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Cooperative Strategies and Networks

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Cooperative strategies and networks play an important role in current state-of-art wireless communications. The cooperation can have many forms and can be utilised at various levels of the processing hierarchy. At the physical layer, the cooperative algorithms revolutionise the design of modulation, coding, and signal processing. It can be directly at the level of channel coding which is *aware* of and pro-actively *utilises* the *network structure* knowledge as is performed by physical layer network coding (PLNC). Apart of the coding itself, the cooperative and relay-aided processing can substantially increase the network performance, most notably by using virtual multiple-input multiple-output (MIMO), distributed processing and smart interference cancellation. The cooperative network layer algorithms allows efficient coordination of the network and its resources.

7.1 Physical Layer Network Coding

The PLNC is concept of channel coding aware of the network structure and fully respecting all the aspect of the physical layer constellation space and channel parametrisation. PLNC-based communication networks deliver the information from sources to destinations through the complex relay network. Each node demodulates, decodes, processes, and re-encodes the hierarchical information (many-to-one function of the component data) directly in the constellation space. Various aspects of the design ranging from the network-coded modulation (NCM) (in many flavors: compute and forward (CoF), Denoising, hierarchical decode and forward (HDF), etc.) over the relay node (RN) strategies (decode and compress) to the Herarchical Information and hierarchical side information (HSI) decoding strategies are discussed in number of works [FLZ$^+$10, KAPT09, LKGC11, NG11, SB11, SB13a].

This Section addresses selected topics from PLNC technique ranging from the basic information-theoretic fundamental limits and concepts through

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particular design technique of NCM (hierarchical constellations, hierarchical network code (HNC) maps) and finally including relay/destination (D) decoding techniques.

7.1.1 Basic Concepts and Fundamental Limits

In the study of Burr and Sykora [BS12], the application of PLNC in a uplink (UL) transmission of a hierarchical wireless network is analysed. The UL is modelled as two-terminal two-relay topology where both relays receive signals from both terminals and relay the information towards a common destination with a utilisation of PLNC. In particular, the outage probability (OP) versus throughput for network coded hierarchical network for various signal–noise ratio (SNR) is evaluated. The simulation is used to obtain the probability density function (Pdf) of the throughput over the random fading, and hence a plot of outage probability against throughput. It is shown that this scenario can increase throughput, giving a number of the benefits of network MIMO, but without increasing the backhaul load. As a baseline for comparison, the equivalent results for a conventional non-cooperative system, in which each relay serves one terminal only. It is observed that first order diversity is obtained, and that outage capacity is much improved in the network coded case: for example for SNR 15 dB the 1% outage capacity is increased by a factor of more than 3.

Uricar et al. [USQH13] address butterfly network topology—two sources SA, SB communicating with their two respective destinations DA, DB through a common relay without a directS-D link SA–DA, SB–DB however having a HSI link SA–DB and SB–DA. HSI link provides only a partial (imperfect) HSI. It is shown that the superposition coding (SC) provides a natural tool for implementation of PLNC in the butterfly network relaying under an *arbitrary* HSI assumption. By splitting the source information into two separate *basic* and *superposed* data streams (and optimisation of rate and power allocated to each particular stream) it is possible to adapt the the processing to actual channel conditions (and hence the available HSI at destinations). Under this optimisation, superposition coding represents a viable solution for the case where only partial HSI is available at both destinations. Classical zero and perfect HSI cases are shown to be a special instances of the proposed superposition coding PLNC. The basic message parts are processed using the minimum cardinality PLNC while the superposed part is carried by the full cardinality map. Destinations decode the desired message with a proper utilisation of the HSI. The information-theoretic bounds for the achievable rates are derived under various settings.

A fundamentally novel approach to solving the PLNC is presented in Sykora and Burr [SB12, SB13b]. It would normally be assumed in the design of a PLNC strategy that each node has full knowledge of all channels, and especially the connectivity between nodes, so that the HNC maps at each node can be selected to ensure that the composite map is invertible. A novel strategy is proposed that works *regardless* of connectivity knowledge which is modelled in terms of a *discrete random* parameter which defines the *channel class*. In the simplest case a binary channel class indicates connection or disconnection. The core concept is to treat the channel class as an additional degree of freedom (DoF) of the received signal, and, therefore, to treat the index of the channel class in the same way as an information symbol. Hence the overall HNC map must be invertible not only in terms of the data, but also of the class index of all channels. The constellation space NCM mapping function play an important role in the design.

The classical signalling solution (Figure 7.1) is based on sensing the channel and then *switching* the HNC map at the node depending on the channel class (connection/disconnection). This sensing and switching is relatively easily solved for links ending at the node where the map should be switched. It can be combined with channel estimation using a suitable preamble, which would be required anyway. Much more important and harder to avoid is that this map must be made available to all succeeding nodes and stages of the larger multi-hop network. This creates at least a *latency*. Since the signalling information must be forwarded reliably it must be coded by long codewords (even if it is itself very short). This cannot be done at the channel symbol level. Scenarios with multiple hops, connectivity loops, and short packet

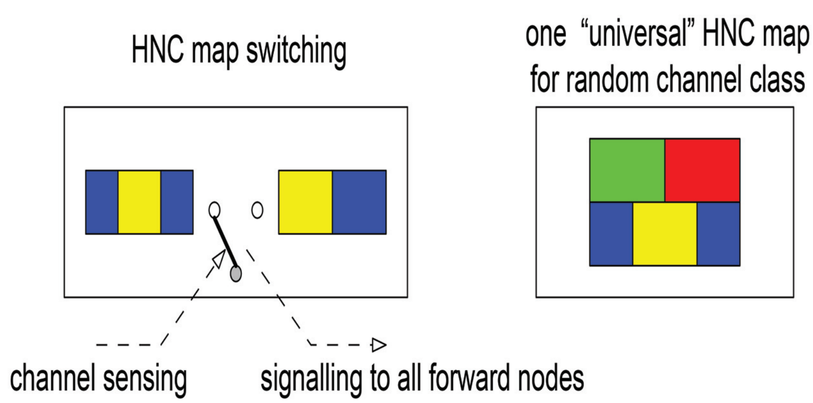

Figure 7.1 HNC map switching for classical signalling solution and "universal" HNC map for random channel class.

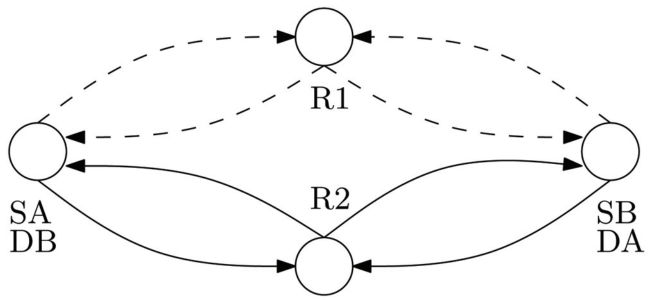

Figure 7.2 Two-way two-relay system example with random unreliable links (*dashed*) associated to relay R1.

services with rapidly changing channel classes are particularly vulnerable to this. In some cases, this reliable signalling is not possible at all. In Figure 7.2, all links at R1 have random channel classes and the destination has no reliable way to obtain the HNC map used at R1. The proposed approach with HNC map inherently containing the channel class does not need this explicit signalling. Of course it is at the expense of larger output cardinality. But since the bottleneck is usually the multiple access channel (MAC) stage, this may not restrict the overall capacity. Moreover, the channel class is contained in each payload channel symbol. This works like a long "repetition" code, so that a long channel class observation is spread over the whole payload.

The design needs to use *a non-linear HNC map* in order to avoid the mapping failures as shown in Figure 7.3. Detailed mutual information numerical results from Sykora and Burr [SB12, SB13b] show that all rates forming the cut-set bound for combined data-channel hierarchical symbols are better than the mean rate of the reference NCM scheme designed as if the channel class was always $a_{B1} = 1$. This result fully justifies this design approach.

7.1.2 NCM and Hierarchical Decoding

Non-coherent and semi-coherent schemes for PLNC in two-way relaying scenarios are investigated by Utkovski and Popovski [UP12]. We distinguish

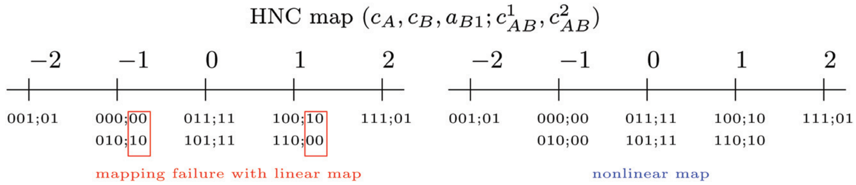

Figure 7.3 NCM hierarchical constellation at the relay for 2S–1R.

between scenarios without any channel knowledge requirements (non-coherent communication) and scenarios when either the relay or the users have receive channel knowledge (semi-coherent communication). We combine the paradigm of subspace-based communication originally developed for non-coherent point-to-point channels, with two-way relaying schemes based on physical-layer wireless network coding with denoise and forward (DNF). The aim is to demonstrate that denoising can be performed non-coherently and to investigate if these schemes offer an improvement over the schemes based on amplify and forward (AF).

