A Low-Complexity Transmit Cooperation Scheme based on Layered Higher Order Modulation

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Abstract: Decode-and-Forward (DF) is a popular approach to transmit information over a cooperative relay channel. However, DF is not optimised for any propagation conditions since it simply combines the received information coming from different sources regardless of their respective link qualities. In this paper, we propose a novel transmit cooperation scheme that can take advantage of asymmetric link qualities using layered higher order modulation. Moreover, this scheme reduces the complexity at the source and relay nodes and transfers most of it to the destination node. This feature can be useful for sensor network applications, where low-complexity nodes are required. Performance evaluation shows that our scheme outperforms an equivalent DF scheme and provides a better spectral efficiency in asymmetric propagation conditions than DF. Additionally, this scheme can accommodate iterative detection to further improve its performance.

Keywords: Cooperative communication, decode-and-forward, multi-layer modulation, mixed-labelling, iterative detection.

1. Introduction

The common approach in decode-and-forward (DF) over a cooperative relay channel is the full decoding of the source message followed by the forwarding of the whole message to the destination node. There, the data which is received directly from the source node and indirectly through the relay node are properly combined ([1]-[6]). In a simple cooperation scenario composed of a source node S, a destination node D, and a single relay node R, three node-to-node links are established, i.e., S-D, S-R, and R-D links. The transmission rate and format employed at S and R transmitters should be properly adjusted according to the expected quality of the links. Due to the broadcast nature of the S transmission targeted towards both R and D, the settings of modulation and coding format for this node face a dilemma in asymmetric link conditions. If R is sufficiently close to S, then R can improve the communication by helping S in its transmission job. This form of operation is commonly known as transmit (Tx) cooperation. In a typical Tx cooperation the S-R link capacity is much larger than the direct S-D link capacity. In this condition, an adjustment of the transmit format of S based solely on the capacity of one of the links leave the other link unexploited.

Here, we propose a different approach than the common DF scheme and create a layered transmission format in order to effectively exploit the capacity of both S-D and S-R links. As a result, we design a novel low-complexity Tx cooperation scheme that can be operated on very simple devices which are used in role of S and R nodes. The main complexity of the scheme is transferred to the destination receiver. Therefore, our new cooperative scheme makes a suitable candidate for application in wireless sensor networks where very simple and low-complexity sensor nodes are desired. Using the proposed

scheme, the sensor nodes can take the relaying role and establish a cooperative communication towards a collector node.

The rest of the paper is organised as follows. An overview of multi-layer modulation is given in Section 2. Further, the system model of our novel low-complexity Tx cooperation scheme is presented in Section 3, along with detailed diagrams of each node. In addition, an enhanced version of the destination receiver using iterative detection is described. Moreover, simulation results of the proposed schemes for various detections at D and under different channel conditions are provided in Section 4. Conclusions are drawn in Section 5.

