Dynamic decode and forward relaying for broadcast transmissions by relay-unaware sources

Mélanie Plainchault*, Nicolas Gresset*, Ghaya Rekaya-Ben Othman†
*Mitsubishi Electric R&D Centre Europe, France
†Télécom Paristech, France

***Abstract*—In this paper, we consider a broadcast transmission from a source to multiple destinations with an OFDM-based system. In order to improve the broadcast services of a cellular system, we consider the use of relays with Dynamic Decode and Forward protocols allowing the source to ignore the existence of relays in the system. A new algorithm executed at the relay is proposed. It allows for maximizing the diversity order at the destinations side by selecting the best relaying protocol and modulation size as function of the relay correct decoding time. No feedback is assumed on any link between the source, relays and destinations.**

I. Introduction

In cellular networks, broadcasting is a fundamental tool for transmitting control signals conditioning the overall system performance. Furthermore, multimedia broadcasting/multicasting has gained interest for outdoor and home communications, which gives another framework to this study. As broadcast transmission is generally designed to provide a given quality of service to the terminal experiencing the worst link quality, they are by essence diversity limited. Thus, we investigate the diversity order improvement by the help of relays. Moreover, as several relays will behave independently one from each other, we assume that the relay-unaware source defined in this paper transmits as if no relays were lying in the system.

Among the wide variety of relaying protocols, the dynamic decode and forward (DDF) protocol [1] has the appealing property of taking the best benefit from the relay use [2], [3], [4], [5], [6]. As soon as the relay correctly decodes the message sent by the source, which occurs at a random time, a joint transmission scheme between the source and the relay is received by the destination. The transmission ends as soon as the destination correctly decodes the message, the DDF protocol thus applies more naturally to closed-loop transmissions.

In this paper, we design adapted DDF protocols for improving the diversity order of braodcast transmissions to as many destinations as possible, without any feedback or control signalling specific to relaying between the source and relays. In section II, the transmission scheme and channel model are presented. In section III, we present the theoretical toolbox needed for understanding the diversity behavior of the coded system including DDF relaying. In section IV, we introduce a criterion for selecting the modulation order at the relay, as a function of the relay correct decoding time. Finally, in section V, we present some simulation results illustrating the gain brought by the proposed coding strategies.

II. System Model and Parameters

Let us consider a source S, one of the relays R and one of the destinations D. The transmission of one information word follows a Bit-Interleaved Coded Modulation (BICM) structure [7], i.e., an information word $\mathbf{b}$, of length K bits, is encoded into an interleaved codeword of a binary code $\mathcal{C}$, which interleaved version $\mathbf{c}$ is modulated using a QPSK discrete modulation carrying $m_S = 2$ coded bits. The codeword $\mathbf{c}$ is sent during a frame, which is segmented into N_b sub-frames, the length of the i-th sub-frame being B_i coded bits, and $B_1 \geq K$. A Cyclic Redundancy Check (CRC) code is embedded in the information word, allowing for the destination D to try to decode the concatenation of the sub-frames, and stops listening to the source S as soon as the CRC check is correct. As no acknowledegment is sent from the destination D to the source S, the whole frame is sent and the performance of one frame transmission is designed to provide a target quality of service to the worst users.

The relay R receives data sent by the source during a phase 1 of the DDF protocol, during which the relay keeps listening to the source as soon as decoding failures occur. The relay R then switches into a phase 2 when the CRC check is correct, and transmits additional redundancy with a 2^{m_R}-QAM modulation to D on the same frequency and time resource as the source S. Thus, the relay R transmits $B_i m_R / m_S$ coded bits during the i-th sub-frame. We note L_1 the number of coded bits transmitted by the source in the first phase, and L_2 and L_R respectively the number of bits transmitted by the source and by the relay in the second phase. The codewords of $\mathcal{C}$ and the additional redundancy sent by the relay are for example generated from a rate matching algorithm associated to a Rate-1/3 turbo-code, as in the 3GPP-LTE standard. We call M the index of the subframe after which the relay could correctly decode the information word. Consequently, the addition of the source and relay signals is received at the destination during Phase 2.