The principle of non-coherent design is based on constructing the concatenated source SA and SB codebook fulfilling certain properties similar to the design criteria for non-coherent space-time codes, the chordal distance and the diversity product being the most important ones. The denoising map is based on the maximum likelihood (ML) decision which consists on the projection of the received subspace on all possible subspaces and the decision about the most probable one based on the Frobenius norm. The ML decision coincides with the search for the subspace which is at the smallest chordal distance from the received subspace, which justifies the choice of the chordal distance as one of the design criterion. The numerical error probability results show that the DNF scheme outperforms the AF scheme in most of the SNR region, and has a higher effective rate, due to the time slots saved in the broadcast stage.

PLNC systems where the final destination has only *imperfect/partial* HSI require relay hierarchical maps with extended cardinality in order to guarantee the overall global solvability. In Prochazka and Sykora [PS12], the solution based on the use of a specific sub-block-structured encoding matrices is proposed. Since the overall goal of NCM design is achieved by independent (layered) use of standard single-user channel outer codes and inner hierarchical maps, the scheme block-structured layered NCM. The problem is situated into 2-source 1-relay 2-paths scenario, with a straightforward way of generalisation. The principle of the proposed design consists in a predefined structure of linear channel encoders and hierarchical maps combining minimal and full cardinality maps. The layered design with *minimal* hierarchical cardinality is used on an equally long part of both source streams and the remaining part of the streams are encoded separately using a *full* cardinality map. Consistency conditions for this design are derived and the error rate performance is verified by the simulation.

The problem of designing NCM for the parametric channel is solved in Fang and Burr [FB12] by introducing rotationally invariant coded modulation for 2-way relay channel (2-WRC). Using a fully-adaptive adaptive soft demodulator and independent decoding levels, the proposed scheme can eliminate the effect of fading on the 2-WRC. To reduce system complexity at the relay, a low-complexity scheme with a series of fixed demodulators is provided. Based on maximising the mutual information between received signal and network coded symbol, the adaptive selection of the demodulators is optimised. The proposed simplified scheme exhibits advantages in terms of flexibility, complexity and performance.

The idea of using linear block codes for the construction of NCM is developed in Burr and Fang [BF14]. In the proposed design, each relay computes a linear combination of source symbols, namely, the HNC symbol and forwards it to the destination. The destination collects all HNC symbols and the original source symbols to form a valid codeword of the linear code. The resulting codeword can be decoded to reliably extract the original source symbols. The core principle is in using HNC linear maps having the same form as Reed–Solomon code which has t-symbol error correcting capability which introduces a diversity into the global HNC map. The numerical results show that our proposed design provides $(m + 1)$-th order diversity when there are m relays. Moreover, the proposed design provides a significant sumrate enhancement over the orthogonal multiple access scheme with network coding described in previous literature.

PLNC schemes based on lattice codes, particularly CoF, provide an excellent information-theoretic insight. However, these results assume idealistic perfect lattice codes. There only few attempts to bring the principles of CoF into a life in a practically realisable encoding schemes. One of them is the WPNC design using low-density lattice code (LDLC) [WB14b]. LDLC possesses high-coding gain and good algebraic structure which is inherently suitable for CoF. LDLC is a lattice code construction in which the lattice is generated by the inverse of a sparse matrix. LDLC was shown to be capable of achieving error free decoding within 0.6 dB of the Shannon bound. Inspired by its high coding gain and the algebraic property, a modified Gaussian mixture model (Figure 7.4) is used for the message representation in the low-complexity LDLC detection. A performance comparison for both non-fading and fading cases is demonstrated in the work. It is also shown that the ring-based constellation can be used to improve the average rate per dimension.

An alternative approach to solving the approximation of complicated density function in the factor graph- based iterative decoding is presented in Prochazka and Sykora [PS13]. The work proposes a message representation and corresponding update rules for both discretely and continuously valued

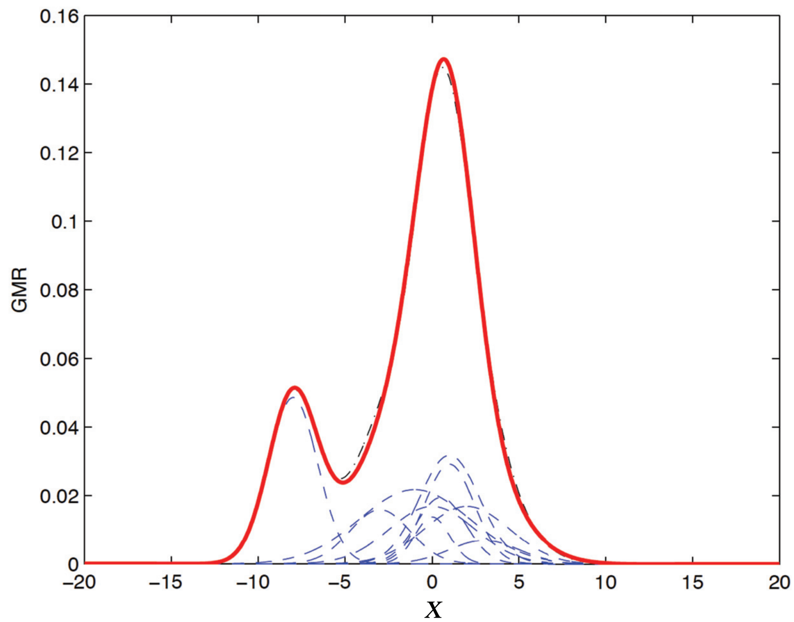

Figure 7.4 A Gaussian mixture (black dash-dot) comprised of N = 10 Gaussian components (*blue dashed lines*) is approximated by another Gaussian mixture (*red thick line*) with $N_{\max} = 3$.

variables with an acceptable exactness—complexity-trade-off. It uses linear message representations with orthogonal canonical kernels and corresponding message update rules. The proposed update rule design is combined with an already known message parameterisation based on the Karhunen–Loeve transform (KLT) of the message. This combination of the proposed generic update rules with the KLT-message representation forms a generic implementation framework of the sum–product algorithm applicable whenever the KLT is defined. This framework preserves the properties of the KLT-message representation that is the best linear approximation in the mean square error (MSE) sense. A particular example on a joint detection and phase estimation is shown to verify the framework and to compare the proposed method with a conventional solution.

7.1.3 Hierarchical Constellation Design

A very specific problem in designing the NCM is the construction of the hierarchical constellation (H-constellation) as is visible at the relay in the perspective of its HNC map. Particularly, the H-constellation should have good performance under arbitrary relative channel parametrisation and also it should properly respect the desired HNC map of the relay. Mainly, it needs to correctly resolve the singular fading.

Work by Uricar and Sykora [US12b] shows how it is possible to improve the performance of the 2-WRC system (in a special case of Rician fading channels) by a design of novel 2-slot source alphabets. The proposed non-uniform 2-slot (NuT) alphabets are robust to channel parameterisation effects, while avoiding the requirement of phase pre-rotation (or adaptive processing) but still preserving the C^1 (per symbol slot) dimensionality constraint (to avoid the TP reduction). Based on the analysis of the hierarchical (Euclidean) distance, a design algorithm for NuT alphabets is introduced and symbol error rate (SER) performance is compared to that of the traditional linear modulation constellations. The core idea of NuT is based on using a pair of properly individually and non-equally scaled symbols from a standard alphabet. The NuT constellation alphabet design could be generally characterised as an alphabet-diversity technique regarding the hierarchical min-distance. A suitable selection of the scaling factor is critical for alphabet performance, since it allows to trade-off the vulnerability to exclusive law failures with the alphabet distance properties.

Hierarchical distance and unresolved singular fading is influenced by many factors, one of them being the indexing of the component alphabets in the connection to a given HNC map. This situation is analysed in Hekrdla and Sykora [HS12a]. The goal is to find what kind of symmetry must be fulfilled by the constellation indexing in order to perform errorless modulo-sum decoding in a noiseless channel (because then the minimal distance of modulo-sum decoding equals to minimal distance of primary constellations). It is shown that the mapping from lattice-coordinates onto lattice constellation indices which is modulo-affine (i.e., constellation indices form modulo-arithmetic progression along each lattice (real) dimension) implies errorless WPNC modulo-sum decoding. The constellation indexing is denoted as an *affine indexing.* Some constellation shapes prevent the existence of affine indexing. These shapes comprise sphere-like shapes which possess maximal shaping gain. A modified greedy-sphere packing algorithm is used for the constellation shape design to maximise the minimal distance while keeping existence of affine indexing.

Work by Hekrdla and Sykora [HS14] targets a constellation design for adaptive PLNC strategy in a wireless 2-WRC. The relay requires an extended cardinality network coding adaptation to avoid all singular channel parameters at the MAC stage if the terminals are using standard 4QAM constellations. The cardinality extension is undesirable since it introduces redundancy decreasing the data rates at the broadcast stage. We focus on a design of constellations avoiding all the singularities without the cardinality extension. It is shown that such a constellation is 4-ary constellation taken from hexagonal lattice (4HEX) which keeps comparable error performance at the MAC stage as 4QAM, however without the cardinality extension (Figure 7.5). The similar properties has been found also by unconventional 3HEX and 7HEX constellations.