2. Multi-Layer Modulation

In digital communications, a finite signal alphabet $X \subset \square$ associated with a one-to-one binary labelling map $\mu : \{0,1\}^m \to X$, where $m = \log_2 |X|$, forms a constellation. Depending upon the associated labelling μ, a symbol error event may lead to different numbers of erroneous bits. Therefore, different labellings will cause different BER performances. Among all the possible labellings, Gray and set partitioning based labellings have been widely used in radio communication systems. Gray labelling has been mainly used in bit interleaved coded modulation systems. It attempts to create proportionality between Hamming distances of input binary sequences and Euclidean distances of the corresponding symbol sequences. For detailed definition of Gray labelling please refer to [7]. Set partitioning based labelling was efficiently employed in [8] to directly improve Euclidean distance structure of jointly designed coded modulation systems. In General, any labelling map will introduce some level of unequal error protection on the input bits. Gray labelling attempts to reduce unequal protection to minimum level while set partitioning based labelling magnifies and utilises this property. A good example is multi-level coded modulation system where set partitioning creates different layers of protection and each layer is separately coded ([9] and [10]).
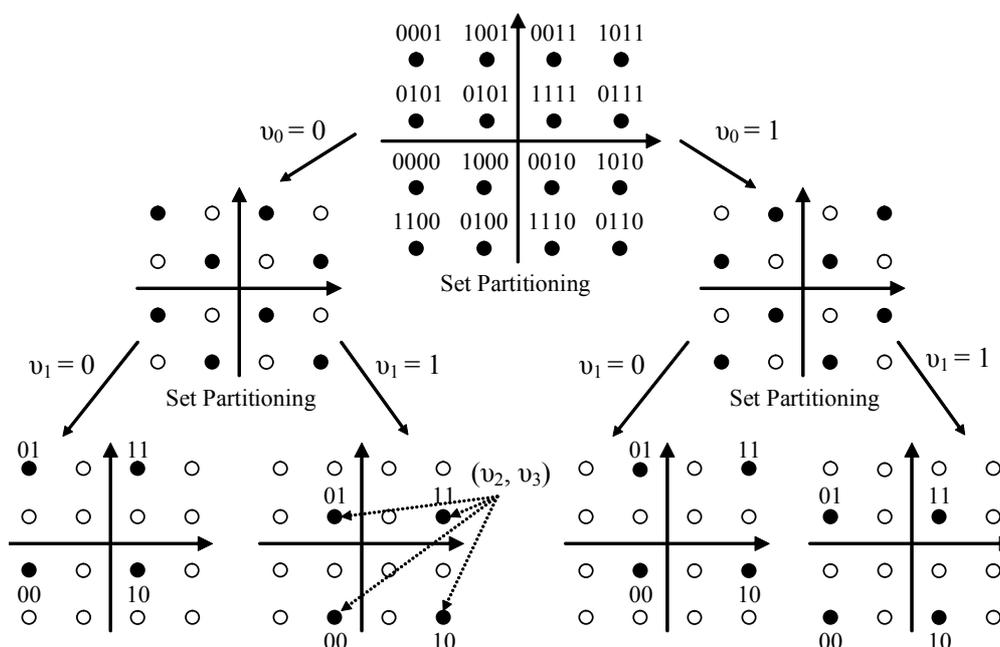

Figure 1: 16-TLQAM Modulation Based on Mixed Labelling

Here we adopt a mixed strategy known as mixed labelling, where set partitioning is performed only for the first stages and then Gray labelling is used for each resulting sub-constellation. This strategy creates multi-layer modulation, as illustrated in Figure 1, where a 16-level Two-Layer QAM (TLQAM) is presented. In this figure set partitioning is applied for only the two first stages resulting in four sub-constellations shown by black dots. Each

sub-constellation is an offset QPSK modulation. The first two label bits (v_0, v_1) are used to select one of the sub-constellations and the last two bits (v_2, v_3) to select a point in the chosen sub-constellation. The last two bits are assigned to sub-constellation points using Gray labelling. This structure allows us to generate two layered streams composed of (v_0, v_1) and (v_2, v_3) bits, respectively. The generated structure can be efficiently utilised in the considered cooperative communication system. If bits (v_0, v_1) are perfectly forwarded through the relay node, then the destination would be aware of the selected sub-constellation and the uncertainty of the direct link would reduce to sub-constellation points. Effectively the source transmission would look like a QPSK modulation for the S-D link and like a 16-QAM for the S-R link.

