

A method of communication

FIELD OF THE INVENTION

The present invention relates to a method of communication, a relay
5 station, a base station, a communication network, a user equipment and an
integrated circuit, and relates particularly though not solely to distributed rate
setting and coding schemes.

BACKGROUND

10 The following abbreviations may be used in this specification:

MAC	multiple access channels
CMAC	cooperative MAC
MARC	multiple access relay channels
BRC	broadcast relay channels
15 DF	decode-and-forward
SNR	signal to noise ratio
FER	frame error rate
RSC	recursive convolutional code
LO	local oscillator
20 AWGN	additive white Gaussian noise
BPSK	binary phase shift keying
CC	convolutional code
BS	base station

	UE	user equipment
	OFDM	orthogonal frequency division multiplex
	SCCP	single carrier cyclic prefix
	OFDMA	orthogonal frequency division multiple access
5	SC-FDMA	single-carrier frequency division multiple access
	DFT-Spread-OFDM	discrete Fourier transform spread OFDM
	FEC	forward error correction
	STBC	space time block code
	LLR	log-likelihood ratio
10	IR	incremental redundancy
	CP	cyclic prefix
	TDMA	time division multiple access
	RS	relay station
	MIMO	multiple input multiple output
15	ACK	acknowledgement
	NACK	negative acknowledgement
	SDMA	spatial division multiple access
	EXIT	extrinsic information transfer
	S	source
20	R	relay
	D	destination
	CC(•)	convolutional code with settings in parenthesis
	PCC(•)	parallel concatenated code with settings in parenthesis

$P_{out}(\bullet)$	probability of information outage
$I(\bullet)$	mutual information
γ_{AB}	the SNR from A to B
$SNR_{AB}^{(N)}$	the SNR from A to B in the N -th time slot

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SUMMARY OF THE INVENTION

In general terms the invention relates to combining distributed Alamouti space-time coding with decode-and-forward cooperative relay strategy using distributed rate-compatible error correction codes. This may have one or more advantages such as:

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1. a simple and/or systematic technique for designing a code for a cooperative relay network may provide increased wireless capacity and link quality;
2. a coding technique for a cooperative relay network with a low
3. a code design for a cooperative relay network which may have an error

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In a first particular expression of the invention there is provided a method of communication according to claim 1.

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In a second particular expression of the invention there is provided a RS as claimed in claim 11.

In a third particular expression of the invention there is provided a RS as claimed in claim 12.

5 In a fourth particular expression of the invention there is provided a BS as claimed in claim 13.

In a fifth particular expression of the invention there is provided a communication network as claimed in claim 14.

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In a sixth particular expression of the invention there is provided a UE as claimed in claim 15.

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In a seventh particular expression of the invention there is provided an IC as claimed in claim 16.

The invention may be implemented according to any of the embodiments in claims 2 to 10.

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BRIEF DESCRIPTION OF THE DRAWINGS

One or more example embodiments of the invention will now be described, with reference to the following figures, in which:

Figure 1 is an illustration of a simple 3-node relay channel model according to a first example embodiment,

Figure 2 is a graph of a Distributed Turbo coding at destination for a relay network with $\alpha = 0.5$, $\gamma_{SD} = -3$ dB and $\gamma_{RD} = -2.1$ dB,

Figure 3 is a graph of an Enhanced Turbo code at relay for a relay network with $\alpha = 0.75$, $\gamma_{SR} = 0.1$ dB, $\gamma_{SD} = -3$ dB and $\gamma_{RD} = -1.2$ dB,

5 Figure 4 is a graph of an Enhanced Turbo Code at destination for a relay network with $\alpha = 0.75$, $\gamma_{SR} = 0.1$ dB, $\gamma_{SD} = -3$ dB and $\gamma_{RD} = -1.2$ dB,

Figure 5 is a graph of a Distributed multiple Turbo code at relay for a relay network with $\alpha = 0.75$, $\gamma_{SR} = -0.2$ dB, $\gamma_{SD} = -3$ dB and $\gamma_{RD} = -1.5$ dB,

Figure 6 is a graph of a Distributed multiple Turbo code at destination for
10 a relay network with $\alpha = 0.75$, $\gamma_{SR} = -0.2$ dB, $\gamma_{SD} = -3$ dB and $\gamma_{RD} = -1.5$ dB,

Figure 7 is a graph of an outage and FER of distributed Turbo coding at destination for a relay network with $\alpha = 0.5$,

Figure 8 is a graph of an outage and FER of an enhanced Turbo coding and multiple Turbo coding at destination for a relay network with $\alpha = 0.75$,

15 Figure 9 is an illustration of a two-user CMAC system according to a second example embodiment,

Figure 10 is an illustration of a two-user MARC system according to a third example embodiment,

Figure 11 is an illustration of a two-user BRC system according to a forth
20 example embodiment,

Figure 12 is a graph of a Multiple Turbo code at destination for a cooperative network with $\alpha_1 = \alpha_2 = 0.375$, $\gamma_{S_1D} = \gamma_{S_2D} = -3.3$ dB,

Figure 13 is a graph of an outage and FER of a multiple Turbo coding and an enhanced Turbo coding at destination for a cooperative network,

Figure 14 is an illustration of the Network configurations,

Figure 15 is an illustration of the CMAC: 1st and 2nd time slot,

5 Figure 16 is an illustration of a CMAC: 3rd time slot without cooperation,

Figure 17 is an illustration of a CMAC: 3rd time slot with cooperation,

Figure 18 is a flowchart of the Joint network and channel encoding,

Figure 19 is an illustration of the MARC: 1st and 2nd time slot,

Figure 20 is an illustration of a MARC: 3rd time slot without cooperation,

10 Figure 21 is an illustration of a MARC: 3rd time slot with cooperation,

Figure 22 is an illustration of a BRC: 1st time slot,

Figure 23 is an illustration of a BRC: 2nd time slot without cooperation,

Figure 24 is an illustration of a BRC: 2nd time slot with cooperation, and

Figure 25 is a flowchart of the encoding structures for distributed coding.