The frame and sub-frame structure, the phases of reception and transmission of the relay, and the decoding failures at the relay are illustrated in Fig. 1.

A classical receiver is applied at the destination, which first converts the received symbols into soft estimates of the coded bits, which are then given to the input of the soft-input decoder.

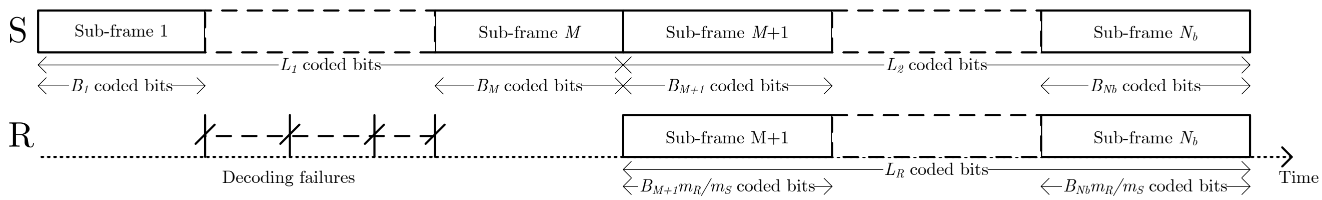

Fig. 1. Frame structure of the open-loop DDF relaying protocol

We assume that the destination has the ability to detect whether the relay is activated or not. This can for example be achieved by the transmission of dedicated pilot or control signals from the relay.

We consider quasi-static flat-fading channels, i.e., the channel remains constant during at least the transmission of one codeword, and is independent from one frame transmission to another. The fading coefficients α_{SD} between the source and the destination and α_{RD} between the relay and the destination are complex-gaussian distributed with zero mean and unity variance. A complex-gaussian noise of variance $2N_0$ is added at the destination receive antenna. The values SNR_{SD}, SNR_{SR} and SNR_{RD} respectively denote the signal-to-noise ratio of the link from the source to the destination, the source to the relay, and the relay to the destination. As a remark, the unbalance between SNR_{SD} and SNR_{RD} theoretically does not change the diversity order of the system. However, it is straightforward to understand that if $SNR_{SD} >> SNR_{RD}$, the relay has no impact on the observed performance. From a system level point of view, the relay is assumed to be placed, or selected among other terminals, such that $SNR_{SD} \simeq SNR_{RD}$ for the lowest values of SNR_{SD}.

As mentioned before, the fact that the relay will transmit or not must be completely transparent to the source. Indeed, as the relay might only be beneficial to a portion of users, the source must not adapt itself according to the relay state. This assertion is meaningful in a case where several relays cover different zones of the source coverage area. We call a source satisfying this property a relay-unaware source. Thus, two different strategies are selected from the existing well-known DDF protocols for allowing a source to be relay-unaware. The phase 2 can be seen as a 2×1-MIMO scheme with two non co-localized antennas, the first antenna being the transmission from the source and the second antenna from the relay.

- The first studied protocol for phase 2 is a transposed version of the distributed Alamouti (DA-DDF), where the pair of symbols $[z_1, z_2]$ is transmitted by the source such as without relaying while the pair of symbols $[z_2^*, -z_1^*]$ is transmitted by the relay with $m_R = m_S$ [8]. At the destination D, the symbols received from the relay and the source in phase 2 are combined by the detector into soft estimates on the coded bits, and the decoded codeword is not longer than without relaying.
- The second studied protocol is a spatial division multiplexing (SDM-DDF) for the phase 2, the first data stream corresponding to the transmission from the source such as without relaying; and the second data stream to the transmission from the relay. In practise, applying the same rate matching algorithm as the one used by the source to the known K information bits, the relay generates additionnal coded bits different from those sent by the source. In other words, at the destination D, the symbols received from the relay and the source in phase 2 are converted by the detector into different soft estimates on the coded bits, and the decoded codeword is longer than without relaying. See [9] for the achievability of close to the outage probability performance on a 2×1 MIMO channel.