3. System Model

Let us assume a simple cooperative communication system which is composed of three nodes: source node S, relay node R, and destination node D. A further assumption is that the nodes' transmission-reception is based on a simple protocol composed of two phases. In the first phase of this protocol S broadcasts its signal to R and D, and in the second phase only R transmits to D. Even though it will be more efficient to allow S and R to jointly transmit in the second phase [11], for the convenience of introduction of the proposed approach we adhere to this simple protocol. Phases I and II are composed of N_0, and N_1 symbol transmissions, respectively. In phase I, S broadcasts signal sequence $x_1 = (x_{1,0},\ldots,x_{1,N1-1})$, and in phase II, R transmits D the signal sequence $x_2 = (x_{2,0},\ldots, x_{2,N2-1})$, where $x_{i,j}$ is a complex symbol. Frequency-flat fading channels are assumed between any pair of transmitting-receiving nodes. Figure 2 depicts the block diagram of the proposed low-complexity transmit cooperation. It illustrates the exploited processing at the three nodes S, R, and D. The source node transmitter uses an M-TLQAM modulator to map a sequence of bits $u = (u,\ldots, u_{N1-1})$ to a vector of N_1 complex symbols, where $u_j=(u_j^{(0)},u_j^{(1)})$ is an m-uple of bits, and $u_j^{(0)} = (v_0, v_1)$, $u_j^{(1)} = (v_2, v_3)$ for $M = 16$.
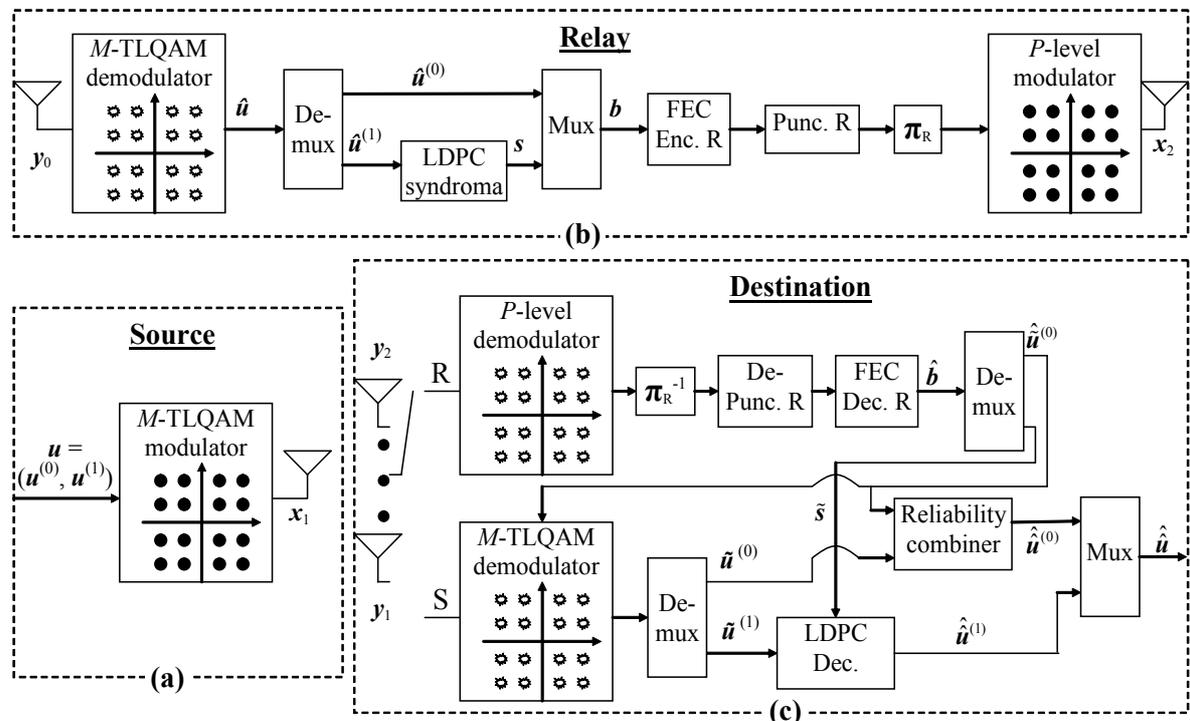

Figure 2: Block Diagram of the Proposed Low-Complexity Transmit Cooperation Scheme: (a) the Source Node Transmitter, (b) the Relay Node Receiver/Transmitter, and (c) the Destination Node Receiver

3.1 Layered Forwarding

A binary sequence $\boldsymbol{u}$, where each bit label $\boldsymbol{u}_j$ contains two layers of information $\boldsymbol{u}_j^{(0)}$ and $\boldsymbol{u}_j^{(1)}$, as shown in Figure 1, is first mapped to symbols $\boldsymbol{x}_{1j}$ ($j=1,...,N_1$) of an M-TLQAM. Then, $\boldsymbol{x}_1$ is transmitted at the same time from S to R and from S to D. On the one hand, we assume that the relay is close to the source and, hence, that the S-D link is highly-reliable, i.e., DF usual assumption. Thus, the relay is able to reliably decode the two bit sub-sequences $\boldsymbol{u}^{(0)}$ and $\boldsymbol{u}^{(1)}$, which are conveyed through the M- TLQAM and represent the two layers of information. On the other hand, we assume that the S-D link is a low-reliability link such that the destination is able to decode the lower-layer of information $\boldsymbol{u}^{(1)}$ provided that in the mean time the upper-layer $\boldsymbol{u}^{(0)}$ has been somehow provided with sufficient reliability. The sequence $\boldsymbol{u}^{(0)}$ is forwarded by the relay and it is used as auxiliary information to decode $\boldsymbol{u}^{(1)}$ as in the scheme which is depicted in Figure 2.