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DETAILED DESCRIPTION

In the following one or more example embodiments are described including a simple relay channel and three MAC network topologies in which multiple users need to exchange information sequences (packets) with a base station, namely, CMAC, MARC and BRC. In MARC, one or more dedicated relays are deployed to assist users' transmission to the base station, whereas in CMAC, no dedicated relays are available. In BRC, only one user is broadcasting with the help of one or more dedicated relays.

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1. System Model

Figure 1 shows a relay channel model 100, with a S, R and D. The channel coefficients between S-R, S-D and R-D nodes are g_0, g_1 , and g_2 , respectively.

5 We assume a quasi-static fading channel, where the channel coherence time is considerably larger than the code word. The channel coefficients are independent and identically-distributed random variables, which remain constant over the whole duration of the codeword, given by Equation 1:

$$g_i = \frac{h_i}{d_i^{\beta/2}}, \quad (1)$$

10 where h_i and d_i are the channel gains and distances between the transmitter and receiver, respectively. The attenuation exponent is β (e.g., $\beta = 2$ for free-space propagation).

The relay operates in half-duplex mode, where the transmitting and listening
15 modes cannot occur simultaneously. In the DF protocol, the block of symbols with length n is split into two phases. In the first phase, the relay is in listening mode and receives the signal from the source. At the end of this phase, the relay decodes the source information message. The relay then switches to transmitting mode in the second phase and sends symbols to help the
20 destination decode the source message. During the first phase, the signal received by the relay is given by Equation 2:

$$y_{r,k} = g_0 x_{s,k} + v_k, \quad k = 1, 2, \dots, \alpha n, \quad (2)$$

and the signal received by the destination is given by Equation 3:

$$y_k = g_1 x_{s,k} + w_k, \quad k = 1, 2, \dots, \alpha n. \quad (3)$$

where $x_{s,k}$ denotes the codeword that is to be transmitted from the source, v_k denotes the additive noise introduced in the channel between the source and the relay, and w_k denotes the additive noise introduced in the channel between the source and the destination. α denotes the proportion of symbols that is to be devoted to the first phase.

During the second phase (i.e. the relay transmitting phase), the signal received by the destination is given by Equation 4:

$$y_k = g_1 x_{s,k} + g_2 x_{r,k} + w_k, \quad k = \alpha n + 1, \dots, n. \quad (4)$$

Here, $\mathbf{x}_s = [x_{s,1} \cdots x_{s,n}]^T$ is the source codeword, drawn from the code χ_s . We assume that the symbols $x_{r,k}$ transmitted by the relay are from an auxiliary code $\mathbf{x}_r$ with length n . Only the last $(1-\alpha)n$ symbols of a codeword are effectively transmitted in the second phase. In the first phase, the relay is idle because of the constraints of half-duplex communication.

The noise variables $v_k \sim CN(0, \sigma_v^2)$ and $w_k \sim CN(0, \sigma_w^2)$ at the relay and destination, respectively, are mutually independent. v_k and w_k are complex variables and the notation $\sim CN(\bullet)$ denotes a complex Gaussian distribution. We also impose the same per-symbol average power constraint for both the source and the relay in Equation 5:

$$E[|x_{s,k}|^2] \leq E_s \text{ and } E[|x_{r,k}|^2] \leq E_s \quad (5)$$

where E_s denotes the symbol energy and $E[\]$ denotes an expectation

operation. The SNRs of the S-D and the S-R links are defined as $\gamma_s = E_s / \sigma_w^2$ and

$\tilde{\gamma} = E_s / \sigma_v^2$, respectively. σ_v^2 and σ_w^2 can be chosen such that $\sigma_v^2 = \sigma_w^2$.

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2. Alamouti-DF Scheme

A DF protocol with the relay code χ_r such that the signal received at the destination forms an Alamouti constellation, shall be referred to as the Alamouti-DF scheme. Assuming that the relay can decode the signal, the signal transmitted by the relay at time k is given by Equation 6:

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$$x_{r,k} = \begin{cases} x_{s,k+1}^*, & k = \alpha n + 1, \alpha n + 3, \dots \\ -x_{s,k-1}^*, & k = \alpha n + 2, \alpha n + 4, \dots \end{cases} \quad (6)$$

$x_{s,k+1}^*$ denotes the complex conjugate of $x_{s,k+1}$. The signal seen by the

destination for $\alpha n + 1 \leq k \leq n$ is an Alamouti constellation. Through linear

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processing of the received signal, the destination obtains the sufficient statistics for decoding, as are given by Equation 7:

$$\tilde{y}_k = \begin{cases} g_1 x_{s,k} + w_k, & k = 1, \dots, \alpha n \\ \sqrt{|g_1|^2 + |g_2|^2} x_{s,k} + \tilde{w}_k, & k = \alpha n + 1, \dots, n \end{cases} \quad (7)$$

where the statistical properties of $\tilde{w}_k$ are identical to those of w_k . The mutual

information per symbol at the destination is given by Equation 8:

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$$I(\gamma, g_1, g_2) = \alpha I(|g_1|^2 \gamma) + (1 - \alpha) I(|g_1|^2 + |g_2|^2 \gamma) \quad (8)$$

On the other hand, if the source does not transmit during the second phase, the mutual information is given by Equation 9:

$$I(\gamma, g_1, g_2) = \alpha I(|g_1|^2 \gamma) + (1 - \alpha) I(|g_2|^2 \gamma) \quad (9)$$

5 With a large n , the probability of a FER is the information outage probability which is defined in Equation 10:

$$P_{out}(\gamma, R) = \Pr\{I(\gamma, g_1, g_2) \leq R\}, \quad (10)$$

where R is the target transmission rate in bits per channel use. For large SNR, the P_{out} is given in Equation 11:

$$10 \quad P_{out}(\gamma, R) \sim \kappa \gamma^{-d}, \quad (11)$$

where κ is the coding gain independent of γ and d is referred to as SNR exponent or diversity.

3. Distributed Coding FEC

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A distributed turbo coding scheme may use a recursive convolutional code (RSC). When decoding the message at the relay, the interleaved message is encoded with another RSC code. To further improve the decoding capability at the relay, an enhanced turbo code scheme may be used. Instead of the RSC, a
 20 turbo code may be used at the source node in the distributed turbo coding scheme. In addition to the systematic bits, the source node transmits a punctured sequence of parity bits from the first and second constituent encoders. The relay then transmits all the punctured parity bits. The punctured

turbo code has more parity bits at the destination, resulting in an enhanced turbo code. Note that in all the above mentioned schemes, systematic codes are used. The distributed turbo coding and the enhanced turbo code schemes may be combined to produce a multiple turbo code at the destination. For the distributed multiple turbo code scheme, the source also transmits using a turbo code. Instead of sending the punctured parity bits at the relay, the interleaved message is encoded with another constituent code.

The coding techniques (such as but not limited to RSC, turbo codes or their corresponding constituent codes) may optionally employ puncturing.

In the following, we assume an AWGN channel (i.e., the channel gain $h_i = 1$) where the SNR of source-destination channel is insufficient to support the desirable rate R .

The setup for the distributed turbo coding scheme is as follows. The non-systematic RSC C_1 at the source is $CC(4/7)$ with $R_1 = 1$ and the RSC C_2 at the relay is $CC(7/5)$ with $R_2 = 1$. These codes are used together with BPSK modulation as shown in Equation 12:

$$x_{s,k} = \{-\sqrt{E_s}, \sqrt{E_s}\}, \quad (12)$$

producing an overall rate of $R = 1/2$ bits per channel use for half-duplex mode with $\alpha = 0.5$. The SNR of the S-D channel is set as shown in Equation 13:

$$\gamma_{SD} = 10 \log_{10} \left(|g_1|^2 \gamma \right) = -3.0 \text{ dB}, \quad (13)$$

which may be sufficient for 1/2 bits per channel use. The relay transmits the codeword from C_2 , assuming the SNR of the S-R channel γ_{SR} is high enough for the relay to decode the message reliably. Figure 2 illustrates the EXIT chart for this distributed turbo coding scheme when the SNR of the R-D channel is set as
 5 out in Equation 14:

$$\gamma_{RD} = 10 \log_{10} \left(|g_2|^2 \gamma \right) = -2.1 \text{ dB}. \quad (14)$$

The average decoding trajectory is also included. A tunnel exists to allow for the convergence of iterative decoding towards a low error rate. A rate of 1/2 bits per channel use is achievable for $\gamma_{RD} = -2.6 \text{ dB}$. Hence, this code operates
 10 approximately 0.4 dB from the theoretic limit.

When γ_{SR} is low, the enhanced turbo code scheme is required for the message to get across reliably to the relay. Again, we select our target rate to be $R = 1/2$ bits per channel use for half-duplex mode. Since γ_{SR} is low, we need
 15 to increase α to get the message across to the relay. We select $\alpha = 0.75$. The SNR for the S-D channel is set at $\gamma_{SD} = -3.0 \text{ dB}$. The codeword sent by the source is formed by puncturing the turbo code which is made up of constituent codes C_1 and C_2 . The puncturing patterns for C_1 and C_2 are [1011] and [1110], respectively. Since the relay only receives data in the first time slot, the relay
 20 would only see C_1 and C_2 , which constitutes a rate 2/3 punctured turbo code. The EXIT chart for the iterative decoding algorithm is given in Figure 3. A tunnel exists to allow for convergence of iterative decoding towards a low error rate at

$\gamma_{SR} = 0.1$ dB. The SNR limit for a rate 2/3 is -0.7dB. The relay then transmits the punctured parity bits to the destination. Figure 4 illustrates the EXIT chart for the iterative decoding at the destination. A tunnel exists to allow for convergence of iterative decoding towards low error rate at $\gamma_{RD} = -1.2$ dB. The theoretical SNR limit is -2.3 dB. Hence, this code is operating approximately 1.1 dB from the theoretic limit.

Instead of sending the punctured parity bits, the relay uses a encoder in the distributed multiple turbo code scheme. The encoder can optionally use puncturing in its coding scheme. The constituent codes C_1 , C_2 and C_3 are CC(4/7), CC(4/7) and CC(3), respectively. In Figure 5, a tunnel exists to allow for convergence of iterative decoding towards low error rate at $\gamma_{SR} = -0.2$ dB, which is lower than the enhanced turbo code scheme in Figure 3. The convergence of iterative decoding towards low error rate is possible at $\gamma_{RD} = -1.5$ dB, as shown in Figure 6. This code is operating approximately 0.8 dB from the theoretical limit.