Thanks to a careful design of the interleaver of the BICM, the soft estimates of the coded bits can be sorted into channel blocks, each channel block being associated to one fading random variable of the channel. The equivalent block-fading channel of the two studied protocols and their impact on the coded performance will be detailed in the following section.

III. Diversity analysis of relaying protocols under error correction coding

In this section, we present theoretical results on the maximal diversity order achievable by a coded system on the equivalent block-fading channel model seen between the output of the error correcting code encoder and the input of the decoder. These results will be used to determine the modulation order and relaying protocol at the relay in the next section.

A. Bound on the diversity for variable length independent block-fading channel

The upper bound on the diversity order of a coded modulation transmitted on a block-fading channel of equal length blocks has been derived in [10]. Due to the dynamic decoding time at the relay, we propose a generalization of the Singleton bound on the diversity order to unequal length block-fading channels:

Proposition: The diversity obtained after decoding a rate-R_c linear code transmitted over a $\mathcal{B}(\mathcal{L})$ independent block-fading channel, where $\mathcal{L} = (L_1, \ldots, L_N)$ is the vector of block lengths and where the fading coefficient of the blocks are independent one from the others, is upper-bounded by $d_{\mathcal{B}}(\mathcal{L}) = N - i + 1$ where i is given by the following inequality:

$$\sum_{j=1}^{i-1} L_{s(j)} < R_c \sum_{j=1}^{N} L_j \leq \sum_{j=1}^{i} L_{s(j)} \quad (1)$$

where $s()$ denotes a sorting operation such that $\forall j, \quad L_{s(j)} \leq L_{s(j+1)}$.

Proof: Let $K = R_c \sum_{j=1}^{N} L_j$ be the number of information bits per codeword. The diversity order of the coded modulation is defined by the lowest diversity order observed among all pairwise error probabilities. Consider permutations Ω of strictly positive integers lower than N. If i is the maximal integer, function of Ω, K, and $\mathcal{L}$, such that $\sum_{j=1}^{i-1} L_{\Omega(j)} < K$, for any code structure, selecting only the coded bits of the blocks of index in $\{\Omega(1), \ldots, \Omega(i)\}$ builds a null-Hamming distance code. Thus, there exists at least one pair of codewords exhibiting a diversity order lower or equal to $N - i + 1$. Furthermore, the configuration Ω maximizing i gives the lowest diversity order $N - i + 1$ among all pairwise error probabilities, which is obtained by choosing $\Omega = s$, sorting the blocks in increasing length order. □

B. Bound on the diversity for Matryoshka channels

In [11], an other class of block-fading channel has been introduced to derive the bounds on the diversity order of coded system over multi-relay channels. The Matryoshka channel $\mathcal{M}(\mathcal{D}, \mathcal{L})$ is defined by N blocks, where $\mathcal{L} = (L_1, \ldots, L_N)$ is the vector of block lengths and $\mathcal{D} = (D_1, \ldots, D_N)$ is the vector of diversity order intrinsic to each block. The Matryoshka channel is characterized in that the fading random variable of the i-th block is a component of the fading random variable of the $i-1$-th block which has a larger diversity order.

The diversity observed after decoding a rate-R_c linear code transmitted over a $\mathcal{M}(\mathcal{D}, \mathcal{L})$ channel is upper-bounded by $\delta_{\mathcal{M}}(\mathcal{D}, \mathcal{L}) = \mathcal{D}_i$ where i is given by the following inequality:

$$\sum_{k=1}^{i-1} L_k < R_c \sum_{k=1}^{N} L_k \leq \sum_{k=1}^{i} L_k \tag{2}$$

It has to be noted that the difference between an independent block-fading channel and a Matryoshka block-fading channel comes from the sorting of the block lengths in the computation of the bound, and it is easy to show that $\delta_{\mathcal{M}}(\mathcal{D}, \mathcal{L}) \geq \delta_{\mathcal{B}}(\mathcal{L})$.