7.1.4 Receiver Processing

The NCM with HDF is known to be vulnerable to the mutual phase rotations of the signals from the sources. In Sykora and Jorswieck [SJ11], the additional degrees of freedom in SIMO channels are used to create a specific receiver beam-forming tailored for given NCM/HDF strategy. A closed form solution of the NCM/HDF specific beam-former is derived and applied on example

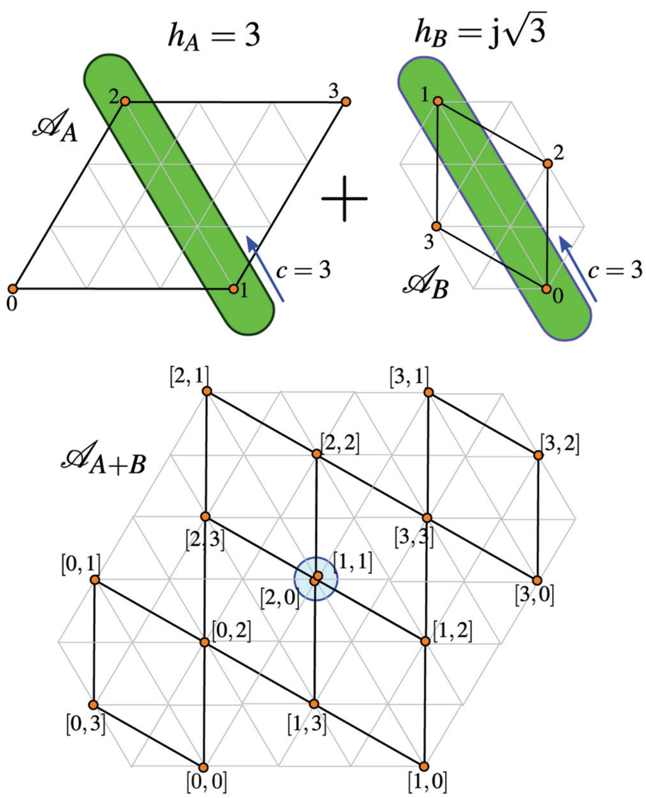

Figure 7.5 Singularity $\alpha = j\sqrt{3/3}$ is avoided by the modulo-sum network coding function if all indices in the critical lattice-dimension (emphasised) are indexed by affine indexing (here with coefficient $c = 3$).

NCMs. The resulting beam-forming is formed on a very different utility optimisation than it is in the traditional beam-forming which is optimised for Gaussian alphabet interference channels (ICs). The beam-forming strategy is equalising the signals at the relay to optimise processing of the *hierarchical* information to take the full advantage of HDF (confront that with classical interference nulling beam-forming). The performance is evaluated in terms of the mean and the outage hierarchical rates. It is shown that these rates significantly benefit from the beam-forming and that the resulting rate significantly outperforms classical (non-PLNC) channel sharing techniques.

A similar target and setup is investigated in Hekrdla and Sykora [HS12b]. In contrary with the previous approach, it does not use an explicit beam-forming equaliser, but the diversity is directly utilised in the receiver demodulator metric. The impact of relative fading on uncoded error performance and ergodic alphabet constrained capacity of representative QPSK alphabet in wireless Rayleigh/Rice channel is investigated. It is concluded that relative fading is sufficiently suppressed by systems with a reasonable level of diversity which is typically assumed if only absolute fading is present.

Successive decoding with interference cancellation (SD-IC) is well understood to be a capacity achieving decoding strategy in MAC. This decoding technique allows a consecutive elimination of interfering signals during the successive decoding of particular user data. The ability to perfectly remove the interfering signal from the subsequent decoder processing (after corresponding user's data have been successfully decoded) relies on a one-to-one mapping between the user data sequence and its signal space representation. However, this is not always guaranteed in PLNC systems, where only specific ("hierarchical") functions of user data are decoded. Work by Uricar et al. [UPS14] analyses this particular problem in a simple binary 3-user MAC channel, which is capable to demonstrate the issues associated with successive decoding in PLNC systems. It is shown that a hierarchical extension of conventional SDIC processing appears to be a viable decoding strategy, even though it does not allow a perfect removal of interfering signals from the receiver observation.

The principle of hierarchical interference cancellation (H-IFC) is analysed from the information-theoretic perspective by Sykora and Hejtmanek [SH14]. Classical CoF relay processing technique complemented with nested lattice type of NCM is believed to be "all-in-one" solution for designing PLNC-based networks. However, we see that it has several deficiencies. The major one is the fact that receiver lattice mismatch is aligned only through the scalar single tap equaliser. It does not provide enough degrees of freedom for multiple misaligned sources. The CoF strategy is generalised by introducing the concept of H-IFC using successive CoF decoding. This technique allows increasing the number of degrees of freedom in lattice misalignment equaliser while using all available hierarchical (many-to-one function) auxiliary codeword maps. The technique is not constrained to use linear map combinations and allows more freedom in choosing a given desired codeword map at the relay in a complicated multi-stage network. The standard CoF assumes essentially that the number of involved source nodes and relays is high and we have plenty of choices to optimise HNC map coefficients that maximise the computation rate. However, in practical situations with a small number of nodes, we are rather limited and frequently only few are allowed in order to guarantee final destination solvability. Respecting subsequent stages of the network (not just the MAC stage of the first stage) frequently dictates further constraints on the map that is required to be processed by the relay. A particular HNC map is typically desired to be processed by the relay. The H-IFC technique is developed in two, joint and recursive, forms. Numerical results show that the achievable computation rates can substantially outperform standard linear multi-map CoF technique.

7.1.5 Relay HNC Map Design

A majority of the research results on PLNC considers only a basic 2-WRC system scenario, where the perfect HSI is naturally available at both destinations. Although an extension of the PLNC principles from the 2-WRC system to the butterfly network could seem relatively straightforward, several new unconventional phenomena arise and need to be considered. First of all, the non-reliable transmission of the HSI can be overcome by an increased cardinality of the relay output. This opens a question how a suitable HNC mapper could be designed for a given quality of the side information link and source alphabet cardinality. Based on the work by Uricar and Sykora [US12a], we focuses on this problem. We introduce a systematic approach to the design of a set of HNC mappers, respecting the amount of available HSI. Observed capacity gains of this extended cardinality relaying pave the way for an adaptive butterfly network, where the achievable TP can be maximised by a suitable choice of the HNC map at the relay.

The core of the solution is based on the assumption that each destination can identify at least subset of bits from the constellation symbol received on the side link. The idea is to partition the source constellation alphabet into smaller subsets (according to the principles similar to Ungerboeck mapping rules) to increase the probability of successful partial side information retrieval at the destination. Hence, the intention is to maximise the distance between the particular subsets.

Linear HNC maps are attractive solution due their apparent simplicity. However the operations does not necessarily be constraint to algebraic field. A relaxation of this requirement allows more flexibility in the map choice. A sequence of works by Burr et al. [Bur13, Bur14b, BFW14] solves this problem first starting with a general formalism of the operation in algebraic rings and fields in the perspective of HNC map. Particularly, it is the global solvability (in some cases not requiring explicit inverses) and capability to give more freedom in resolving singular fades of PLNC in parametric channel. It is first investigated in the 2-WRC scenario [Bur13], then generalised into more complex scenarios in Burr et al. [BFW14]. Work by Burr [Bur14b] generalises linear PLNC HNC maps using constellations obtained from nested lattices of Gaussian integers. These constellations are isomorphic either to a ring or a field, either of integers or of first order polynomials. It shown how the coefficients of linear HNC maps which resolve singular fading states may readily be obtained in these structures, and also discuss unambiguous decodability in some simple networks.

The core idea of linear HNC function in these frameworks can be extended to various forms of ring, rather than being restricted to algebraic fields, provided care is taken with the choice of the coefficients from the ring. In particular, to ensure unambiguous decodability, the coefficients which appear in the matrix relating the symbols received at the destination to the transmitted symbols must not be zero-divisors within the ring; or equivalently, they must be uniquely invertible. Constructions with functions based on the ring of integers and also on the ring of square binary matrices were considered.

Also it was shown that care must be taken with the choice of network code function in order to minimise the effect of relative fading of wireless channels leading to a relay node. In particular, it should be as far as possible ensured that singular fade states, in which two or more different symbol combinations at the source nodes lead to the same (or nearly the same) signal at the relay, are resolved by the choice of network code function. In this context, resolution means that such combinations encode to the same network coded symbol, so that the singular fade state does not result in ambiguity of the network coded symbol.

The performance of linear PLNC is examined by Burr [Bur14a] using linear mapping functions based on rings over integers. In PLNC, the effect of the wireless channel is fundamental. The effect of fading coefficients of the channels between nodes has to be taken into account. In particular, some fade coefficients of incoming channels at a node will cause certain mapping functions to fail, even if none of the channels is subject to severe amplitude fading. It is the relative rather than the absolute values of the coefficients that give rise to this effect, and these relative fading coefficient values are referred as singular fade states. The primary objective of this work is to extend the investigation of the relative fading effects on the performance to the full range of possible relative fade states. The equivocation is determined as a function of the relative fade coefficient, and hence has determined the outage probability for the scheme. A significant improvement in outage performance, of 4–5 dB, through the use of non-minimal mappings. However, these have the disadvantage that they increase the cardinality required in the broadcast phase of the relay operation, potentially degrading the outage capacity at that point, and also that channel coding is not easily implemented.

An important aspect of the HNC design in large PLNC networks is initialisation and self-organisation. It should determine the local maps at nodes depending on the situation in their direct (Dir) radio visibility neighbourhood while optimising the performance utility of the network. The first step is the sensing and classification of the local signals received in the superposition in hierarchical MAC stage. The work by Hynek and Sykora [HS12c] addresses initialisation of the PLNC procedure in stochastic unknown connectivity network. The algorithm is based on a blind clustering of the received constellation by simple k-means algorithm. The algorithm provides the estimation of the number of the operated sources received by the given relay. The channel states can be also determined from the position of the centroids.