4. Alamouti-DF Scheme with Distributed Coding

According to an example embodiment, an Alamouti-DF scheme is used with a distributed turbo code, an enhanced turbo code and a multiple turbo code schemes. The fading coefficients $\{h_i\}$ are Rayleigh distributed as represented in Equation 15:

$$p(h_i) = 2h_i e^{-h_i^2}, h_i \geq 0 \quad (15)$$

Figure 7 shows the outage probability and FER performance of an Alamouti-DF scheme with distributed turbo code. The setting of the relay is such that $d_1^{-\beta} = 1$ and $d_2^{-\beta} = 1.23$, where d_1 denotes the distance between the source and the destination and d_2 denotes the distance between the relay and the destination. The slot allocation is $\alpha = 0.5$ and the target rate is $R = 0.5$. With BPSK modulation, the outage probability has a diversity of 2. The FER of the distributed turbo code (C_1 and C_2) is about 1dB from the outage limit and has the same order of diversity.

Figure 8 shows the outage probability and FER performance of an Alamouti-DF scheme with enhanced turbo code and multiple turbo code. We set $\alpha = 0.75$, $d_1^{-\beta} = 1$ and $d_2^{-\beta} = 1.51$. The outage probability has a diversity of 2 only if $R \leq (1 - \alpha)$. With $R = 0.5$, only a diversity of one may be achieved. Similarly, the FER of the enhanced turbo code $PCC(4/7 + 5/7)$ and the multiple turbo code $PCC(3 + 4/7 + 4/7)$ is around 1dB from the outage limit with diversity one.

5. Rate setting

According to the first example embodiment a node (for example the relay) acquires the channel state information, e.g., the SNR parameters, via, e.g., estimation based on preambles sent by the node, or feedback from the other

nodes in the network. The transmission rate is set based on the channel state information by using a rate setting algorithm.

Firstly a target rate is set for the user. If the channel quality information
5 shows that the target rate can be supported, then direct link transmission is used. If the target rate cannot be supported by direct link transmission, then distributed coding is used.

For distributed coding, given the SNRs of the network, parameters may be
10 selected to ensure reliable transmission is possible. For example, the slot duration for each phase of transmission should be minimized, e.g., by using high-rate coded modulation, so as to improve the overall efficiency. The slot duration in some communication phases can be optimized by, e.g., using an information theoretical approach to obtain the rate region of the protocol
15 adopted. This rate region provides a minimum SNR threshold which is required for operating at a certain rate. With these values, the minimum power to support the target rate can be obtained. If the SNR is below the minimum threshold, the target rate is reduced and the rate setting procedure starts all over again.

20 As discussed later a FEC approach is taken to achieve the selected rate. The rate information and the FEC parameters are transmitted to the nodes in the network and the nodes then start the transmission based on the set rate, code, and protocol.

6. Transmission Protocol

The transmission protocol for the relay network in Figure 1 will now be described. A Node S works in cooperation with a Node R to deliver its packets to a Node D. In the 1st time slot Node S transmits and Node R receives the coded bits and tried to decode its information. We consider two distributed coding scheme: (i) incremental bits and (ii) joint network and channel coding. Their encoding structures are shown in Figure 25. For incremental bits, Node S sends the codeword (c_{11}, c_{21}) during the first time slot. c_{11} is the codeword produced by Encoder 1 and c_{21} is the codeword produced by Encoder 2 during the first time slot. When joint network and channel coding is used, Node S sends the codeword (c_1, c_2) . c_1 and c_2 respectively are the codewords produced by Encoder 1 and Encoder 2. ACK/NACK information is sent out from node R to Node S and D.

In the 2nd time slot, if NACK is received from Node R, the source will operate in a non-cooperative mode. If ACK is received, Node S and D will operate in a cooperative mode. In cooperative mode Node R sends either (c_{12}, c_{22}) or (c_3) with the source using a STBC. c_{12} and c_{22} are the codewords produced by Encoder 1 and Encoder 2 respectively during the 2nd time slot while c_3 is the codeword produced by Encoder 3. In the non-cooperative configuration, Node S transmits additional coded bits during the 2nd and last time slot for additional

redundancy. For incremental bits, S1 sends (c_{12}, c_{22}) while for joint network and channel coding, S1 sends (c_3) .

7. Encoding scheme

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Two types of distributed coding schemes are shown in Figure 25. Firstly the incremental bit encoders are rate 1 convolutional or recursive convolutional codes with appropriate puncturing patterns. The rate of codeword (c_{11}, c_{21}) is optimized for the SNR of the source to relay channel, while the rate of codeword $(c_{11}, c_{12}, c_{21}, c_{22})$ is optimized for the SNR of the relay to destination and the source to destination channel. Optimization of the code is done by pairing the extrinsic information transfer function of each of the component code, so that the SNR of the decoding threshold is minimized.

15 The joint network and channel coding encoders are rate 1 convolutional or recursive convolutional codes with appropriate puncturing patterns. The rate of codeword (c_1, c_2) is optimized for the SNR of the source to relay channel, while the rate of codeword (c_1, c_2, c_3) is optimized for the SNR of the relay to destination and the source to destination channel. Similarly, extrinsic
20 information transfer functions are used to minimize the SNR of the decoding threshold.