C. Diversity analysis of the coded DA-DDF

During the phase 2 of the DA-DDF protocol, the symbols transmitted by the source and the relay are combined into the same soft estimates of the coded bits, which are dependent of $\alpha_{SD}^2 + \alpha_{RD}^2$. The soft estimates of the L_1 coded bits of phase 1 are only dependent of α_{SD}^2. Thus, the equivalent block-fading channel seen by the code is a $\mathcal{M}(\{2, 1\}, \{L_2, L_1\})$ Matryoshka channel and the code rate of the code decoded at the destination is $R_c = K/(L_1 + L_2)$, as the received codeword is not longer than without relaying. If the relay is assumed to correctly decode the information word after the M-th block, then $L_1 = \sum_{i=1}^{M} B_i$ and $L_2 = \sum_{i=M+1}^{N_b} B_i$. From 2, the diversity order $\delta_{DA}(M)$ is given by

$$K \leq \sum_{i=M+1}^{N_b} B_i, \quad \Rightarrow \delta_{DA}(M) = 2 \tag{3}$$

$$K > \sum_{i=M+1}^{N_b} B_i, \quad \Rightarrow \delta_{DA}(M) = 1 \tag{4}$$

D. Diversity analysis of SDM-DDF

It is well known that a BICM transmitted over a MIMO channel with spatial multiplexing can be modeled as an independent block-fading channel from the decoder point of view (e.g., [9]), where the number of blocks is equal to the number of streams of the spatial multiplexing, and the fading random variables are independent one to each other.

When using the SDM-DDF protocol, the $L_1 + L_2$ coded bits sent by the source see the fading random variable α_{SD}, whereas the L_R coded bits independently sent by the relay see the fading random variable α_{RD}. Thus, the equivalent channel is an independent block-fading channel $\mathcal{B}(L_1 + L_2, L_R)$ and the code rate is $R_c = K/(L_1 + L_2 + L_R)$, as the received codeword is longer than without relaying.

Whenever the relay correctly decodes the information word, the number of coded bits seeing the α_{SD} fading coefficient remains constant and equal to $L_1 + L_2 = \sum_{i=1}^{N_b} B_i$. If the relay is assumed to correctly decode the information word after the M-th block, then $L_R = \sum_{i=M+1}^{N_b} B_i m_R / m_S$.

Taking into account that $B_1 \geq K$, and from 1, the diversity order $\delta_{SDM}(M)$ is given by

$$K \leq \sum_{i=M+1}^{N_b} B_i \frac{m_R}{m_S} \Rightarrow \delta_{SDM}(M) = 2 \tag{5}$$

$$K > \sum_{i=M+1}^{N_b} B_i \frac{m_R}{m_S} \Rightarrow \delta_{SDM}(M) = 1 \tag{6}$$

As a remark, we restrict the study to one relay in this paper, but all the theoretical material needed to understand and design a multi-relay system is presented in this section, and will be the topic of future work, as well as the impact of larger orders of frequency selectivity.

IV. Protocol and modulation selection at the relay

The diversity analysis of the studied DDF protocols shows us that, depending on the segmentation strategy of the blocks and on the correct decoding time at the relay, the frame error probability $p_e(M)$ exhibits different diversity orders. The sooner the relay activates for transmission, the better the chance to achieve full diversity is. However, the source to relay link also suffers from fading. That makes the correct decoding time M dynamic. Let us define $P_R(M)$ the probability of correct decoding at the relay after the M-th transmitted block, then the average probability of error of the transmission is

$$P_e = \sum_{M=1}^{N_b} P_R(M) p_e(M) \tag{7}$$

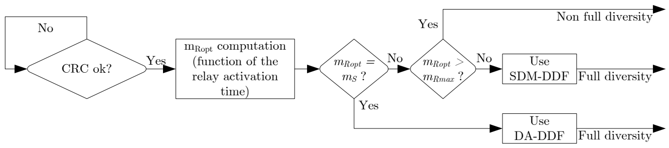

Fig. 2. Algorithm executed at the relay.