3.2 Destination Receiver: Non-Iterative Detection

At the receiver side of R, $\boldsymbol{x}_1$ is received as $\boldsymbol{y}_0$ and demodulated as $\hat{\boldsymbol{u}}$. Notice that only the upper-layer of information $\hat{\boldsymbol{u}}^{(0)}$ is required at the destination to retrieve the lower-layer of information $\hat{\boldsymbol{u}}^{(1)}$. Therefore, $\hat{\boldsymbol{u}}^{(1)}$, which requires less protection than $\hat{\boldsymbol{u}}^{(0)}$ can be compressed via an LDPC compressor and used to refine $\tilde{\boldsymbol{u}}^{(1)}$ at the receiver side of D. The output syndrome of the LDPC compressor $\boldsymbol{s}$ is multiplexed with $\hat{\boldsymbol{u}}^{(0)}$ to obtain $\boldsymbol{b}$, then the channel coding is applied to protect $\boldsymbol{b}$ that is finally mapped into a vector of symbols $\boldsymbol{x}_2$ using a P-level modulation, e.g., QAM, and transmitted towards D. Notice that the levels of modulation M and P can be adjusted independently. This makes our scheme fairly flexible in terms of data rate, which can be adapted in function of the propagation conditions. At the receiver side of D, the signal received from R, $\boldsymbol{y}_2$, is de-interleaved, de-punctured and de-convoluted such that $\hat{\boldsymbol{b}}$ is extracted and then de-multiplexed into $\hat{\tilde{\boldsymbol{u}}}^{(0)}$ and $\tilde{\boldsymbol{s}}$. In the mean time, $\boldsymbol{y}_1$ is received at D from S, and $\tilde{\boldsymbol{u}}^{(1)}$ is extracted from $\boldsymbol{y}_1$ via the M-TLQAM demodulator using the auxiliary information $\hat{\tilde{\boldsymbol{u}}}^{(0)}$ forwarded by R. Then, $\tilde{\boldsymbol{u}}^{(1)}$ is refined using $\tilde{\boldsymbol{s}}$, which is provided by R, and $\hat{\boldsymbol{u}}^{(1)}$ is obtained at the output of the LDPC decoder. Also, $\hat{\tilde{\boldsymbol{u}}}^{(0)}$ is refined using $\tilde{\boldsymbol{u}}^{(0)}$, which is provided by S, and gives $\hat{\hat{\boldsymbol{u}}}^{(0)}$. Finally, $\hat{\boldsymbol{u}}^{(0)}$ and $\hat{\boldsymbol{u}}^{(1)}$ are recombined into $\hat{\hat{\boldsymbol{u}}}$. The complexity of this scheme is low, especially the source part that does not requires channel coding, and the relay receiver complexity is only limited to a simple bit demodulator and the rest of its complexity is related to encoding function that are far less complex than their peer decoding functions. Therefore the main complexity of the scheme is related to the destination receiver.

3.3 Destination Receiver: Iterative Detection

This scheme can also accommodate iterative detection technique, based on Soft-Input Soft-Output (SISO) algorithms for FEC decoders and LDPC de-compressors, to enhance further its performance. The destination node is then modified as shown in Figure 3, and its complexity increases slightly. In comparison with the previous receiver design in Figure 2(c), $\boldsymbol{l}\hat{\boldsymbol{b}}$, $\boldsymbol{l}\hat{\boldsymbol{u}}_{ex}^{(0)}$, $\boldsymbol{l}\hat{\boldsymbol{u}}_{ex}^{(1)}$, $\boldsymbol{l}\hat{\boldsymbol{s}}$, $\boldsymbol{l}\tilde{\boldsymbol{u}}_{ex}^{(0)}$, $\boldsymbol{l}\tilde{\boldsymbol{u}}_{ex}^{(1)}$, $\boldsymbol{l}\hat{\boldsymbol{u}}^{(0)}$, $\boldsymbol{l}\hat{\boldsymbol{u}}^{(1)}$ and $\boldsymbol{l}\hat{\boldsymbol{u}}$ are all soft-values.