With Incremental bits, in the cooperation phase, the source and the relay act like a virtual MIMO system and send the codeword (c_{21}, c_{22}) using a STBC. With joint network and channel coding, in the cooperation phase, the source and the relay act like a virtual MIMO system and send codeword (c_3) using a STBC.

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8. Extension to Other Systems

The Alamouti-DF scheme with distributed coding for the relay network can also be extended to other systems, like the second example embodiment CMAC shown in Figure 9, the third example embodiment MARC shown in Figure 10 and the forth example embodiment BRC shown in Figure 11. Orthogonal channels can be assigned to each pair by using, e.g., TDMA, OFDMA, SC-FDMA, DFT-Spread-OFDM or SDMA.

8.1 CMAC topology

We consider two users, S1 and S2, communicating with the BS using OFDM/SCCP in Figure 9. The cooperative distributed coding and Alamouti transmission may use three time slots to complete one cooperation cycle.

8.8.1 Time slot 1

S1 transmits a FEC-coded and OFDM/SCCP modulated sequences, where the FEC code rate is given in Equation 16:

$$R_1 \leq \alpha_1 I(SNR_{S_1 S_2}^{(1)}) \quad (16)$$

where α_1 is the fraction of time slot 1 and $SNR_{S_1S_2}^{(1)}$ is the SNR from S1 to S2.

The coding scheme used in the transmission from S1 may optionally employ puncturing.

5 8.1.2 Time slot 2

S2 transmits FEC-coded and OFDM/SCCP modulated sequences, where the FEC code rate is given in Equation 17:

$$R_2 \leq \alpha_2 I(SNR_{S_2S_1}^{(1)}) \quad (17)$$

where α_2 is the fraction of time slot 2 and $SNR_{S_2S_1}^{(1)}$ is the SNR from S2 to S1.

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8.1.3 Time slot 3

In this time slot, Alamouti-DF scheme with the enhanced turbo code and the multiple turbo code schemes can be used. The procedure of encoding for the enhanced turbo code scheme is the same as that for the relay network
 15 illustrated in Figure 1. As for the multiple turbo code scheme, each user interleaves the two information sequences separately, followed by feeding the sequences alternatively to an encoder.

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S1 and S2 then transmit the sequence with distributed Alamouti STBC. The Alamouti STBC provides diversity gain and reduces outage in a fading channel. The BS collects the received sequence, and computes the LLR based STBC decoding for the IR. It then performs FEC decoding using all the LLR information collected during the 3 time slots.

The rate region for time slot 3 for the enhanced turbo code scheme is similar to that for the relay network. For the multiple turbo code scheme, the rate region is given by Equation 18:

$$\begin{aligned}
 R_1 &\leq \alpha_1 I(SNR_{S_1D}^{(1)}) + \alpha_3 I(SNR_{S_1D}^{(2)} + SNR_{S_2D}^{(2)}) \\
 R_2 &\leq \alpha_2 I(SNR_{S_2D}^{(1)}) + \alpha_3 I(SNR_{S_1D}^{(2)} + SNR_{S_2D}^{(2)}) \\
 R_1 + R_2 &\leq \alpha_1 I(SNR_{S_1D}^{(1)}) + \alpha_1 I(SNR_{S_2D}^{(1)}) + \alpha_3 I(SNR_{S_1D}^{(2)} + SNR_{S_2D}^{(2)})
 \end{aligned} \tag{18}$$

where α_3 is the fraction of time which slot 3 occupies, $\sum_{i=1}^3 \alpha_i = 1$. The achievable rate of the system is given by the intersection of the rate regions. Note that Users 1 and 2 do not have any new information to send during this slot.

8.1.4 BS processing

At the BS, iterative decoding is performed to decode the information bits of Users 1 and 2, which is the same as the relay network if the enhanced turbo code scheme is used. For the multiple turbo coding scheme, iterative decoding is also used for the information sequences.

Figure 12 illustrates the EXIT chart for the multiple turbo coding scheme when $\gamma_{S_1D} = \gamma_{S_2D} = -3.3$ dB in an AWGN channel. γ_{S_1D} and γ_{S_2D} respectively denote the SNRs of the S1-D and the S2-D links. The settings of the network is such that $d_{S_1D}^{-\beta} = 1$ and $d_{S_2D}^{-\beta} = 1$. d_{S_1D} denotes the distance between S1 and D while d_{S_2D} denotes the distance between S2 and D. The slot allocation used is

$\alpha_1 = \alpha_2 = 0.375$ and the target rate is $R_1 = R_2 = 0.25$. S1 and S2 use the multiple turbo code $PCC(3+4/7+4/7)$. The upper bound curve 1200 and the lower bound curve 1206 respectively illustrate the extrinsic log-ratios from C_1 and C_2 for the EXIT function $I(u^{(1)}; E^{(1)}(u_1)E^{(2)}(u_1))$ of S1, where $u^{(1)}$ denotes the information bits from S1, while $E^{(1)}(u_1)$ and $E^{(2)}(u_1)$ denote the extrinsic LLR from the C_1 and C_2 of S1. Each vertical step in the EXIT chart corresponds to an activation of the iterative decoding for S1, until convergence occurs. Similarly, each horizontal step corresponds to the activation of the iterative decoding for S2 until convergence occurs. The step curve 1202 corresponds to the mutual information measured at the output of the decoders under such an activation scheme. For lower complexity, we considered the activation of S1 ($C_1 - C_2 - C_3$) and S2 ($C_1 - C_2 - C_3$). The step curve 1204 corresponds to the mutual information measured at the output of the decoders. The convergence of iterative decoding towards low error rate is possible since a tunnel exists at -3.3dB. The theoretic limit for the target rates is -3.6dB.

