Scheme and Basic Relay Functionalities

The transmission scheme considered is an OFDMA one, which allocates to each user a chunk (resource allocation unit) composed of S sub carriers during E OFDM symbol periods, modulated on a channel carrier F_1. Therefore this chunk could be defined by a bandwidth $BW_{ch}= f_s \cdot S$ and chunk period $T_{ch}= E(1+G)/f_s$ corresponding to a chunk rate $C_{ch} = 1/T_{ch}$; f_s denotes the frequency separation between sub-carriers and G the percentage of the T_s, allocated to the guard interval.

The chunk contains U payload QAM symbols that are „loaded" with n bits, according to the E_b/N_0 of the channel. For the sake of simplicity, this papers considers $U = E \cdot S$ (no "service" QAM symbols) and n = 1. This approach would allow the RN to receive simultaneously from two UTs. The data is transmitted using a bipolar (+/-1) transmission affected by Gaussian noise and block Rayleigh-fading (when specified).

A second assumption involves that the RN is able to receive on the F_1 channel carrier and transmit simultaneously its cooperative messages towards the BS in its dedicated chunk placed on the same channel carrier F_1 or on another channel carrier F_2. This approach, denoted as Sim, would allow the continuous transmissions, both on the UT^j-BS and UT^j-RN channels and on the RN-BS channel. The cooperative messages corresponding to an UT^j message, transmitted by the RN, would arrive in the BS with a constant delay of one T_{ch} but the time resources (meaning elementary T_{ch} time intervals) required to transmit the a payload chunk/UT would be of $1.5T_{ch}$ if the RN serves 2 UTs and $2T_{ch}$ if the RN serves only one UT. The transmission delay perceived by the source and the employed time resources for successful decoding are two different things in this situation. It was also considered that the RN's chunk can not be divided and no more additional check bits are transmitted, because we want to keep the global coding rate of the turbo code R_g, see next paragraph, at the same value as the mother RSC code.

A second approach, assumes that the RN should transmit on the same channel carrier F_1 and in one of the chunks assigned to the served UTs (possible in an alternative manner). If only one UT is served, it should transmit every other chunk period (odd index) and the relay would transmit its messages in the chunk periods with an even index; so, the latency inserted equals $2T_{ch}$ and the average time required to transmit a payload chunk is $2T_{ch}$. If the RN serves two UTs, they should transmit every two chunks out of three, leaving their every third chunk period for the RN transmission. This would insert a global delay on the cooperation cluster of $3T_{ch}$ and the average time required to transmit a payload chunk/UT equals $1.5 \cdot T_{ch}$. This approach performs a consecutive transmission of the messages involved by cooperation, and is called Con.

3 Algorithm Description

The basic idea of this algorithm is to reduce the complexity of the SNCC algorithm, by using the linearity property of the turbo codes, i.e. a linear combination of two code words of the involved code generates another codeword.

By using the soft network coding concept, [5], the complexity required by the implementation of the

SNCC algorithm in the RN and BS is significantly decreased. Figure 2 presents the schematic diagram of this algorithm.