The self-organisation of the HNC maps is solved by Hynek and Sykora [HS13]. It provides an analysis of game theoretical approach to the distributed selection of the decision maps at each individual relay in complex multi-source multi-node network based on PLNC. The wireless network consist of arbitrary number of independent selfish source nodes, one layer of relay nodes (named a cloud) and a set of destinations. Network connectivity is globally unknown. The game uses a particular example of local relay utility function defined as cardinality of the output hierarchical symbol. It is shown that the distributed algorithm has promising properties in game theoretical sense and has atleast one Nash equilibrium. It can be also shown that the myopic better response dynamics converges to this equilibrium (or to some of them in case of the game with multiple equilibriums). By the straightforward extension it can be shown that those properties remain valid even in case of the games with more then two players. The proposed game is suitable for any decode and forward (DF) PLNC for wireless as well as wire-line networks.

7.2 Cooperative and Relay-Aided Processing

The research activities performed in this area were focused mainly in the three major directions, listed below, and are presented in the corresponding subsections:

- Virtual MIMO and RA distributed processing, which studied the reliability and/or spectral efficiency (SpE) improvements brought by the proposed algorithms based on these techniques in typical wireless environments.
- Relay-assisted (RA) algorithms that aimed at increasing the energy efficiency (EE) of the wireless transmissions under imposed reliability and SpE requirements.
- Interference analysis and cancellation algorithms in RA wireless transmissions.

7.2.1 Virtual MIMO and RA Distributed Processing

One of the approaches the improves bit error rate (BER) performance of RA transmissions is the space–time (frequency) block coding (ST(F)BC) technique. The technical report by Urosevic et al. [UVPD13] proposes a modified orthogonal STBC (OSTBC) code with a diversity order of 4 which requires two antennas only at the base station (BS). In order to reduce the processing at the RN, the proposed algorithm performs only permutation and forwarding of the signal sequences, omitting the coding procedure. This algorithm has a coding rate equal to the one of the quasi-orthogonal STBC (QOSTBC) schemes available and greater than the one of the OSTBC schemes and aims at ensuring a BER performance comparable with the ones of OSTBC. The BER performance provided by the proposed algorithm and by the "classical" OSTBC and QOSTBC schemes are compared by means of computer simulations that assume Ricean fading on the BS-RN channel and Rayleigh fading on the RN-(D) channel. The results show that the proposed scheme provides SNR gains compared to the QOSTBC scheme, at the same coding rate, and gets close to the BER performance of the OSTBC scheme, which has a smaller coding rate, only for high values of the Ricean constant, i.e., $K > 8$.

Paper by Bota et al. [BPV13] proposes and analyses the block error rate (BLER) performance provided by an alamouti adaptive distributed scheme (AADS) which implements a modified Alamouti SFBC encoding–decoding algorithm by using selective relaying (SR) at two fixed DF-RNs and only single-antenna devices over block Rayleigh-faded channels. The SR used at the RNs, replaces the wrongly decoded blocks by null blocks and signalises this fact to D. The receiver at D uses an adaptive alamouti decoding algorithm (AADA), which uses different decoding algorithms for the cases when the RNs have transmitted both or only one part of the Alamouti encoded message, according the RNs signalling. The paper derives the theoretical BLER expressions of the proposed scheme, of the distributed Alamouti scheme (ADS), which does not use SR at the RNs and does not adapt the SFBC decoding algorithm at D, and of the "classical" non-distributed Alamouti scheme. These theoretical expressions are derived by using approximate models of the Rayleigh-faded channel and of the channel code correction capability.

The BLER performance is evaluated and validated for both UL and DL directions versus the SNRs of the component links, showing that the proposed AADS ensures smaller BLER values than ADS or ANS, as shown in Figures 7.6 and 7.7. The paper also points out the different BLER versus SNRs behaviours of the DL and UL transmissions.

The employment of several successive VAA is considered in paper by Xie and Burr [XB12] to increase the capacity of the link between a source node S

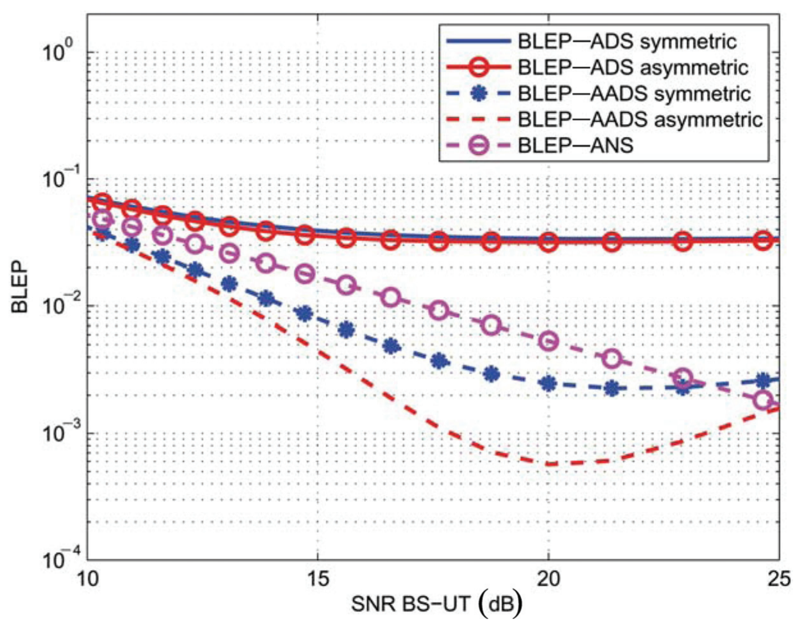

Figure 7.6 BLER versus $\text{SNR}_{\text{BS-UE}}$ of ADS, AADS and ANS in DL symmetric and asymmetric scenarios.

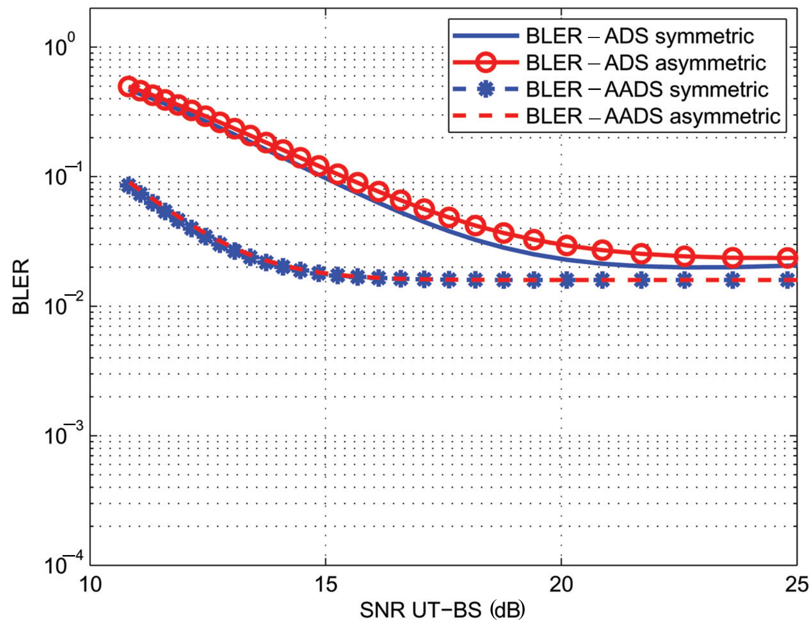

Figure 7.7 BLER versus SNR_{BS-UE} of ADS and AADS in UL symmetric and asymmetric scenarios.

and a final destination node D. The paper focuses on the link between the virtual antenna array (VAA) at the receiving end and D and uses the Slepian–Wolf coding, implemented by the repeat accumulate repeat (RAR) code, to compress the information and thus to increase the SpE. In order to support the Slepian–Wolf coding, the paper analyses and evaluates several quantisation and de-quantisation methods.

The received signals at the destination-VAA are quantised, compressed by the RAR encoder and, finally, are transmitted simultaneously to D via a MAC. At D, signals are separated by the multiple user detector and decompressed by the Slepian–Wolf decoder, the output of which is then input into the de-quantiser. It either reconstructs the received signals or produces soft information directly for the outer decoder, according to the different analysed de-quantising algorithms.

The numerical results, obtained in a Raleigh-faded scenario, with two sets of two AF relays as VAAs, show that the quantiser–dequantiser implemented by a demodulator and log-likelihood ratio (LLR) combination ensures a significant SNR gain, compared to the one composed of a demapper–decoder and LLR combination.

Paper by Tao and Czylwik [TC13] analyses the optimal design of the source's S and RN's beamforming vectors and the RN selection if the channel state information (CSI) is available at all nodes, as a way to improve the reliability of a half-duplex MIMO network with multiple AF–RNs. To this end, the authors jointly optimise the beamforming vectors and RN selection matrix, and use the direct S–D link as well to increase the diversity gain.

To decrease the number of required feedback bits, the paper proposes a new scheme that extends to a multiple RNs scenario an available iterative algorithm of designing the beamforming vectors and selecting the best RN. This scheme uses Grassmanian codebooks which also maximises the total received SNR at the destination, by combining the signals from the best RN and from the source. Then the authors propose a sub optimal scheme with limited feedback in which D uses only the singular values of the S–RN channels to obtain their SNRs.