By maximizing the diversity order of each discrete input outage probability $p_e(M)$, the average error rate P_e is decreased. As a remark, $P_R(M)$ is a function of SNR_{SR} while $p_e(M)$ is a function of SNR_{SD} and SNR_{RD}. Thus, the relays can be deployed for improving the coverage area of broadcast services, or for increasing the data rate of broadcasting at the cell edge.

The probability of correct decoding at the relay after receiving the M-th block of data is computed from the mutual information $I(SNR_{SR}, \alpha_{SR})$ of the data link between the source and the relay as follows

$$P_R(M) = Pr\left(\sum_{i=1}^{M-1} B_i < \frac{Km_S}{I(SNR_{SR}, \alpha_{SR})} \leq \sum_{i=1}^{M} B_i\right) \tag{8}$$

Let us remark that $m_R \geq m_S \Rightarrow \delta_{SDM}(M) \geq \delta_{DA}(M)$ with equality for $m_R = m_S$, which means that the SDM-DDF protocol exhibits full diversity under configuration where the DA-DDF does not. However, when using SDM-DDF protocols, the receiver must be able to recover the diversity of the coded SDM scheme, which is not feasible with low complexity SISO detectors. This last remark is in favor of DA-DDF protocols for complexity-limited devices.

Let us consider that the segmentation of the codeword is fixed and known to the receivers. When the relay correctly decodes the information word after the M-th transmission block, it can easily compute the minimal m_{Ropt} that will provide full diversity for the $SDM-DDF$ protocol, i.e.

$$m_{Ropt} = \left\lceil m_S K / \sum_{i=M+1}^{N_b} B_i \right\rceil \tag{9}$$

Additionally, if $m_S = m_{Ropt}$, the DA-DDF protocol can be used instead of the SDM-DDF protocol for reducing the receivers complexity or power consumption.

We now assume for simplicity that the blocks B_i for $i > 1$ have an equal length of B_1/γ coded bits. Thus, $m_{Ropt}(\gamma, N_b)$ becomes

$$m_{Ropt}(\gamma, N_b) = \left\lceil \gamma \frac{m_S}{N_b - M} \frac{K}{B_1} \right\rceil \tag{10}$$

As a remark, if the modulation size at the relay is limited by $m_R \leq m_{Rmax}$, then cases where $m_{Ropt} > m_{Rmax}$ cannot achieve full diversity. The protocol and modulation selection executed at the relay are summarized in Fig. 2.

V. Simulation results

In this section, we consider the outage probability of the channel with discrete modulation input, as it follows the bounds on the diversity order of the equivalent block-fading channel [12]. We consider that $K/B_1 = 1$, i.e., that the first block contains only data. The reference SNR is defined as SNR_{SD}, the available transmit power at the base station for broadcasting being the more important limiting resource of the system (i.e., we consider that the relay load is low).

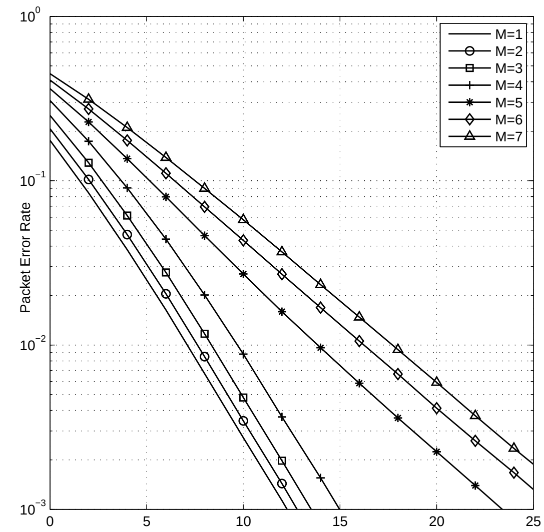

Fig. 3. Discrete input Outage Probability of DA-DDF for $\gamma = 3$, $N_b = 7$, $m_S = 2$.