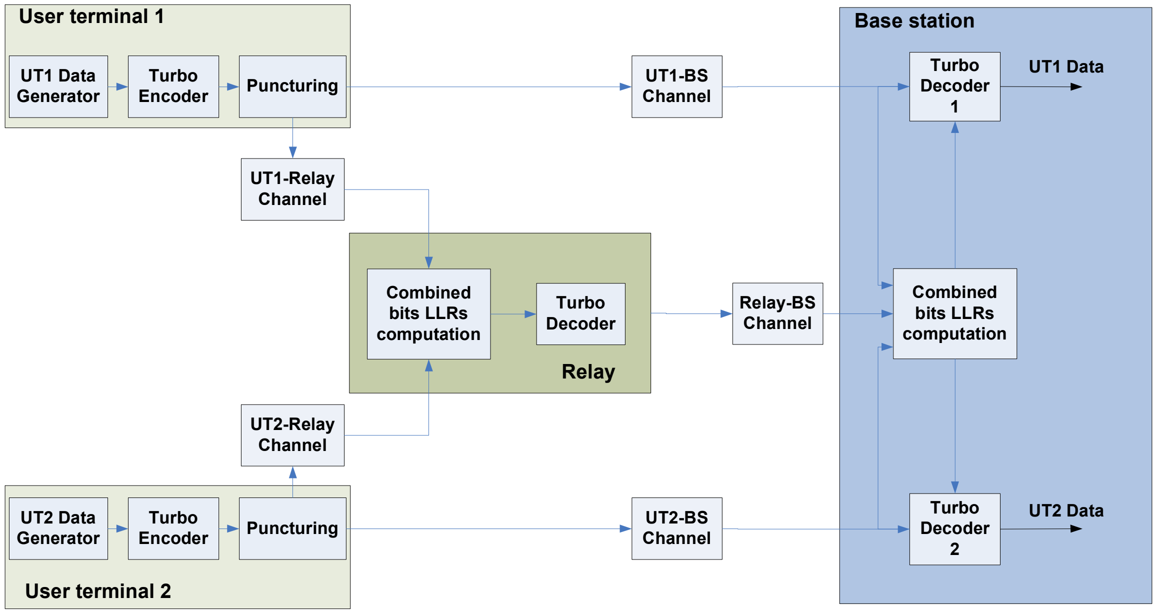


Figure 2. Block diagram of the cooperation scheme based on the LC-SNCC algorithm

Considering the turbo code linearity and the fact that the network coding process is a linear mapping, the order of these processes can be exchanged as shown in [5], compared to their order in the SNCC algorithm, [6] [7].

This inversion can be accomplished by extracting at the RN the LLRs of data received from UT[1] (X1) and UT[2] (X2), then computing the LLRs of the network encoded flows and using these network encoded LLRs as input information for the RN's turbo decoder.

The log-likelihood ratio of $X1 \oplus X2$ can be expressed, based on the UT[j]-RN channels' observations, as [5]:

$$LLR_{X1\oplus X2} = \ln\left(\frac{1+e^{(LLR_{X1}+LLR_{X2})}}{e^{LLR_{X1}}+e^{LLR_{X2}}}\right) \approx sign\left(LLR_{X1}\right)\cdot sign\left(LLR_{X2}\right)\cdot \min\left(\left|LLR_{X1}\right|,\left|LLR_{X2}\right|\right) \quad (3)$$

By turbo-decoding the set of LLRs we obtain the network encoded block which is transmitted over the RN-BS channel without any channel encoding. This is a second modification of the SNCC algorithm aimed to decrease the implementation complexity in the RN.

The BS, equipped with only two turbo decoders, as opposed to the three turbo decoders required by the SNCC algorithm, extracts the LLRs from the signals received on the direct UT[j]-BS channels and on the RN-BS channel.

Then, the LLRs of the RN-BS channel are used to compute the additional information for the two turbo decoders of the two data flows, as shown in (4).

$$\mathrm{LLR}^{\mathrm{UT1}}_{\mathrm{additional}} = \ln\left(\frac{1+\mathrm{e}^{(\mathrm{LLR}_{\mathrm{RN}}+\mathrm{LLR}_{\mathrm{UT2}})}}{\mathrm{e}^{\mathrm{LLR}_{\mathrm{RN}}}+\mathrm{e}^{\mathrm{LLR}_{\mathrm{UT2}}}}\right); \quad \mathrm{LLR}^{\mathrm{UT2}}_{\mathrm{additional}} = \ln\left(\frac{1+\mathrm{e}^{(\mathrm{LLR}_{\mathrm{RN}}+\mathrm{LLR}_{\mathrm{UT1}})}}{\mathrm{e}^{\mathrm{LLR}_{\mathrm{RN}}}+\mathrm{e}^{\mathrm{LLR}_{\mathrm{UT1}}}}\right); \quad (4)$$

The two flows are separately turbo decoded using the direct channel observations and the additional LLRs computed using the other channel's observations.

By using the approximation in (3), the complexity of the computation of the additional LLRs block is drastically reduced.

Because the RN data block is sent without any channel encoding, the global coding rate of each flow increases, compared to the one ensured for SNCC [6] [7], and can be computed by:

$$R_g = \frac{2 \cdot N_i}{2 \cdot N_{UT} + N_i} = \frac{2 \cdot N_i \cdot R_{UT}}{2 \cdot N_i + R_{UT} \cdot N_i} = \frac{2 \cdot R_{UT}}{2 + R_{UT}} \tag{5}$$

where N_i and N_{UT} denote the information respectively the encoded bits generated by UT and R_{UT} is the coding rate of UT.