The proposed scheme's SER performance is compared to the ones of three previously proposed schemes, the optimal one, the Grassmanian codebook and the random quantisation schemes in a single RN transmission. The proposed scheme is shown to outperform the other schemes and require less feedback bits than the Grassmanian quantisation, with only a slight performance loss compared to optimal beamforming.

The two-user MIMO with two-way AF RNs scheme over block fading channels is studied in [UE13] in the non-coherent setting, where neither the user equipments (UEs) nor the RN have knowledge of CSI. It presents the derivation of a lower bound of the achievable sum-rate, assuming isotropically distributed input signals, and determines an achievable pre-log region, which is regarded as the main performance indicator of a particular relaying strategy in the high-SNR regime. The paper also makes a comparison of the analysed scheme to the time-division multiple access (TDMA) scheme and points out the coherence time values for which the two-way AF relaying provides greater sum-rates than non-coherent or coherent TDMA.

The BLER and SpE performance of two variants of the Two-Way Relay Channel is studied in paper by Bota et al. [BBV14a] over Rayleigh block-faded channels in a generic cellular scenario. The 2-WRC variant only uses the relay-path, while the Enhanced-2-WRC (2-WRCE) variant uses the direct link and the relay path between S and D and a hard network decoding (HND) method at Ds. To decrease BLER both methods use SR. The paper derives the theoretical expressions of the BLER and SpE provided by these schemes and validates against computer simulation results.

The BLER performance of the 2-WRC(E) is compared to the performance of the two-hop relaying (OwR) and of the Direct (Dir) transmission, for different modulation orders and for various positions of the UE versus the BS and RN. The theoretical and simulation results show that the proposed 2wRCE provides the lowest BLER for almost all positions of the UE within the cell. They also show that the use of higher modulations in the relaying phase of 2wRCE provides smaller BLER than the Dir, as shown in Figure 7.8, and increases its SpSE, under a BLER constraint.

In order to improve the reliability of RA links in which the S-RN link is not error-free, paper by Zhou et al. [ZCAM12] proposes and analyses a distributed joint source-channel coding (DJSCC) strategy to exploit spatial and temporal correlations simultaneously for transmitting binary Markov sources. This approach regards the BER on the S–RN link as measure of the spatial correlation between the S and RN nodes, estimates the spatial correlation and employs in the iterative processing at D.

Moreover, the temporal correlation of the Markov source is also utilised at D by a modified version of the BCJR algorithm, derived by the authors. This modified version performs successively horizontal andvertical iterations using the LLRs provided by two single-input single-output (SISO) decoders. The convergence of the proposed algorithm is studied by means

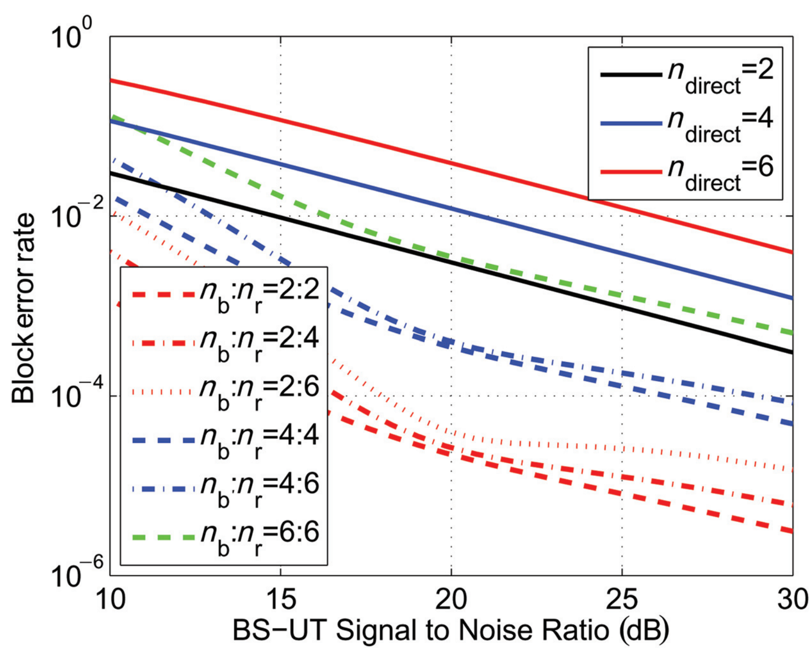

Figure 7.8 BLER versus $SNR_{BS\text{-}UE}$ of 2wRCE and Dir for n_b, n_r and n_d 2, 4, 6.

of extrinsic-information transfer (EXIT) charts. The paper also analyses the BER performance of the proposed scheme, pointing out separately the impacts of the spatial and temporal correlations upon BER at destination. The numerical results show that this approach brings very high SNR gains versus the performance of the same channel code decoded without using the two correlations; the SNR gains are reported to be of 1.9 dB up to 6.8 dB, depending on the error-rate of the S–RN link, for a memory-1, $\frac{1}{2}$ convolutional code.

Paper by Bota and Botos [BB13] analyses the BLER and SpE performance provided by two-level rateless-forward error correction (FEC) coding, which is used within two RA distributed schemes, namely the cooperative repetition coding (CoRCo) and separate source-relay (SSR) coding, within a two-phase cooperation scheme. Within CoRCo the RN retransmits the entire rateless-FEC-coded message received from the source. Within SSR, the RN transmits only additional symbols of the FEC-encoded rateless code symbols computed from the initial message received from the source, while the destination combines the two sets of rateless symbols to recover the S's message.

The paper derives expressions of the message non-recovery probability (p_{NR}) and of the SpE of the two schemes and studies the influence of the schemes' parameters, i.e., the coding rates modulation orders, upon the performance metrics.

The numerical results show that the CoRCo scheme provides smaller P_{NR} values, at the expense of lower SpE, while the SSR scheme provides better SpE, but requires channels of better qualities. The CoRCo is not affected by the S–RN channel's quality, while SSR exhibits an error-floor. The authors conclude that the two cooperative schemes should be used adaptively, adding a new dimension to the link adaptation (LA) process.

Paper by Anwar and Matsumoto [AT12] proposes an iterative spatial demapping (ISM) algorithm for simultaneous full data exchange in three-way AF relaying systems, without direct links between the UEs, which ensures simultaneous connections between three UEs using only a two-phase cooperation, i.e., the UEs transmit simultaneously in the first phase, while the RN transmits the received composite signal to all UEs in the second phase.

The proposed algorithm involves a convolutional encoder and a rate-1 doped accumulator (D-ACC), while the decoder includes an ISM block, providing the extrinsic LLRs of the desired bits from the received signal, and two turbo-loops, including a D-ACC decoder based on the Bahl, Cocke, Jelinek, Raviv (BCJR) algorithm. The BER performance exhibits a turbo-cliff behaviour at low SNRs, i.e., 2 dB for binary phase shift keying (BPSK) and memory-2, $\frac{1}{2}$ convolutional code, on additive white Gaussian noise (AWGN) channels, while in Rayleigh-faded ones the performance is affected by the phase offsets that cannot be completely controlled in three-way relay channel schemes.

The problem of determining the capacity bound of a multi-way relay network in the domain of high SNRs is analysed in Hasan and Anwar [HA14]. The authors propose a scheme that allows uncoordinated simultaneous transmissions between multiple users, who send their messages randomly according to a probability distribution, with the assistance of a single AF–RN which always forwards the received information to all users in the broadcast phase. To avoid interference and collisions, the authors adopt the concept of random access with a graph-based decoding algorithm. The proposed scheme employs at the receiving ends an iterative demapping technique to decode colliding packets, which uses alternatively the maximum *a posteriori* (MAP) decoding, successive interference cancellation (SIC) and the iterative demapping algorithm of Anwar and matsumoto [AT12] between the user and the slot nodes, to increase the TP, while working at relatively low SNRs.

The asymptotic analysis presented derives the nodes' degree distribution and the capacity bound of the proposed system. The numerical results show that it can ensure significantly greater traffic than the coded slotted ALOHA system.

Paper by Kocan and Pejanovic-Djurisic [KPD12] studies the BER performance of the orthogonal frequency division multiplex (OFDM) RA dual-hop scheme that uses a fixed gain (FG) RN which employs ordered subcarrier mapping (SCM), assuming that the RN has full knowledge of the CSI of both S–RN and RN–D channels.

The authors present an analytical derivation of the BER performance of OFDM AF FG relaying for the best-to-best (BTB) and best-to-worst (BTW) variants of SCM.

The theoretical BER expressions are validated against computer simulations and show a very good accuracy. Then, it is shown that the SCM–BTB scheme provides the best BER performance at high SNRs, while the SCM–BTW performs better at medium SNRs, when compared to FG AF relaying and the direct transmission.

The BER and ergodic capacity performance of an RA bi-directional scheme that uses analogue network coding (ANC), in the presence of phase noise (PN) is analysed in paper [LGAJ13] under the assumption of perfect CSI knowledge at all receivers.

The paper derives a PN model, which includes the inter carrier interference (ICI) at the RN and D, and derives the expression of the signal-to-interference plus noise ratio (SINR) degradation due to PN, the authors concluding that the ICI at D has the greatest impact on the SINR degradation. It also presents a method to compute the average BER and the ergodic capacity provided by this scheme. The paper concludes that the SINR degradation increases with the PN linewidth for medium $\frac{E_b}{N_0}$ values, and the BER and ergodic capacity performance are more sensitive to the PN at D.