Fig. 3 and Fig. 4 illustrate the performance obtained when $\gamma = 3$, $N_b = 7$, and $SNR_{SD} = SNR_{RD}$. Thus, if $M = 7$, the relay never transmits additional redundancy. The outage probabilities with QPSK input and DA-DDF or SDM-DDF are shown as a function of the correct decoding time M of the relay.

From equations (3) and (5), we show that the relay brings a gain of diversity only if $M < 5$. From (10), we see that the full diversity order can be achieved with SDM-DDF and $M = 5$ only if $m_R \geq 3$. Thus, if the relay correctly decodes the data at the 5-th block, we will choose to transmit additional redundancy with a 16-QAM modulation, which full diversity performance curve is shown in Fig. 4.

For $M = 6$, the relay must choose $m_R \geq 6$, which justifies why the performance with 16-QAM input does not reach the diversity order 2 anymore while the performance with 64-QAM input does. For $M = 7$, no diversity improvement can be achieved. Fortunately, the performance for $M = 7$ is designed for the worst destinations and a good positioning or selection of the relay will make the probability of not decoding before $M = 7$ negligible.

In Fig. 5, we make the signal-to-noise ratio between the source and the relay SNR_{SR} vary. We assume that the relay experiences a diversity-1 flat fading channel. The probability $P_R(M)$ of correct decoding of the relay after the M-th block transmission by the source is evaluated as in equation (8), and multiplies the outage probabilities of Fig. 3 and Fig. 4 as in

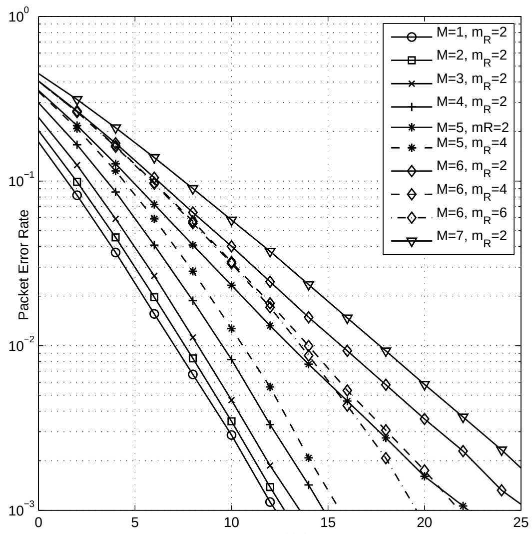

Fig. 4. Discrete input Outage Probability of SDM-DDF for $\gamma = 3$, $N_b = 7$, $m_S = 2$.

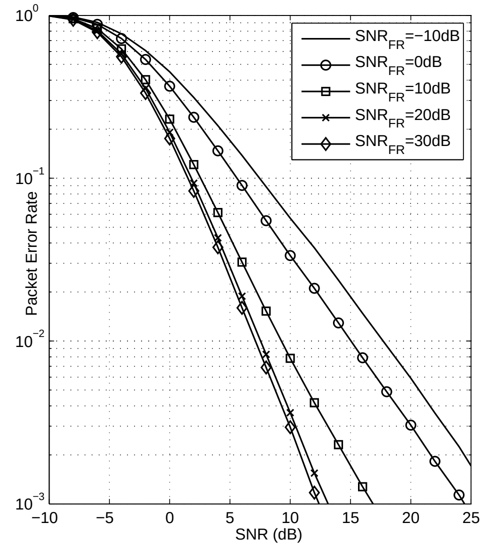

Fig. 5. Average performance for $\gamma = 3$, $N_b = 7$, DA-DDF for $1 \leq M \leq 4$, 16-QAM-SDM-DDF for $M = 5$ and 64-QAM-SDM-DDF for $M = 6$.

equation (7).