4 Performances of the LC-SNCC Algorithm

The performances of the LC-SNCC algorithm are evaluated in the same scenarios as the ones employed for the SNCC algorithm [6] [7] as showed in section 2.1. The "mother" SNCC algorithm and the non-cooperative turbo coded (TC) transmission performances are used as references for all considered scenarios.

Feedback generator polynomial	13_8
Feed forward generator polynomial	15_8
"Mother" code rate	0.50
UT coding rate	0.75
No. of iterations of the turbo decoders	8
No. of blocks for each E_b/N_0 value	2000
No. of info bits/block	1500

Table 2 Parameters of the employed coding scheme and of the simulation scenarios.

The parameters of the RSC code employed and those of the simulations performed in this study are summarized in table 2.

The E_b/N_0 of the UT[1]-BS channel, the reference channel of each simulation, was varied within the limits defined in Table 1 for each of the scenarios which considers block Rayleigh-faded channel. The E_b/N_0 values of the other channels involved are kept greater than the ones of the reference channel with the amounts specified in Table 1.

4.1 BER and PER Performances in the SS-EF Scenario

Figure 3 presents the BER and PER performances of the LC-SNCC algorithm in the SS-EF scenario. Since the two UTs have identical parameters, their performances would be similar and therefore only the performances of UT[1] are shown.

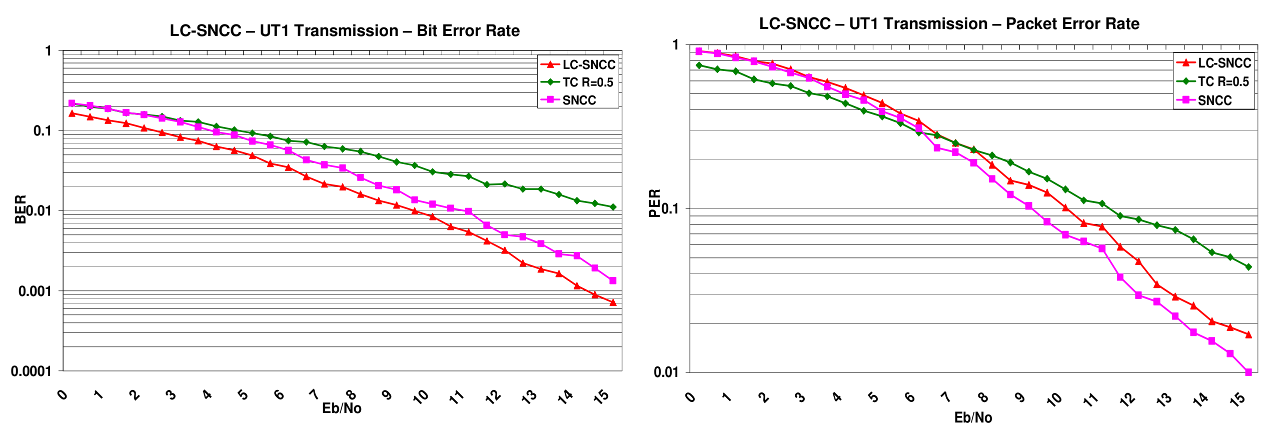


Figure 3. BER and PER performances of the LC-SNCC algorithm in the SS-EF scenario

The LC-SNCC algorithm outperforms both, the SNCC and TC algorithms in terms of BER, providing approximately 5 dB gain at a bit error rate equal to 10^{-2} compared to TC transmission. The PER performances of the LC-SNCC are slightly worse than the ones of SNCC algorithm, but outperforms the

TC transmission. This behavior might be explained by the different distribution of the bit-errors within packets.

4.2 BER and PER Performances in the AS-EF Scenario

Since the UT^j-BS direct channels of the two UTs have significantly different E_b/N_0 values, see Table 1, the performances of the two UTs are expected to be different and therefore they will be presented separately in Figure 4.