The LA of DF RA transmissions in orthogonal frequency-division multiple access (OFDMA)-based systems is approached in paper by Varga et al. [VBB12] which presents an LA algorithm that selects the transmission type (RA or Dir), the modulation orders and amount and type of redundancy needed to ensure a target BLER at each phase of the two-phase cooperation, while requiring the smallest possible numbers of radio resource blocks. Within this algorithm, which uses convolutional turbo codes (CTC), the RN provides either repetition coding, or incremental redundancy or a hybrid redundancy, by using the rate-matching technique. The BLER is predicted by a method based on mean mutual information per coded bit (MMIB) and is used to select the Dir or RA transmission and the modulation orders and redundancies which ensure the highest SpE under the BLER constraint. The proposed LA algorithm has linear complexity with the number of available resource blocks and is applied to each type of supported service by only changing the specific target BLER.

The SpE performance, i.e., the number of information bits per quadrature amplitude modulation (QAM) symbol, is very good, thus emphasising the benefit of cooperative relaying, mainly at low and medium SNRs, as shown in Figure 7.9 for several sets of involved channels' SNRs.

The BLER performance abstraction in RA hybrid automat repeat request (H-ARQ) schemes is further analysed by Varga et al. [VPB14]. The paper proposes an analytical method to compute the MMIB for the bits which were repeated by the RN during the H-ARQ process. To this end the authors derive the expression of the pdf of LLRs of the repeated bits provided by the rate-matching algorithm, using an approach based on Hermite polynomials. The proposed theoretical method is validated against measurement results, showing that it provides good accuracies both for transmissions over Gaussian and frequency-selective channels.

Paper by He et al. [HZM14] analyses the BER performance of a cooperative practical coding/decoding scheme for data gathering in a WSN, which exploits the correlation knowledge among sensors' data at the fusion centre (FC),

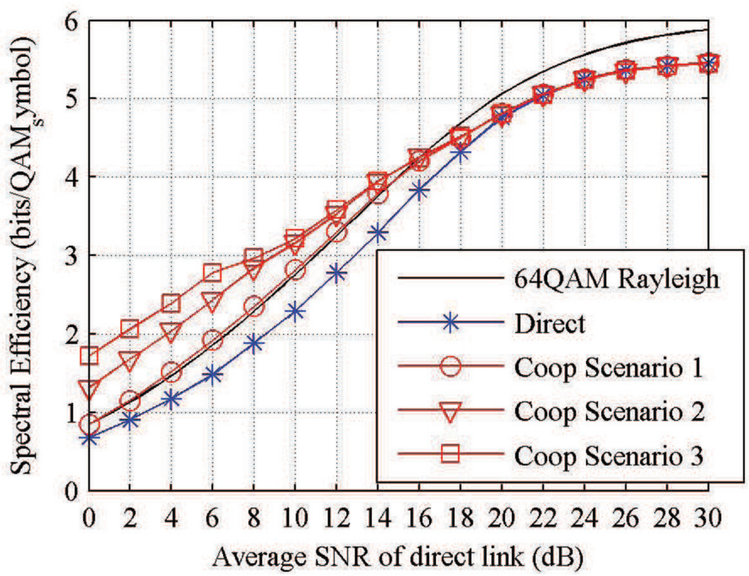

Figure 7.9 SpE versus $SNR_{BS\text{-}UT}$ of RA, Dir, and 64-QAM transmissions.

by modelling the wireless sensor network (WSN) by the binary chief executive officer (CEO) problem. Then, it analyses the theoretical limit of the sum rate based on the Berger-Tung inner bound and shows by simulations that the BER performance of the proposed scheme is very close to the theoretical limit. The error floor of the BER performance is further predicted by using the Poisson binomial process and validated by simulations. The authors conclude that the BER performance can be improved by increasing the number of sensors monitoring the same process, and that their coding decoding method reduces the energy consumption of the data gathering by exploiting the correlation knowledge.

7.2.2 Energy Efficient RA Algorithms

In paper by Tralli and Conti [TC12], the authors propose a multipurpose framework, composed of an useful cell and an interference generating cell, for the analysis of RA wireless networks on Rayleigh faded channels, which enables: (i) evaluation of the outage capacity for DF-RA links; (ii) computation of coverage and energy saving at given OP and SpE; (iii) analysis of the power allocation methods' impact on the OP and SpE.

By using the mutual information approach, the authors derive the expression of the OP and use it to compute the maximum SpE for which OP and transmitted power stay under imposed target values. Then, the paper analyses the OP performance for the uniform and balanced transmitted power's allocation between the S and RN, and concludes that in the presence of interference an optimal power allocation tends to the balanced power allocation. The numerical results presented point out the trade-off between EE, OP, and SpE of RA transmissions in the presence of interference.

The EE of RA and Dir transmissions is analysed by Dimic et al. [DZB12a]. The authors consider the SINR threshold and encapsulate the receiver parameters into the received power threshold, thus aiming at a generalised energy consumption model which includes non-identical transceivers, adaptive modulations and N-hop relaying. To this end, the authors propose a modified power consumption model which accounts for the received SINR. Using this modified model, the paper presents an EE comparison of the two-hop and Dir links, for non-identical transceivers at S, RN, and D, defining the regions of higher EE of the two transmissions. It then uses the ratio of their energy consumptions as an indicator of the border between their regions of optimality.

Moreover, the paper analyses the N-hop RA transmissions for identical transceivers, using adaptive transmission power control (ATPC), and concludes that the total transmitted power is dependent on channel loss, while the received power margin allows LA.

The EE of two-hop RA and D is further studied by Dimic et al. [DZB13], for heterogeneous transceivers, considering the SINR. The authors derive a power consumption model which expresses the transmitted power in terms of the link path loss, so that the SINR at the receiver antenna equals the minimum value needed to ensure the error-rate target. Then, they derive the energy consumption of the RA and Dir transmissions that use perfect ATPC, in the assumptions of the same modulations and transmission bandwidth. The energy expressions are then used to derive the conditions under which each of the two transmissions has a higher EE, leading to the determination of the respective regions of optimality. These expressions are used to evaluate the EE of two-hop RA and Dir transmissions in a generic cellular scenario.

In paper by Dimic et al. [DBB14a], the energy consumption model derived from the paper by Dimic et al. [DZB13] is applied to perform a comparison of the EE provided by a BS-RN-UE transmission via Type 1a RN and the BS-UE link in LTE-Advanced. The model is completed by the inclusion of the PHY and protocol parameters and is obtained by overlapping the set of channel losses with the set of transmit powers, which are linked by the link budget equation.

The analysis and numerical results are presented in two perspectives, i.e., in the space of channel losses, where the equipotential planes of the energy consumption ratio in the transceivers' operating regions are pointed out, and in the equivalent space of transmit powers, which indicates the required power levels to enable certain constellation and coding rate pairs, under the reliability constraint. Then, the paper analyses the trade-off between increasing the EE and SpE versus reducing the interference levels in the RA and Dir transmissions. They conclude that the trade-off EE versus generated interference can be tuned by adjusting the transmit powers, constellation size and coding rate.

Paper by Pejanovic-Djurisic and Ilic-Delibasic [PDID13] studies the increase of the EE in two-hop RA links provided by the use of a dual-polarised antenna at D. It analytically examines the BER performance of a standard DF RA scheme if the line of sight (LoS) S–RN is positioned to ensure LoS S–RN and RN–D links, i.e., Ricean-fading channels. Further on, it analyses the additional BER improvements obtained by using a dual-polarised antenna at D, in the assumption of two correlated and non-identical Ricean-fading channels for the RN–D link and performing maximum ratio combining (MRC) of the received signals at the D's receiver. The performance comparison of the proposed scheme to the standard DF–RN system with single antenna terminals shows that by using polarisation diversity only on Ricean channels, target BER values can be obtained at significantly lower SNRs, and the SNR gain increases significantly with the Ricean factor K, reaching 10 dB at BER = 10^{-4} for K = 10. The SNR gain is a measure of the energy saved by the proposed approach.

The paper by Moulu and Burr [MB14] tackles the problem of maximising the ergodic capacity of a MIMO RN network under low SNR on the RN–D hop. To this end the paper proposes and studies the use of the largest eigenmode relaying (LER) transmission in the RN. The study assumes a dual hop, half duplex non-coherent MIMO system, with one antenna at D, and with no CSI available at sources.

The authors analyse the transmission via the strongest eigenmode and derive a necessary and sufficient condition under which it maximises the capacity, concluding that whenever the necessary and sufficient condition is fulfilled, in order to achieve capacity, the entire power in the relay must be assigned only to the largest eigenvector. Then the authors discuss the optimality of the LER scheme at low SNR and high-SNR cases, and conclude that, regardless of the other system parameters, LER is the best relaying strategy, compared to the equal gain transmission and smallest eigenmode relaying.

Paper by Bagot et al. [BBN+14] explores the increasing of the EE in a digital TV broadcast scenario by using adaptive beamforming techniques and antenna arrays at the transmission tower, according to the user's CSI. The proposed broadcast scheme involves TV sets with channel monitoring and internet connection capabilities, and a dedicated controller at the provider's end. The simulation results show that the percentage of served users in a given area could be increased significantly, compared to a non-adaptive broadcasting, at the same transmitted power. The paper also shows that CSI feedback provided only by 25% of users would bring significant coverage improvement.