Figure 13 shows the outage probability and FER performance. The outage probability of the multiple turbo code has a diversity of 2, which is higher than that of the enhanced turbo code scheme, which has a diversity of 1. The multiple turbo code $PCC(3+4/7+4/7)$ has an outage that is around 0.3dB from the outage limit.

8.1.5 Training for channel estimation

Normal training for time slot 1 and time slot 2 and orthogonal training sequence, e.g., the training sequences of $[a \ a]$ for S1, $[a \ -a]$ for S2.

5 8.1.6 Time and Frequency Synchronization

Conventional time and frequency synchronization can be used for time slot 1 and time slot 2. For time slot 3, the two sequences should be aligned within the CP at BS so as to maintain subcarrier orthogonality. The two users should also use the same LO reference, e.g., the BS LO frequency, for easier frequency
10 synchronization at BS.

8.1.7 Transmission Protocol

For the CMAC network in Figure 9, S1 and S2 work in cooperation to deliver their packets to a common destination BS. In the 1st time slot Node S1 transmits,
15 while Node S2 transmits in the 2nd time slot. Each S node receives the coded bits sent by its partner node and attempts to decode its partner information. The transmission scheme for these 2 time slots is shown in Figure 15. The codeword transmitted depends on which distributed coding scheme is used. For incremental bits, Node S1 sends the codeword (c_{11}, c_{21}) . When joint network and
20 channel coding is used, Node S1 sends the codeword (c_1, c_2) . If decoding is successful, then this information will be relayed to the destination BS.

ACKs/NACKs information is sent out from the source nodes to indicate whether they are cooperating or not in the 3rd time slot.

In the 3rd time slot, cooperation occurs when both the sources send ACKs.

5 Otherwise, the sources will operate in a non-cooperative mode. In the cooperative configuration, as shown in Figure 17, Node S1 and S2 encode both information bit streams either jointly or separately and transmit them to the destination BS using a STBC. For separate encoding, the codeword $(c_{12}, c_{22}, \tilde{c}_{12}, \tilde{c}_{22})$ is sent by S1 and S2 using STBC. For joint network and channel
10 encoding, as shown in Figure 18, S1 and S2 send the codeword (c'_3) to the destination, also using STBC. c_{12} and c_{22} are the codewords sent by S1 while $\tilde{c}_{12}$ and $\tilde{c}_{22}$ are the codewords sent by S2.

In the non-cooperative configuration, as shown in Figure 16, Node S1 and
15 S2 transmit their own additional coded bits in turn during the 3rd and last time slot for additional redundancy. For incremental bits, S1 sends (c_{12}, c_{22}) while for joint network and channel coding, S1 sends (c_3) .

8.2 MARC topology

20 Figure 10 shows S1 and S2, communicating with a BS through a RS using OFDMA. Orthogonal subcarrier sets are assigned to the two users.

The proposed cooperative incremental redundancy space-time-coded relay transmission may need two time slots to complete one cooperation cycle.

8.2.1 Time slot 1

5 S1 transmits punctured FEC-coded and OFDM modulated sequences, where the FEC coded-modulation rate is R_{S_1R} according to Equation 19:

$$R_{S_1R} \leq \alpha_1 I(SNR_{S_1R}^{(1)}) = R_1^{(1)} \quad (19)$$

α_1 is the fraction of time slot 1. When TDMA is used for user multiple access, α_1 denotes the fraction of time user 1 occupies in slot 1.

8.2.2 Time slot 2

S2 transmits punctured FEC-coded and OFDM/SCCP modulated sequences, where the FEC coded-modulation rate is R_{S_2R} according to Equation 20:

$$R_{S_2R} \leq \alpha_2 I(SNR_{S_2R}^{(1)}) = R_2^{(1)} \quad (20)$$

15 α_2 denotes the fraction of time slot 2 used for transmitting S2's information. For frequency division-based orthogonal multiple access such as OFDMA, SC-FDMA and DFT-Spread-OFDM, $\alpha_1 = \alpha_2$. For TDMA, α_2 denotes the fraction of time that S2 occupies in slot 2. R_{S_1R} and R_{S_2R} may or may not be the same. The BS and RS collect the received sequence. The RS will also decode the
20 information sequence from S1 and S2. The BS then computes and stores the LLR.

8.2.3 Time slot 3 and 4

The RS re-encodes the information sequences of S1 and S2 with their original rate-compatible FEC. The RS then maps the punctured coded bits to symbols, and then uses OFDMA to modulate the modulated symbols of the two users.

S1 and S2 will also produce the same codeword and map the punctured coded bits to the same symbols as that of the RS, and then to the assigned subcarriers for OFDM transmission processing. Then S1, S2, and the RS transmit the signals simultaneously to the BS, using Alamouti coding scheme.

The overall rate region is given by Equation 21:

$$\begin{aligned} R_1 &\leq \alpha_1 I(SNR_{S_1D}^{(1)}) + \alpha_3 I(SNR_{S_1D}^{(2)} + SNR_{RD}^{(2)}) = R_1^{(2)} \\ R_2 &\leq \alpha_1 I(SNR_{S_2D}^{(2)}) + \alpha_4 I(SNR_{S_2D}^{(2)} + SNR_{RD}^{(2)}) = R_2^{(2)} \end{aligned} \quad (21)$$

where α_3 and α_4 are the fraction of resource which S1 and S2 used, respectively. The overall achievable rates are given by Equation 22:

$$\begin{aligned} R_1 &\leq \min(R_1^{(1)}, R_1^{(2)}) \\ R_2 &\leq \min(R_2^{(1)}, R_2^{(2)}) \end{aligned} \quad (22)$$

However, if multiple turbo code is used with joint network-channel coding, STBC cannot be employed. The rate region is similar to that of the CMAC.