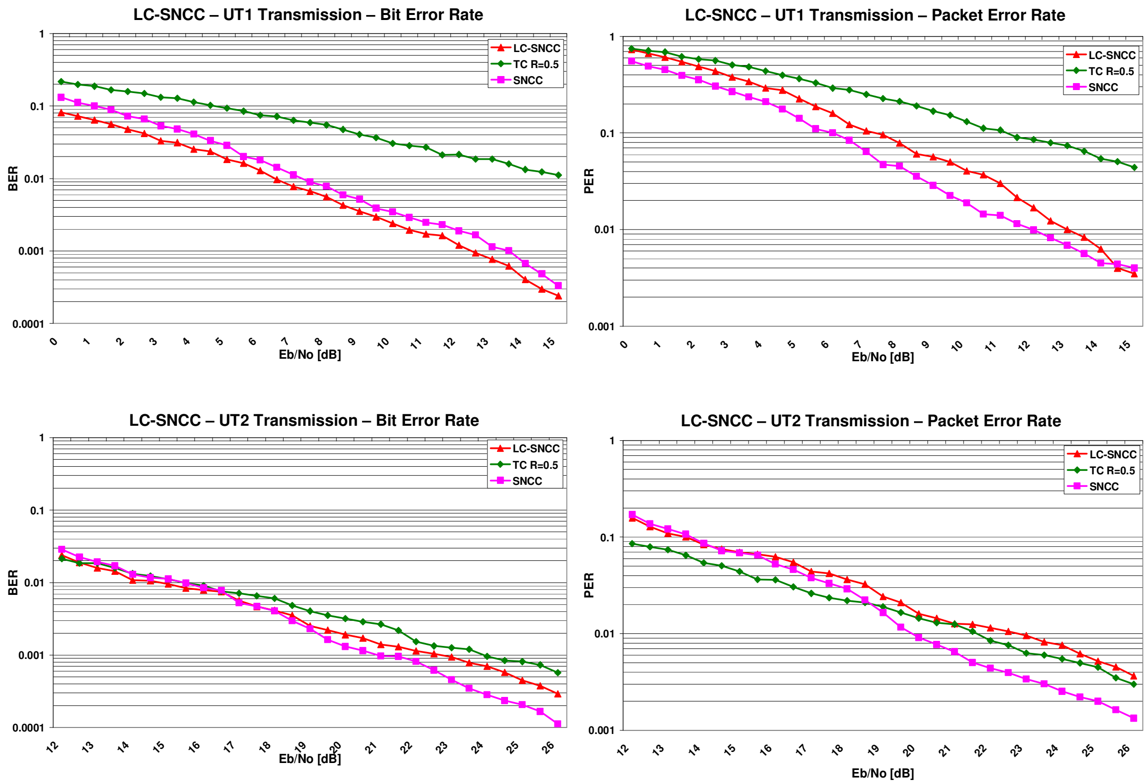


Figure 4. BER and PER vs. E_b/N_0 provided by LC-SNCC in the AS-EF scenario; BER and PER of UT^1 - upper row - left and right; BER and PER of UT^2 - lower row - left and right.

For UT^1 transmission, the LC-SNCC algorithm provides a significant cooperative coding gain (CCG), in terms of BER. A gain of approximately 8 dB is obtained compared to TC scheme and 0.7 dB compared to the SNCC algorithm. This is explained by the fact that UT^2 provides "better quality" cooperation, due to its "better" position. The negative gain or very low gain provided for UT^2 is due to the better performances of the reference transmission, which has a better UT^2-BS channel and to the „lower help" received from UT^1. The performances of the LC-SNCC algorithm are slightly worse for the "better positioned" UT, i.e. UT^2. As for the PER performances, the SNCC outperforms the LC-SNCC algorithm.

The obtained results, figure 4, can be summarized as follows:

- The LC-SNCC provides smaller BER than SNCC for UT^1 (a CCG greater with 1 dB), while for UT^2 it ensures a greater BER, (a CCG smaller with 1 dB).
- The LC-SNCC ensures higher values of PER than SNCC for both UTs involved. This decrease of the PER performances, compared to the ones of the SNCC algorithm, could be explained by the absence of the error detection mechanism on the direct and relay channels.

4.3 BER and PER Performances in the SS-WE Scenario

Since the two UTs have identical parameters, their performances would be similar and therefore only the performances of UT^1 are shown.