7.2.3 Interference Analysis and Cancellation Algorithms

Paper by Clavier et al. [CWS+12] analyses the BER performance of a generic RA-DF transmission in the presence of non-Gaussian multiple-access interference (MAI), which is modelled using α-stable distributions. The authors propose a non-linear receiver that uses normal inverse Gaussian (NIG) distributions to approximate the noise plus interference distribution, and compare its BER versus signal-to-interference ratio (SIR) performance to the one of a generic linear receiver, based on MRC, and to the ones of a non-linear receiver that uses the p-norm. Finally, the paper concludes that the non-linear receivers outperform the linear one in the presence of interferences, and that the NIG receiver is to be used when interferences can be modelled by α-stable distributions.

The generalised degree of freedom (GDoF) of the interference relay channel (IRC) is analysed in Gherekhloo et al. [GCS14] in the case when the S–RN link is stronger than the strong interference at D, within a transmission strategy which is a combination of DF, CoF and cooperative interference neutralisation (CIN), proposed by the authors, which includes block-Markov coding and lattice codes. The paper characterises the GDoF of the IRC in the strong interference regime, derives a new upper bound of the sum capacity and shows that the proposed transmission scheme achieves this new upper bound in the Gaussian channel. By comparing the GDoF of the IRC with that of the IC, the authors point out an increase in the GDoF even if the RN–D link is weak, and show that in the strong interference regime the GDoF can decrease as a function of the interference strength, a behaviour which is not observed in the IC.

Paper by Tian et al. [TNB14b] also analyses the DoF regions for the multi-user interference alignment, the analysis being made in a distributed RN system with greatly delayed and moderately delayed CSI feedback. It proposes some new transmission schemes for the RN interference alignment, based on the Maddah-Ali-Tse (MAT) scheme and space–time interference alignment (STIA), intended to operate either over delayed S–D channels and ideal CSI of the RN–D channels, or over non-delayed CSI of the RN–D channels. The proposed adaptive precoding scheme implementing the MAT interference alignment algorithm is based on a distributed cooperative relay system (DCRS), which includes a relay control station (RCS) and several distributed remote units acting as RNs.

The paper derives the sum DoF ensured by the two proposed schemes, for ideal or delayed RN–D's CSIs, expresses the sum DoF gain in terms of the number of delayed RN–UE CSIs, and shows that they ensure greater sum DoFs than the MAT algorithm, if the number of connected UEs is large. The proposed distributed precoding scheme has a lower complexity at the BS, some of the precoding matrices being computed at the RNs.

The impact of beamforming at the RN upon the destination's SINR is analysed in [SNB13]. The paper derives the analytical expression of the global SINR at the destination UE, provided by a fixed AF–RA transmission which uses the direct enhanced node B (eNB)-UE link, in a generic LTE-A cellular environment and evaluates the UE's SINR with variable 3 dB beamwidth antenna-pattern at the RN, aiming at the maximisation of the smallest UE SINR in the sector, to increase fairness and coverage. The presented results show that the optimum RN antenna 3 dB beamwidth is 96°, which improves by 2 dB the sector 10%-tile SINR at poor SINRs, and by 2.7 dB the 80% tile at good SINRs, relative to the direct eNB-UE link.

7.3 Cooperative Networks

In this section, we mainly focus on cooperative relay networks and cooperative cognitive radio networks (CRNs). Relay networks is a very promising cost-efficient solution to improve wireless network performance without adding much cost. The emerging M2M communications paradigm can be traced back to the concept relay. Further, cognitive radio adds intelligence into wireless communications and it is able to boost the performance in terms of high capacity, energy efficiency, and spectrum utilisation. It is envisioned that both M2M and relay as well as cognitive radio networks will be key enabling technologies for 5G and beyond.

7.3.1 Cooperative Relay Networks

In cooperative relay networks, we will concentrate on channel modelling, optimal relay selection, energy efficiency and cooperative schemes. M2M communication, as a promising technique, will be also studied.

The cross-correlation behaviour of the channels for designing and optimising performance. In particular, the correlation of the small-scale characteristics of channel has not been studied. To address this, we need to build model for the channel cross-correlation in the small-scale for realistic environments and application scenarios. The study Yin et al. [XPKC12] proposed a new stochastic geometrical model for the cross-correlation of small-scale-fading in the channels between the relay station and the mobile station, and between the BS and the mobile station. The underlying measurement data was collected using the relay-Band-Exploration-and-Channel-Sounder systems in urban cooperative relay scenarios. It has been demonstrated that the measurement system is capable of measuring two co-existing channels simultaneously. Six geometrical parameters are proposed as variables in the presented models. These key parameters describe the geographic features of a three-node relay system consisting of a BS, a relay station and a mobile station. The proposed model also reveals the variation of cross-correlation coefficients. The illustrative results indicate that the small-scale fading in the two channels are more correlated when the angle between the direct links from the BS to the mobile station and from the relay to the mobile station decreases.

Relay networks has a very promising benefit with respect to saving energy consumption. This is achieved mainly by reducing path loss due to short transmission range and using low transmission power. Reducing energy consumptions is very related to the problem on relay selection. Taking into account the coordination overhead, the energy efficiency of the cooperative communication may degrade with the increase of the number of cooperators. The relay can be selected according to different criterions, e.g., the maximum SNR, the best harmonic mean, the nearest neighbour selection, and contention based selection. The study by Ling et al. [LRYG14] focused on a network where a user is selected as a relay for primary user. Selection criteria are based on maximisation of the network energy efficiency. The associated three-phase cooperation procedure shown in Figure 7.10.

In this system model, secondary users act as relay to assist in the transmission of primary users with the reward to transmit its own information. On one hand, the secondary user is selected using the metric of the energy efficiency by considering the outage capacity and energy consumption in a decoding and forward relaying. On the other hand, optimal power allocation and secondary

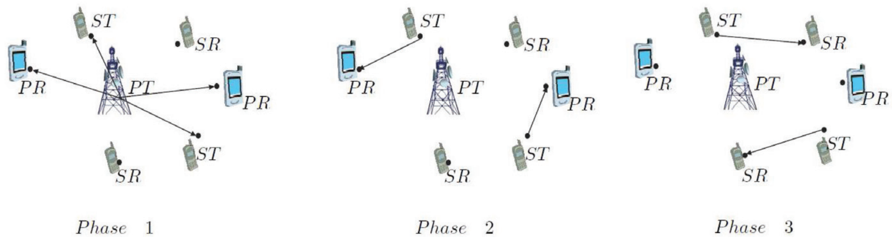

Figure 7.10 Cooperation in three phases.

user selection are performed in the scenario. The cooperative relay sharing procedure can be divided into three phases, i.e., primary users' direct transmission, secondary user's relay, and secondary user's own transmission. The optimal power allocation is obtained by solving an convex optimisation problem with the boundary conditions of QoS requirement. It is observed that cooperative communication performs better than non-cooperation transmission in saving network consumption. More candidates of the SUs may lead to lower power consumption of the network and better energy efficiency.

Relay is a flexible technology and can be applied in different networks. In the optimisation of cellular planning for fixed WiMAX, the use of relays reduces the necessary extent of wire-line backhaul, improving coverage significantly whilst achieving competitive values for system TP. Moreover, relays have a much lower hardware complexity, and using them can significantly reduce the deployment cost of the system as well as its energy consumption. Consequently, frequency reuse topologies have been explored for 2D broadband wireless access topologies in the absence and presence of relays, and the basic limits for system capacity and cost/revenue optimisation have been discussed. Relays are also amenable to opportunistic utilisation of power-saving modes.

The study by Robalo et al. [RHV$^+$12] investigated the use of relays in WiMAX network deployments and concentrates on the cost/revenue performance and energy efficiency trade-off in such cases. Layered and cooperative elements such as femto-cells and relays can improve performance or energy efficiency in mobile networks. However, they consume energy *per se* and their durations in operational state must, therefore, be minimised. Specifically, the study investigates the performance achievable by networks that are deployed in various sectorisation configurations with and without relays, and matches this to varying traffic loads at different times of the day to maximise the use of sleep modes, where possible, by relays, also in consideration of coverage requirements. The study performs real measurement in the hilly area of

Covilhã, Portugal. Results show that through the maximal use of power saving by relays at low traffic times, considerable energy savings in the relays' power consumption are achievable, typically 47.6%. These savings are shown to map to a financial saving for the operator of 10% in the operation and maintenance cost.

Device-to-Device (D2D) has been known to be a key technology for 5G and beyond. Relay is the fundamental technique in D2D communications. The study by Komulainen and Tolli [KT14] proposed linear coordinated transmit-receive beamforming methods for spatial underlay direct device-to-device communication in cellular networks where the user terminals employ multiple antenna elements. A cellular system model includes one multi-antenna BS and multiple multi-antenna user terminals.

In the cellular mode, spatial multiplexing for both UL and DL user signals is employed so that the DL forms a MIMO broadcast channel and the UL forms a MIMO MAC. Furthermore, the data streams are transmitted via linear spatial precoding and that each receiver treats the signals intended to other receivers as coloured noise. The model is further extended by allowing spatial underlay device-to-device communication so that some terminal pairs are allowed to directly transmit to each other. As a result, the system model becomes a mixture of MIMO IC, broadcast channel, and MAC. For a D2D terminal pair, direct communication is a beneficial alternative compared to the cellular mode, where the devices communicate to each other via a BS that acts as a relay. For mode selection, spatial scheduling, and transmitter-receiver design, the study formulates a joint weighted sum-rate (WSR) maximisation problem, and adopts an optimisation framework where the WSR maximisation is carried out via weighted sum MSE minimisation.