8.2.4 Rate setting

Select a target rate for S1 and S2, while assuming values for the SNR_{S_1D} and SNR_{S_2D} . The values of SNR_{S_1D} and SNR_{S_2D} may for example be estimated through the process of channel estimation. If the channel is found to have a transmission rate that is sufficiently high, a direct transmission mode may be used. For example, if both SNR_{S_1D} and SNR_{S_2D} are above a predetermined threshold, a direct transmission mode may be used.

For given values of $SNR_{S_1R}^{(1)}$ and $SNR_{S_2R}^{(2)}$, we can select α_1 and α_2 such that reliable transmission is possible on both channels. The slot duration should be minimized, i.e., using high-rate coded modulation, so as to improve the overall efficiency based on two considerations. The first consideration is, for decode-forward scheme to work, the RS needs to be close to the source nodes; The second consideration is, the transmission in these two slots do not have any space-time diversity at the BS, whereas the second slot sequences have.

With α_3 , α_4 and the rate region, we can look for a minimum $SNR_{RD}^{(2)}$ threshold which satisfies the target rate. If $SNR_{RD}^{(2)}$ is too low, we will have to lower our target rate and start all over again. Once the rate is determined, a FEC scheme can be chosen to approach this rate.

8.2.5 Receiver Processing

The decoding process is similar to that for the relay network.

8.2.6 Training for channel estimation

Training signals can be transmitted in both time slots. In this case, constant-modulus training signals can be used by the S nodes in time slot 1 with which
5 the S-RS channel estimates can be obtained and constant-modulus training signals can be used by the RS in time slot 3 with which the RS-BS channel estimates can be obtained.

Alternatively, we can choose to transmit training signals only in time slot 3.
10 In this case, orthogonal training sequences need to be used between the S and the RS in the respective subcarriers from which the S-BS and the RS-BS channel coefficients can be obtained.

8.2.7 Time and Frequency Synchronization

15 Concurrent transmissions should be aligned within the CP at the receiving node so as to maintain subcarrier orthogonality; S1, S2 and RS should also use the same LO reference, e.g., the LO reference of the BS, for easier frequency synchronization at the D or the R.

20 8.2.8 Transmission Protocol

Two source nodes S1 and S2 work in cooperation with the RS to deliver their packets to the BS. In the 1st time slot, node S1 transmits while node S2 transmits in the 2nd time slot. The R receives the coded bits sent by both nodes and attempts to decode their information as shown in Figure 19. For

incremental bits, the node S1 sends the codeword (c_{11}, c_{21}) . For joint encoding, the node S1 sends the codeword (c_1, c_2) . If decoding is successful, then this information will be relayed to the destination BS. ACK/NACK information is sent out from the RS to indicate whether they are cooperating or not in the 3rd time slot.

In the 3rd time slot, cooperation occurs when the relay sends an ACK. Otherwise, S1 and S2 will operate in a non-cooperative mode. In the cooperative configuration that is shown in Figure 21, the information is decoded correctly. The RS can encode both information bit streams separately and transmit the additional coded bits with the corresponding source together with a STBC, or the RS can jointly encode both information bit streams and transmit to the BS.

If the RS fails to decode information from either of S1 or S2, then S1 and S2 will operate in a non-cooperative mode. In Figure 20, Nodes S1 and S2 transmit their own additional coded bits in turn during the 3rd and last time slot for additional redundancy in the non-cooperative configuration. Similarly, for incremental bits, S1 sends (c_{12}, c_{22}) and for joint encoding, S1 sends (c_3) .

20

8.3 Broadcast Relay System

Figure 10 shows a downlink scenario where the BS communicates with two users, S1 and S2 through a RS using OFDMA.

The proposed cooperative incremental redundancy space-time-coded relay transmission may use two time slots to complete one cooperation cycle.

5 8.3.1 Time slot 1

To communicate with S1, BS transmits a punctured FEC-coded and OFDM modulated sequence, where the FEC coded-modulation rate is R_1 . The rate is set such that the BS can decode the data correctly with a high probability, according to Equation 23:

$$10 \quad R_1 \leq \alpha_1 I(SNR_{BR}^{(1)}) \quad (23)$$

where α_1 is the fraction of time slot 1 and $SNR_{BR}^{(1)}$ is the SNR from the BS to the RS.

To communicate with S2, the BS transmits a punctured FEC-coded and
15 OFDM modulated sequence, where the FEC coded-modulation rate is R_2 . The rate is set such that the BS can decode the data correctly with a high probability. According to Equation 24:

$$R_2 \leq \alpha_2 I(SNR_{BR}^{(1)}) \quad (24)$$

where α_2 denotes is the remaining fraction of time slot 1.

20

S1, S2 and the RS use the received sequences for decoding. The RS will decode both the information sequences meant for S1 and S2. S1 and S2 will then compute and store the LLR.

8.3.3 Time slot 2

The BS and the RS will both transmit concurrently as follows. The RS re-encodes the information sequences of S1 and S2 with their original rate-compatible FEC. The RS then maps the punctured coded bits to symbols and then OFDMA modulates the modulated symbols of S1 and S2.