From the previous section, we choose to use the DA-DDF protocol for $M < 5$. The SDM-DDF with 16-QAM at the relay is selected as the only way to achieve full diversity for $M = 5$ and the SDM-DDF with a 64-QAM at the relay as the only way to achieve full diversity for $M = 6$. First, we observe that for very low SNR_{SR} values ($< 10dB$), few gain is observed from relaying, the slope-one $p_e(N_b)$ performance curve dominates the final performance. If $SNR_{SR} \geq 10dB$, the diversity order brought by the relay and the smart selection of the coding scheme and modulation size drastically improves the performance. It has to be noted that since $p_e(N_b) > 0$, the theoretical diversity of the system is one. If $p_e(N_b)$ is sufficently low, the asymptote of the performance is met for very low error rates, which makes high SNR_{SR} performance behave as full diversity systems. Furthermore, it has to be noted that if $SNR_{SR} = 10dB$, the relay suffers from an error rate of around 10^{-1}, which is a worst case of location of the relay (the open-loop system is designed such that worst users suffer from an error rate below 10^{-2}). Even in that case, the gain brought by DDF-relaying is around $8dBs$. We recall that the presented results are shown for equals SNR_{SD} and SNR_{RD} and that a fair evaluation of the gain brought by the presented technique can only be done with the help of a system level simulator, which will be the next step of this study.

VI. Conclusions

In this paper, we have shown the positive impact of using DDF relaying protocols in order to improve the performance of open-loop transmissions. The relay selects the transmission mode depending on the time it correctly decodes the message and the presented techniques allow for the source to be relay-unaware, i.e., to ignore the relay reception/transmission state. This last property is particularly relevant for broadcast services. The choice of the coding scheme and modulation size is made in order to maximize the diversity order for the worst users from theoretical limits of coding on block-fading and Matryoshka channels. In future works, the impact of multiple relays and the evaluation in system level simulators will be investigated.

References

[1] K. Azarian, H. El Gamal, and P. Schniter. On the achievable diversity-multiplexing tradeoff in half-duplex cooperative channels. *IEEE Transactions on Information Theory*, 51(12):4152–4172, 2005.

[2] N. Prasad and M.K. Varanasi. High performance static and dynamic cooperative communication protocols for the half duplex fading relay channel. In *Proc. IEEE Globecom*, 2006.

[3] P. Elia and P.V. Kumar. Approximately-Universal Space-Time Codes for the Parallel, Multi-Block and Cooperative-Dynamic-Decode-and-Forward Channels. *Available Online: http://arxiv.org/abs/0706.3502*, 706, 2007.

[4] A. Murugan, K. Azarian, and H. El Gamal. Cooperative lattice coding and decoding. *IEEE Journal on Selected Areas in Communications*, 25(2):268–279, 2007.

[5] K.R. Kumar and G. Caire. Coding and Decoding for the Dynamic Decode and Forward Relay Protocol. *IEEE Transactions on Information Theory*, 55(7):3186–3205, 2009.

[6] J.N. Laneman, D.N.C. Tse, and G.W. Wornell. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE Transactions on Information Theory*, 50(12):3062–3080, 2004.

[7] G. Caire, G. Taricco, and E. Biglieri. Bit-Interleaved Coded Modulation. *IEEE Transactions on Information Theory*, 44(3):927–946, 1998.

[8] S. M. Alamouti. A simple transmit diversity technique for wireless communications. *IEEE J. Sel. Areas Commun.*, 16:1451–1458, 1998.

[9] N. Gresset, L. Brunel, and J.J. Boutros. Space-Time Coding Techniques With Bit-Interleaved Coded Modulations for MIMO Block-Fading Channels. *IEEE Transactions on Information Theory*, 54(5):2156–2178, 2008.

[10] R. Knopp and P.A. Humblet. On coding for block fading channels. *IEEE Transactions on Information Theory*, 46(1):189–205, 2000.

[11] Ghassan M. Kraidy, Nicolas Gresset, and Joseph J. Boutros. Coding for the Non-Orthogonal Amplify-and-Forward Cooperative Channel. *Information Theory Workshop 2007 (ITW'07), Lake Tahoe, California, USA.*, 2007.

[12] A. Guillen i Fabregas and G. Caire. Coded modulation in the block-fading channel: Coding theorems and code construction. *IEEE Transactions on Information Theory*, 52(1):91, 2006.