Figure 7.11 shows the system sum rate utility in terms of average direct D2D channel gain. The results indicate that the joint design always outperforms the other designs. However, when the D2D channel becomes stronger, the rate provided by direct D2D transmissions increases rapidly, and the additional gain from the joint design disappears.

7.3.2 Cooperative Cognitive Radio Networks

Recently, cooperative networking technologies, which inherently exploit the broadcasting nature of wireless channels and the spatial diversity of cooperative users, are introduced as a powerful means to facilitate the design of CRNs. Two types of cooperation paradigms in CRNs have been studied up to date: cooperation between primary users (PUs) and secondary users (Sus; or called PU–SU cooperation), and cooperation only among SUs

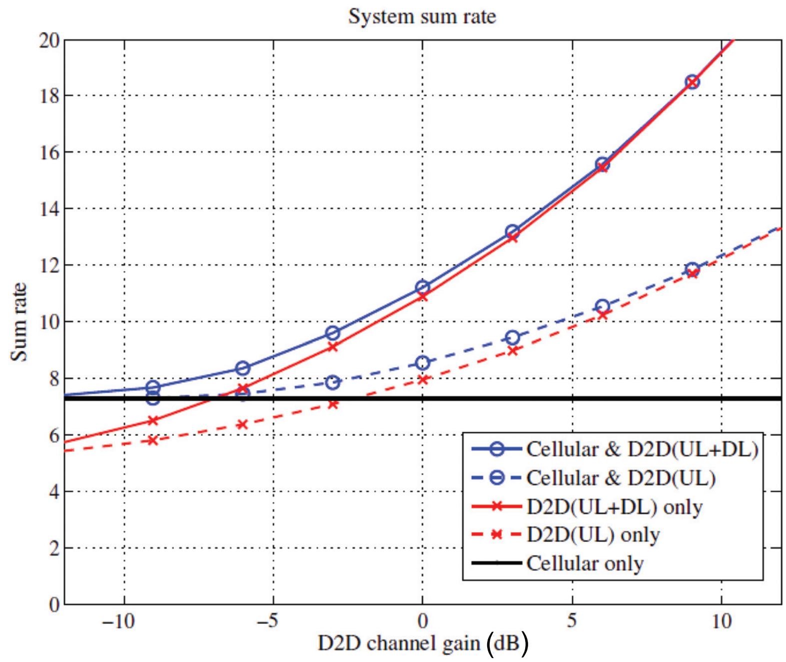

Figure 7.11 System sum rate in D2D.

(or called inter-SU cooperation). For the PU–SU cooperation, PUs are aware of the existence of SUs. The primary system regulates the spectrum leasing policy for the secondary system. The SUs utilise a small segment of the licensed spectrum, and in return, cooperate with PUs to improve the quality of primary transmissions. For the inter-SU cooperation, there is no interaction between primary and secondary systems. Cooperative spectrum sensing is a promising technique in CRNs by exploiting multi-user diversity to mitigate channel fading.

The study by Yu et al. [YZX$^+$13] identified that both sensing accuracy and efficiency have very significant impacts on the overall system performance. Then, several new cooperation mechanisms, including sequential, full-parallel, semi-parallel, synchronous, and asynchronous cooperative sensing schemes.

Figure 7.12(a) shows the sequential cooperative sensing, where the cooperative SUs (SU1–SU6) are scheduled to sense a single channel at the same time t_i. Figure 7.12(b) shows the full-parallel cooperative scheme scheme, where each cooperative SU senses a distinct channel in a centralised and

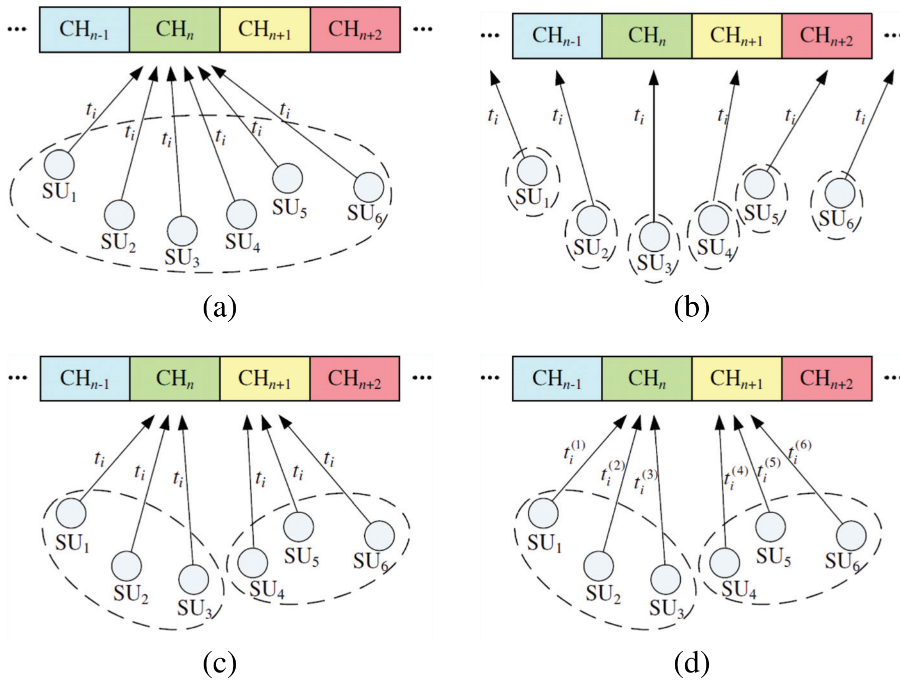

Figure 7.12 Illustration of cooperation mechanisms: (a) sequential cooperative sensing; (b) full-parallel cooperative sensing; (c) semi-parallel cooperative sensing; and (d) asynchronous cooperative sensing.

synchronised mode. To tradeoff the sensing accuracy and efficiency, the semi-parallel cooperative sensing is proposed and described in Figure 7.12(c). Figure 7.12(d) presents the asynchronous semi-parallel cooperative sensing. All the cooperative SUs are allowed to have different sensing moments. Although the cooperative SUs of a same group cooperate to sense the identical channel, their sensing moments are different.

The proposed cooperation mechanisms and the sensing accuracy–efficiency tradeoff in these schemes are elaborated and analysed with respect to a new performance metric achievable TP, which simultaneously considers both transmission gain and sensing overhead. Illustrative results indicate that parallel and asynchronous cooperation strategies are able to achieve much higher performance, compared to existing and traditional cooperative spectrum sensing in CRNs.

Spectrum management is an important mechanism in CRNs. Wang et al. [WCF13] noticed the transmission collisions between the SU and the PU and proposed periodic spectrum management for cognitive relay networks. In particular, unreliable sensing results lead to low successful switch rates, accompanied by intolerant SU's transmission collision with the PU. The study discussed a spectrum sensing and handoff model in a selective relay scenario. A partial soft sensing and fusion algorithm is proposed under the stringent signalling cost. The reliability of secondary transmission in light of the collision probability and TP is also derived analytically. The problem of spectrum leasing in CRNs is studied by Sharma and Ottersten [SO15]. This work proposed an overlay CRN where the primary users lease access time to the secondary users in exchange for their cooperation. The pairing problem among the primary and the secondary users is modelled as a one-to-one matching problem and a matching mechanism, based on the deferred acceptance algorithm, is applied in the CRN under consideration. The numerical results evaluate the performance of the proposed scheme, in terms of primary and secondary utility, compared to a random pairing mechanism.

Cooperative beamforming is the key concept for CRNs. Cooperative communication with spectrum sharing has been proved to be an efficient way to reduce energy consumption. The work by Wang et al. [WCF13] presented an optimal power allocation algorithm for mobile cooperative beamforming networks. The optimal power allocation scheme is obtained by solving a convex optimisation problem oriented to minimise network energy consumption while guaranteeing quality of service (QoS) for both PU and SUs. Illustrative results show that a cooperative beamforming network improved with our proposed power allocation algorithm performs better with more SUs in terms of higher energy efficiency and less power consumption per unit TP. Additionally, the proposed scheme outperforms the conventional relay selection approach with respect to high energy efficiency.

Cooperative cognitive radio can be applied in different environments. The work by Díez [Die13] discussed the performance of cooperative cognitive radio in indoor environments. The study shows the factors that have considerable influence on the behaviour of a cooperative CRN. Different detection techniques and the hypothesis testing techniques have been implemented in a basic and simple way, decreasing the detection times of the final testing model. The study also proved that the most accurate of the implemented detectors is the wave-based form detector and it has been studied the difference between both daughter boards with and without automatic gain control. Without automatic gain control, in some test points the level of the signal saturates the USRP and in this case, the occupied channels are mistakenly detected. This implies a reduction of the cognitive radio system quality.

A recent research by Sharma and Ottersten [SO14] focused on cooperative spectrum sensing for heterogeneous sensor networks. Existing cooperative spectrum sensing methods mostly focus on homogeneous cooperating nodes considering identical node capabilities, equal number of antennas, equal sampling rate and identical received SNR. However, in practice, nodes with different capabilities can be deployed at different stages and are very much likely to be heterogeneous in terms of the aforementioned features. In this context, the study evaluates the performance of the decision statistics-based centralised cooperative spectrum sensing using the joint PDF of the multiple decision statistics resulting from different processing capabilities at the sensor nodes. The performance is shown to outperform various existing cooperative schemes. The investigations in indoor and sensor networks are very important and can be straightforwardly extended to D2D scenarios.