The BS will also produce the same codeword and maps the punctured coded bits or new coded bits to the same symbols as that in the RS, and then to the assigned subcarriers for OFDM transmission processing. The BS and the RS then transmit the signals simultaneously to S1 and S2, using an Alamouti coding scheme.

The rate region for time slot 2 is given by Equation 25:

$$\begin{aligned} R_1 &\leq \alpha_1 I(SNR_{BS_1}^{(1)}) + \alpha_3 I(SNR_{BS_1}^{(2)} + SNR_{RS_1}^{(2)}) \\ R_2 &\leq \alpha_2 I(SNR_{BS_2}^{(1)}) + \alpha_4 I(SNR_{BS_2}^{(2)} + SNR_{RS_2}^{(2)}) \end{aligned} \quad (25)$$

where α_3 and α_4 respectively are the fraction of resources in which User 1 and User 2 will use. The overall achievable rates for both slots are constrained by the right-hand side of the above inequalities. Thus according to Equation 26:

$$\begin{aligned} R_1 &\leq \min(\alpha_1 I(SNR_{BR}^{(1)}), \alpha_1 I(SNR_{BS_1}^{(1)}) + \alpha_3 I(SNR_{BS_1}^{(2)} + SNR_{RS_1}^{(2)})) \\ R_2 &\leq \min(\alpha_2 I(SNR_{BR}^{(1)}), \alpha_2 I(SNR_{BS_2}^{(1)}) + \alpha_4 I(SNR_{BS_2}^{(2)} + SNR_{RS_2}^{(2)})) \end{aligned} \quad (26)$$

8.3.4 Transmission Protocol

The BS works in cooperation with RS to deliver its packet to S1 and S2. In the 1st time slot, the BS transmits, as shown in Figure 22. For incremental bits, node S1 sends the codeword (c_{11}, c_{21}) . For joint encoding, node S1 sends the
 5 codeword (c_1, c_2) . The RS receives the coded bits and attempts to decode its information. If decoding is successful, this information will then be relayed to S1 and S2. Alternatively if it fails, the BS will operate in a non-cooperative mode. The ACK/NACK information is sent out from the RS to indicate whether the nodes are cooperating or not in the 2nd time slot.

10

In the 2nd time slot, cooperation occurs when the RS sends an ACK. Otherwise, S1 and S2 will operation in a non-cooperative mode. For the cooperative configuration in Figure 24 where the information is decoded correctly, the BS and the RS jointly transmits additional codewords (c_{12}, c_{22}) or
 15 (c_3) to both destinations using a STBC.

20

In the non-cooperative configuration illustrated in Figure 23, the BS transmits additional coded bits during the 2nd and the last time slots for additional redundancy. The codeword (c_{12}, c_{22}) is sent if an incremental bit is used, and the codeword (c_3) is sent when joint encoding is used.

The hardware such as the ICs, UE (eg:S1 and S2), RS, BS, the central office and other network equipment may be programmed with software to

operate according to one or more of the example embodiment methods, and otherwise compatible with common standards such as 3G, pre4G and/or 4G. These standards are incorporated herein by reference.

- 5 Whilst example embodiments of the invention have been described in detail, many variations are possible within the scope of the invention as will be clear to a skilled reader.

- 10 In this specification, the terms “user”, “user equipment” (or its abbreviation “UE”), node S1 and node S2 are to be interpreted as equivalents. In some network topologies such as C-MAC, other users may act as a RS, and RS and R are to be interpreted accordingly.

CLAIMS:

1. A method of communication comprising:
determining whether to use distributing coding between a S, R and D,
5 based on a predetermined transmission rate;
if the determination is positive, determining a forward error correction
scheme using distributed Alamouti space-time coding, wherein the scheme is
determined based on the predetermined transmission rate, a channel SNR and
a network topology;
10 relaying coded data from the S to the D using the determined forward
error correction.
2. The method in claim 1 wherein the forward error correction scheme is
selected from the group consisting of distributed turbo coding, enhanced turbo
15 coding and multiple turbo coding.
3. The method in claim 2 wherein the selection is based on which forward
error correction scheme has the rate region that includes the predetermined
transmission rate.
20
4. The method in any preceding claim wherein the determination to use
distributing coding is made by determining if the SNR from the S to D is too low
to support direct transmission.

5. The method in any preceding claim wherein the network topology is selected from the group consisting of a relay network, a CMAC network, a MARC network and a BRC network.

5 6. The method in any preceding claim wherein the forward error correction scheme includes a plurality of slots in the time domain, a first slot being used by S to transmit a code word, if R can decode the code word then in a subsequent slot the relaying coded data is done cooperatively by the S and R.

10 7. The method in any preceding claim wherein the relaying coded data uses rate 1 convolutional or recursive convolutional codes with puncturing patterns.

8. The method in any preceding claim wherein a code word is optimized based on the channel SNR.

15

9. The method in claim 6 wherein the code word is relayed using a STBC.

10. The method in any preceding claim using ODMA, TDMA, OFDMA, SC-FDMA, DFT-Spread-OFDM or SDMA.

20

11. A RS configured to communicate with a plurality of UE according to the method of any of claims 1 to 10.

12. A RS configured to communicate with a BS according to the method of any of claims 1 to 10.
13. A BS configured to communicate with a plurality of UE according to the
5 method of any of claims 1 to 10.
14. A communications network configured to communicate according to the method of any of claims 1 to 10.
- 10 15. A UE configured to communicate with a BS according to the method of any of claims 1 to 10.
16. An integrated circuit or processor including stored instructions, the instructions when executed control communication between a BS and a UE
15 according to the method of any of claims 1 to 10.