The first iteration of the detection is similar to the one of the non-iterative detection. At the end of the first iteration, the various soft-values become extrinsic information for the second iteration and so on and so forth. In Figure 3, the large-dash connections represent the exchange of extrinsic information from the SISO FEC decoder to the SISO LPDC de-compressor and the small-dash connections depict the exchange of extrinsic information from the SISO LPDC de-compressor to the SISO FEC decoder. At the end of the last iteration, $\boldsymbol{l}\hat{\boldsymbol{u}}^{(0)}$ is extracted from $\boldsymbol{l}\hat{\boldsymbol{b}}$ and combined with $\boldsymbol{l}\hat{\boldsymbol{u}}^{(1)}$ into the output $\boldsymbol{l}\hat{\boldsymbol{u}}$.
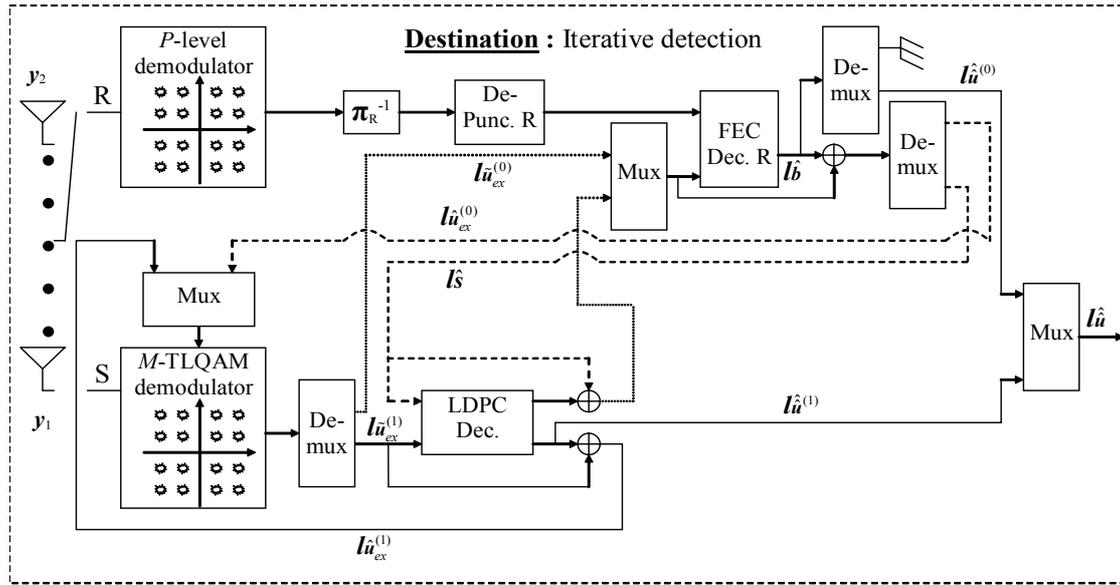
Figure 3 : Block Diagram of our Scheme Destination Node Receiver with Iterative Detection

4. Simulation Results

The BER and PER performance of our new transmit cooperation scheme have been obtained according to the parameter values provided in Table 1. Different SNR offset from $\Delta_{S-R}= 0$ to 10 dB are considered for the S-R link, in order to evaluate the sensitivity of our scheme to the quality of this link. The R-D link offset is set as $\Delta_{R-D}= 0$ or 5 dB. The offsets of these two links are given with respect to the S-D link SNR. All the nodes are assumed to have a single transmit/receive antenna. The performance of the S-R link, i.e., u vs. $\hat{u}$, of the R-D link, i.e., b vs $\hat{b}$ of the first stream S_0, i.e., $u^{(0)}$ vs. $\hat{u}^{(0)}$, of the second stream S_1, i.e., $u^{(1)}$ vs. $\hat{u}^{(1)}$, and of the aggregate stream Agg, i.e., u vs. $\hat{u}$ are evaluated.

Table 1: Simulation Parameters of the Proposed Low-Complexity Transmit Cooperation Scheme

Parameters	S-D	S-R	R-D
Channel	Rayleigh Fast Fading, (one tap)	AGWN	Rayleigh Fast Fading, (one tap)
Normalised Doppler (D_f*T_F)	100	100	100
Block size (bits)	408	408	616
Modulation	16-TLQAM	16-TLQAM	16-QAM
FEC	None	None	(7,5) CCZP, rate ½
LDPC	None	None	Weight: 5, CR: 2:1.

In Table 1, D_f and T_F stands for Doppler frequency and frame time, respectively.