Figures 5 and 6 present the BER and PER performances provided by the LC-SNCC algorithm for UT[1] in this scenario, for E_b/N_0 = 6 dB (simulation 1) and E_b/N_0 = 4.5 dB (simulation 2) on UT^j-RN channels, respectively. The corresponding values of BER on these channels are BER = $3{\cdot}10^{-3}$ or 10^{-2}. The figures also show the performances of the direct turbo coded transmission, TC, and the ones of the SNCC algorithm [6] [7], as references.

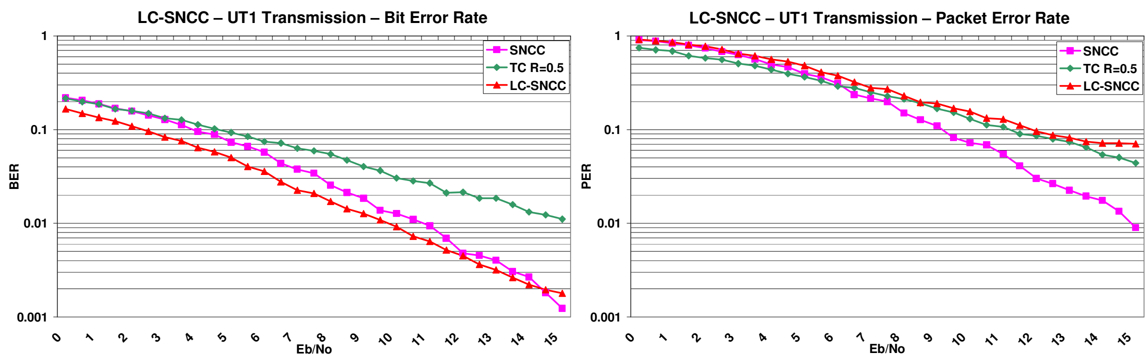


Figure 5. BER (left) and PER (right) vs. E_b/N_0 provided by LC-SNCC - SS-WE Scenario - simulation 1

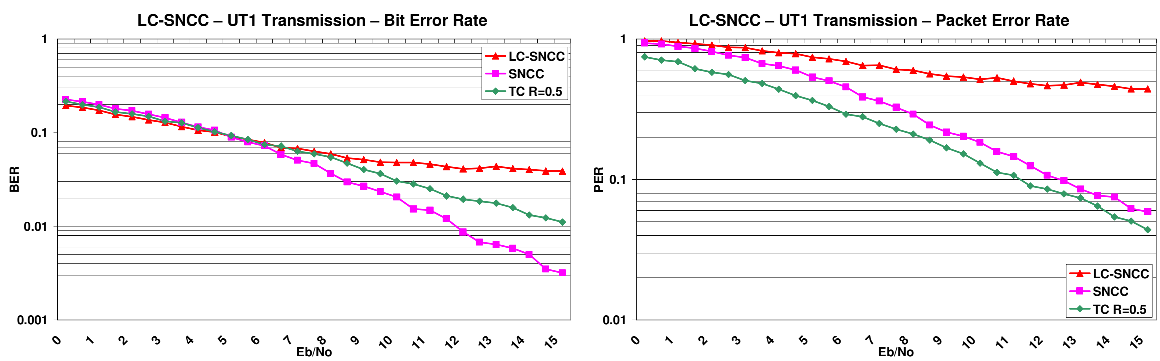


Figure 6. BER (left) and PER (right) vs. E_b/N_0 provided by LC-SNCC - SS-WE Scenario – simulation 2

If the E_b/N_0 of UT^j-RN is above a threshold value (simulation 1) the LC-SNCC provides a CCG of about 5 dB, compared to TC transmission at a BER of 10^{-2} while, if it is below that threshold the BER performances of the LC-SNCC becomes worse than the ones of the direct transmission TC and the ones of the SNCC algorithm, exhibiting an error-floor. As for the PER performances, the LC-SNCC performs worst than the SNCC and TC.

The error detection mechanism of the SNCC scheme on the direct and relay links makes this scheme less sensitive to the UTs-RN channels quality. Another cause of the poorer performances obtained by the LC-SNCC algorithm in this scenario is that of the poorer error correcting power of the codes used on the UTs-RN links, as shown in [5], due to the combination of the two encoded blocks before the channel decoder.