4.1 Intrinsic Performance of Our New Transmit Cooperation Scheme

In Figure 4(a) and (b), the PER performance of the links listed above are evaluated for various Δ_{S-R} values and $\Delta_{R-D}= 0$ and 5 dB, respectively. The results show that if the quality of the S-R link is not good enough, then increasing the quality of the R-D link does not affect too much the overall performance of the scheme, and the performance of the aggregate link is similar to the performance of the S-R link. The performance of Agg cannot go beyond the one of the S-R link. Moreover, if $\Delta_{R-D}= 0$ dB, and Δ_{S-R} increases by 10 dB, then the performance of S_1 increases almost accordingly, i.e., 8 dB, while S_0 performs only 4 dB better, at a PER of 10^{-2}. Also, the aggregate performance of the scheme, i.e., Agg, is linked to the one of S_0. If $\Delta_{R-D}= 5$ dB, and Δ_{S-R} increases by 10 dB, then the performance of every link increases almost accordingly, i.e., 9 dB, at a PER of 10^{-2}. The

performance of Agg is still similar to the one of S_0, and the performance of S_1 is linked to the one of the S-R link. Likewise, if $\Delta_{S-R}= 10$ dB, and Δ_{R-D} increases by 5 dB, then the performance of every link increases accordingly, apart from S_1 that can not perform beyond the S-R link.
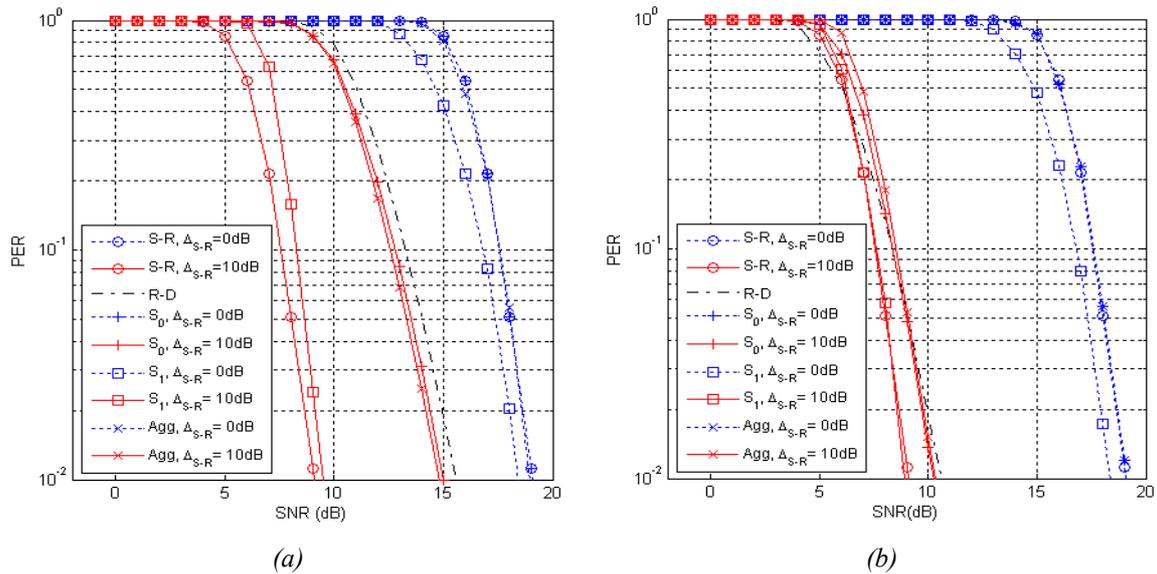

(a)   *(b)*

Figure 4: PER Performance of Our Low-Complexity Transmit Cooperation Scheme for
(a) $\Delta_{R-D}= 0dB$ and (b) $\Delta_{R-D}= 5dB$, and Various Δ_{S-R} Values

4.2   Performance of New Transmit Cooperation Scheme Against Equivalent DF Scheme

In Figure 5 (a) and (b), we compare the PER performance of our new scheme presented in Figure 2 against the performance of an equivalent DF scheme with S and R nodes designed as shown in Figure 2, except for the LDPC encoder at the relay node, and with a destination node as depicted in Figure 6.
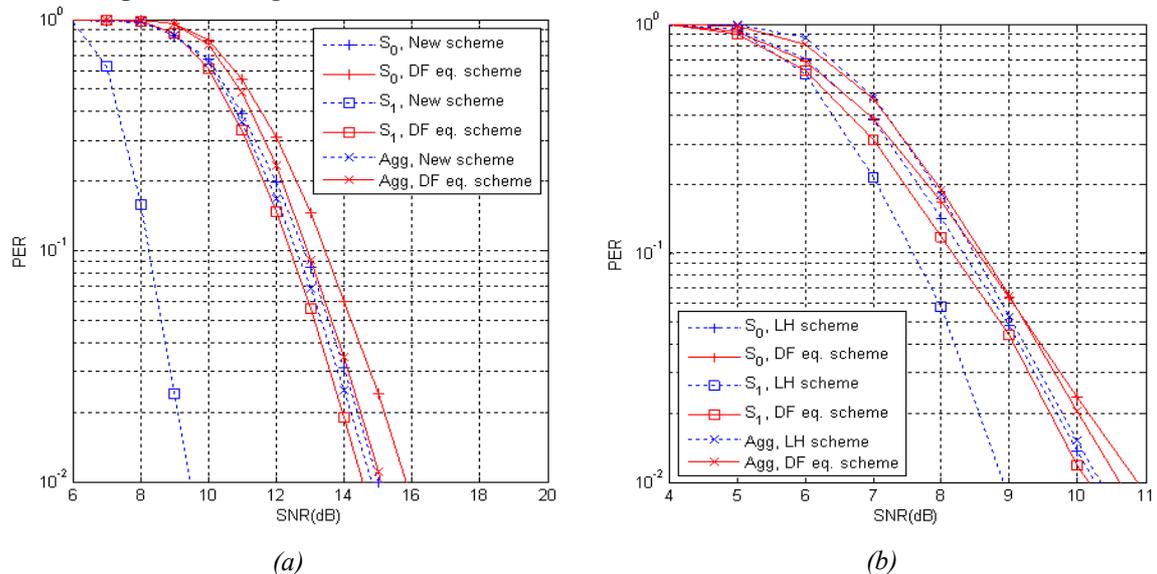

(a)   *(b)*

Figure 5: PER Performance of Our Low-Complexity Transmit Cooperation Scheme vs. Equivalent DF
Scheme for (a) $\Delta_{S-R}= 10dB$ and $\Delta_{R-D}= 0dB$ and (b) $\Delta_{S-R}= 10dB$ and $\Delta_{R-D}= 5dB$
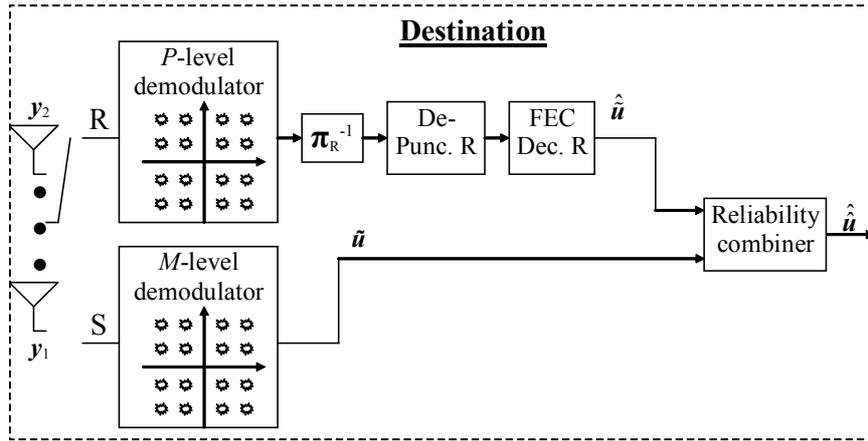
Figure 6: Equivalent DF Scheme Destination Node

The equivalent DF scheme settings are similar to those of our low-complexity transmit cooperation scheme given in Table 1, except for the source modulation that is a 16-QAM, and the block size of the R-D link which is equal to 820 bits. Also, no LDPC codec is used in that scheme. The result plotted in Figure 5 (a), i.e., the PER performance for Δ_{S-R}= 10 dB and Δ_{R-D}= 0 dB, show that our scheme increases greatly the performance of S_1, i.e., 5 dB at a PER of 10^{-2}, and outperforms the equivalent DF scheme by around 0.3 dB. Equivalently, the results depicted in Figure 5 (b), i.e., the PER performance for Δ_{S-R}= 10 dB and Δ_{R-D}= 5 dB, indicate that our scheme provides enhanced performance compared to the equivalent DF scheme, in terms of PER. Notice also that our scheme provides a better spectrum efficiency for the R-D link, i.e., a gain of 4/3, since only 616 bits are transmitted over the R-D link with our new scheme compared to 820 bits with the equivalent DF scheme.