4.4 Spectral Efficiency Performances of LC-SNCC

The spectral efficiency provided by the proposed cooperative coding scheme is significantly affected by the transmission scheme employed and by the functionalities available in the RN. Some brief considerations about these issues were presented in section 2.2.

Considering the approach that would allow a continuous transmission on both UT^j-BS and RN-BS channels, denoted by Sim, the time interval required to transmit the two messages required by cooperation is one T_{ch}, while the bandwidth required to transmit the messages required by one MS equals $\frac{2+R_{UT}}{6}\cdot BW_{ch}$. Recall that the cooperative coded scheme employs, in the particular case studied in this paper, half of RN's transport capacity for one UT.

As for the Con approach described in 2.2, the time required to transmit the two messages for one UT would be $\frac{2+R_{UT}}{6}\cdot T_{ch}$ while the occupied bandwidth would equal BW_{ch}.

The spectral efficiency provided by the proposed cooperative coded scheme is computed by dividing the throughput to the employed frequency bandwidth. The spectral efficiencies of the two transmission schemes, with simultaneous transmission in the RN (Sim) or with consecutive transmissions only on F_1 (Con), are expressed by:

$$\begin{aligned}
&\eta_{LC}(SNR)[bps/Hz]=\frac{C_{ch}\cdot U\cdot n\cdot R_{UT}}{BW_{ch}}\cdot(1-PER_{LC})=\frac{f_s\cdot U\cdot n\cdot R_{UT}}{(1+G)\cdot E\cdot S\cdot 1.458\cdot f_s}\cdot(1-PER_{LC})=\\
&=\frac{R_{UT}}{(1+G)\cdot 1.458}\cdot(1-PER_{LC})=0.457\cdot(1-PER_{LC})\quad \text{Sim}\\
&\eta_{LC}(SNR)[bps/Hz]=\frac{C_{ch}\cdot U\cdot n\cdot R_{UT}}{1.458\cdot BW_{ch}}\cdot(1-PER_{LC})=\frac{f_s\cdot U\cdot n\cdot R_{UT}}{1.458\cdot(1+G)\cdot E\cdot S\cdot f_s}\cdot(1-PER_{LC})=\\
&=\frac{R_{UT}}{1.458\cdot(1+G)}\cdot(1-PER_{LC})=0.457\cdot(1-PER_{LC})\quad \text{Con}
\end{aligned}\qquad (6)$$

In (6), G denotes the guard interval which was considered, G=1/8 of T_s, R_{UT} = 0.75 and the index *LC* denotes this cooperative coding algorithm.

The direct transmission (Dir), which employs the same OFDMA scheme coded with an R_g = 0.5 coding rate, has its message transmitted during one T_{ch} period using a bandwidth equaling BW_{ch}. Therefore its spectral efficiency is:

$$\eta_d(SNR)[bps/Hz]=\frac{C_{ch}\cdot U\cdot n\cdot R_g}{BW_{ch}}\cdot(1-PER_d)=0.44\cdot(1-PER_d)\quad \text{Dir}\qquad (7)$$