Clearly the performance bottleneck of our scheme is the performance of S_0. As it as been shown in [12], iterative detection can restore some of the loss induces by multi-layer design and mixed-labelling, and therefore can improve the overall system performance as shown in the next section.

4.3 Performance of Our New Transmit Cooperation Scheme with Iterative Detection
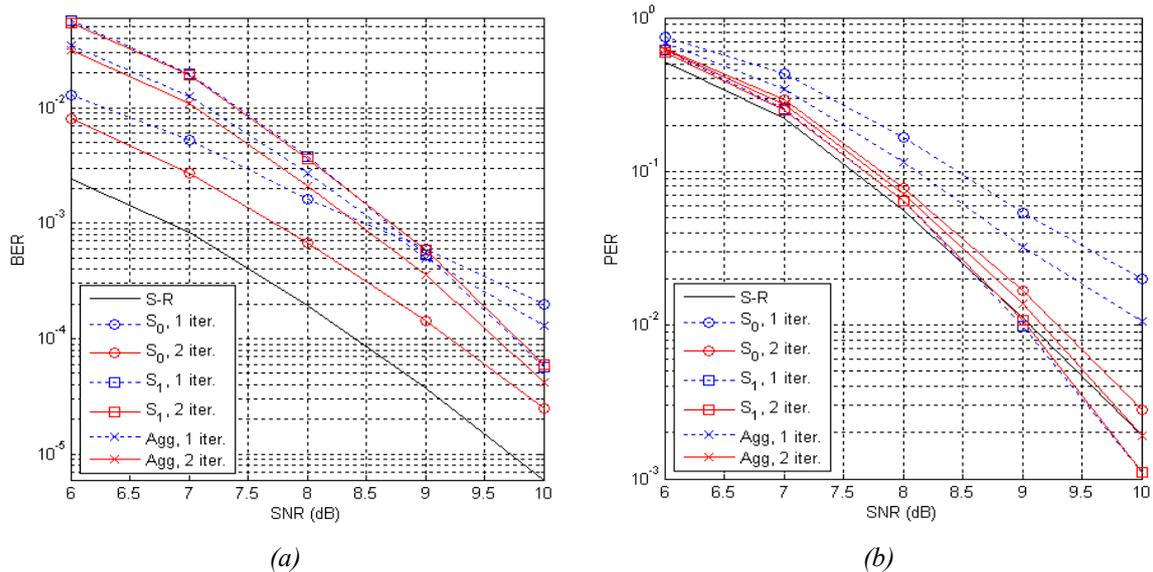

(a)

(b)

Figure 7: (a) BER and (b) PER Performance of Our New Transmit-Cooperative Scheme Based on LHOM Using ID, for Various Numbers of Iterations, and Δ_{S-R}=10 dB and Δ_{R-D}= 5dB

In Figure 7 (a) and (b), the BER and PER performance of our new transmit cooperation scheme using iterative detection are plotted against the SNR for various numbers of

iterations, Δ_{R-D}=10 dB and Δ_{S-R}= 5dB. The results show that the performance of S_1 is already optimised for a single iteration. However, the performance of the stream S_0 can be increased using the iterative process and, hence, the aggregate performance of the scheme is also increased by around 1dB at a PER of 10^{-2}. We also noticed that only two iterations are needed to obtain most of the performance enhancement, and therefore the decoding complexity remains sensible.

5.   Conclusions

A novel transmit cooperation scheme that can take advantage of asymmetric propagation condition has been designed in this paper. A different approach than the common DF scheme has been followed to create a layered transmission format in order to effectively exploit the capacity of both S-D and S-R links. Moreover, it has been showed that our scheme reduces the complexity at the source and relay nodes, and transfers most of it to the destination node. This feature can be useful for sensor network applications, where low-complexity nodes are required. Performance evaluation has indicated that our scheme outperforms an equivalent DF scheme and it provides a better spectral efficiency in asymmetric propagation conditions than DF. Additionally, it has been shown that this scheme can accommodate iterative detection to further improve its performance without a considerable extra decoding complexity.

Acknowledgment

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