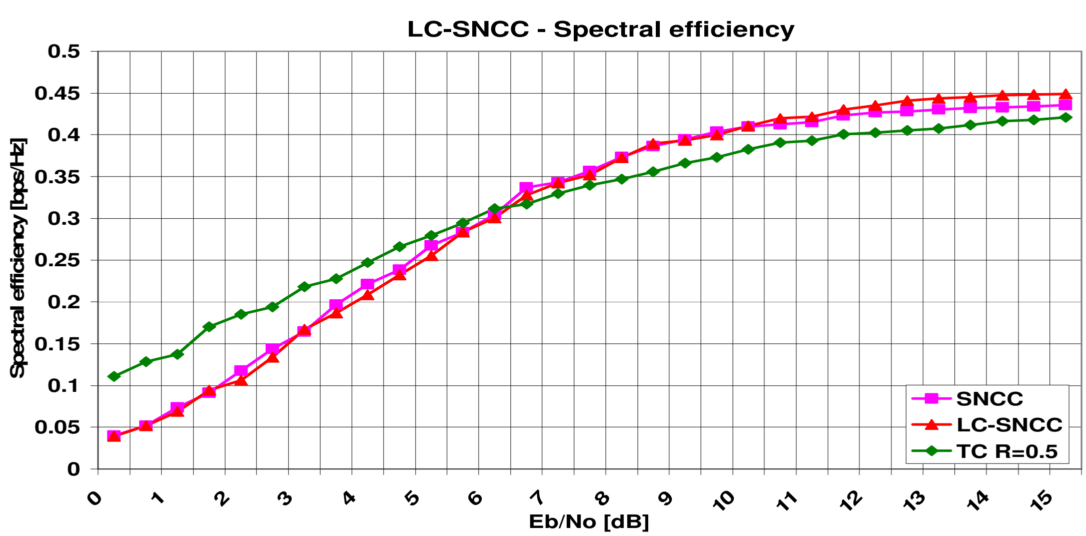


Figure 7. Spectral efficiencies vs. E_b/N_0 provided by the LC-SNCC, SNCC and TC algorithms in the SS-EF scenario

The spectral efficiency performances ensured by the LC-SNCC algorithm depend on the transmission scheme employed and on the PER. Due to its structure, the LC-SNCC algorithm ensures a slightly greater nominal spectral efficiency (without considering the PER values) than the SNCC algorithm, for the same transmission scheme, as shown by (6), but the PER performances of the LC-SNCC are poorer than the one of SNCC. Figure 7 presents the variations of the spectral efficiencies provided by the LC-SNCC, SNCC and TC algorithms in the SS-EF scenario. Figure 7 shows that the LC-SNCC and SNCC scheme provides the same spectral efficiency performances.

5 Conclusions

The paper proposes a low complexity cooperation algorithm, LC-SNCC, which employs network coding and distributed channel coding techniques. This algorithm is a modified version of the SNCC algorithm that aims to decrease the implementation complexity especially in the relay node, being more appropriate for integration in cellular networks using non-dedicated relays.

The LC-SNCC algorithm requires a simpler implementation, since it uses only one turbo decoder and two soft-demapping circuits in the RN and only two decoder and three soft-demapping circuits in the BS. The complexity of the UT is similar to the one required by SNCC algorithm.

As was shown in the paper for quasi error free UTs-RN channel scenarios LC-SNCC performs better in terms of BER, than the SNCC algorithm, but the PER performances are slightly poorer than the ones of the SNCC. In the case of the “with errors” scenarios the LC-SNCC seems to be more sensitive to the UTs-RN channels quality due the absence of the error detection mechanisms and the decreased error correcting power of the codes employed on these links.

It was also shown that the nominal spectral efficiency is higher than the one of complete SNCC algorithm, due to the increase of the global coding rate of the LC-SNCC scheme. The spectral efficiency performances obtained are similar with the ones of the SNCC scheme due the better PER performances of the SNCC scheme.

6 Acknowledgment

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7 References

[1] B. Zhao, M.C. Valenti, “Distributed turbo coded diversity for relay channel”, Electronics Letters, vol. 39, 15 May 2003

[2] Arnab Chakrabarti, Elza Erkip, Ashutosh Sabharwal, and Behnaam Aazhang, “Code Designs for Cooperative Communication”, IEEE Signal Processing Magazine, Vol. 24, Issue 5, Sept. 2007 , pp. 16 - 26

[3] R. Ahlswede, N. Cai, S.-Y. R. Li and R. W. Yeung, “Network information flow”, IEEE Transactions on Information Theory, 46(4):1204-1216, July 2000.

[4] Christoph Hausl, Philippe Dupraz, “Joint Network-Channel Coding for the Multiple-Access Relay Channel”, SECON 2006, Vol. 3, pp. 817-822

[5] Shengli Zhang, Yu Zhu, Soung-Chang Liew, and Khaled Ben Letaief, “Joint Design of Network coding and channel decoding for wireless networks”, IEEE WCNC, 2007

[6] M.P. Stef, Zs. A. Polgar, V. Bota, “Performance Analysis of Some Distributed Network and Channel Coding Schemes in Cooperative Transmissions” , COST 2100 TD(08) 654, Lille, France, 2008

[7] “Preliminary PHY layer algorithm selection for integration in the prototypes”, Deliverable D.3.2a, FP7-ICT-2007-215477, CODIV Project. www.ict-codiv.eu