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DOCTORAL THESIS STATEMENT

CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Electrical Engineering
Department of Radioelectronics

Design of Modulations for Wireless (Physical-Layer) Network Coding

Doctoral thesis statement for obtaining the academic title of “Doctor”, abbreviated to “Ph.D.”

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Contents

1 Preface

The thesis “Design of modulations for Wireless (Physical-Layer) Network Coding (WNC)” is primarily submitted as a partial fulfilment of the requirements for the PhD degree. It summarizes my up-to-date research activities as a PhD candidate at the Faculty of Electrical Engineering, the Czech Technical University in Prague.

1.1 Goals of the Thesis

There are two major goals of the thesis. The thesis is intended to

1. introduce **current state-of-the-art of WNC strategy** supported by a detailed and actual list of **references**. We tried to support the introduction by sufficient number of basic examples and illustrations to explain the most important parts also to the readers not working in the field.

2. **Present our original contributions** and map them to the current state-of-the-art of WNC research.

2 Current State-of-the-art of Wireless Network Coding Strategy

WNC is an emerging approach for wireless networking which holds a lot of expectations in the research community today. Its origin dates back to 2006, when parallely three research groups [1], [2] and [3] introduced the concept of network coding at the physical-layer. WNC originates and shares basic ideas of Network Coding (NC). Particularly, *a) the relaying nodes perform some form of information compression* similarly as does network coding (in wired error-free networks in order to reach a max-flow min-cut capacity bound) and *b) shared wireless medium is utilised as natural broadcast* rather than an interference producing Point-to-Point (P2P) link. The last corner stone of WNC, which is distinct from NC, is *c) a physical-layer processing.* NC has been originally build upon error-free bit-pipes manipulating with data packets and using algebraic operations over finite fields [4]. In WNC, we demand an equivalent operations with real signals at the PHY layer over unreliable wireless channel. This challenging approach (on optimal conditions) allows to exploit interference and turns it into the extra capacity benefits. For reference and introductory literature, we recommend survey paper [5] with plenty of creditable references, book chapter [6] and tutorials [7] and [8].

2.1 Origin of WNC

New and strikingly simple idea of [1], [2] and [3] was that the relay does not need to decode jointly $[d_A, d_B]$ at the Multiple Access (MA) stage of a two-way relaying but rather directly a function of the data which will be broadcast at the BroadCast (BC) stage (here, the function of data is an invertible function providing one of the data message e.g. bit-wise XOR $d_A \oplus d_B$). In this text, we denote the invertible function providing one of the data message as a *network coding function*, although functions used in the standard NC approach are often considered over finite-field but functions admitted in WNC are more general algebraic structure – Latin squares [9]. The information theoretic rates in case of WNC are not limited by the MAC capacity region. The scheme is briefly depicted in Fig. 1. As conjectured in [10], the rectangular capacity region given by the cut-set bound theorem [11] can be potentially achieved. Work [10] compares 2-stage protocols using Amplify-and-Forward (AF), Joint-Decode-and-Forward (JDF) and WNC strategy (here denoted as De-Noise-and-Forward (DNF)). It concludes that the highest achievable rate for symmetric channel links and high SNR provides WNC. In the low SNR region are achievable rates of WNC and JDF asymptotically identical [12].

2.2 Tutorial Example: WNC in a 2-WRC

Let us consider WNC approach in a 2-WRC as a tutorial example. Although the information theoretical analysis in [10] predicts the highest achievable rates to WNC when terminals use long codewords, we can simply demonstrates the basic principles on per-symbol relaying (which is also practical for real implementation). For the sake of simplicity, assume an ideally time-synchronised scenario with AWGN disturbance[1]. Assuming that both terminals use Binary Phase Shift Keying (BPSK) modulation alphabet $\mathscr{A}_A = \mathscr{A}_B = \mathscr{A}_{\text{BPSK}} = \{-1, 1\}$, the received signal at the MA stage is $x = s_A + s_B + w$, where constellation points $s_A, s_B \in \mathscr{A}_{\text{BPSK}}$ and w denotes an AWGN

[1]This could be a baseline model in a static frequency-flat environment with wireless channel cancellation adaptation.

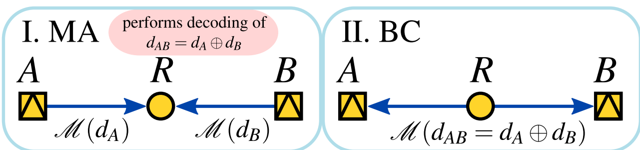

Figure 1: One round of 2-way communication in a 2-WRC using the WNC strategy.

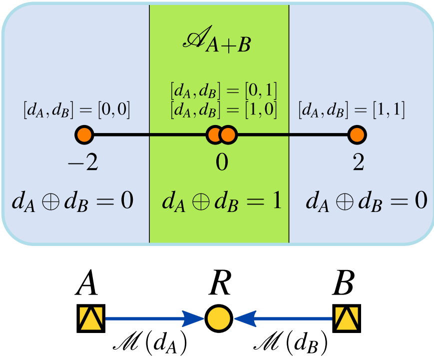

Figure 2: Decision regions of $d_{AB} = d_A \oplus d_B$ decoding at the MA stage of the WNC 2-way relaying.

noise. We define a one-to-one data-to-signal modulation mapper as

$$\mathscr{M} : d_A = 0 \to s_A = -1, \quad d_A = 1 \to s_A = 1. \tag{1}$$

Superimposed constellation point $s_A + s_B$ attains one of the three possible points from $\mathscr{A}_{A+B} = \{-2, 0, 2\}$. Notice that constellation points -2 and 2 uniquely correspond to data pairs $[d_A, d_B] = [0, 0]$ and $[d_A, d_B] = [1, 1]$, but constellation point 0 may correspond to either $[d_A, d_B] = [0, 1]$ or $[d_A, d_B] = [1, 0]$ and we cannot decide between them. But this is not a source of errors, because the relay decodes and broadcasts a network coded data symbol d_{AB} being a bit-wise XOR function $d_{AB} = d_A \oplus d_B$ which for both undistinguishable cases $[0, 1]$ and $[1, 0]$ yields the same $d_{AB} = 0 \oplus 1 = 1 \oplus 0 = 1$, see decision regions for d_{AB} decoding in Fig. 2.

2.3 Channel Coded WNC

The tutorial example from the preceding section presents an uncoded per-symbol relaying. The per-symbol relaying is practical in the sense that no additional delay is induced at the relay, however it possess much higher error performance as would have with channel coding. There are several ways how to implement channel coding into the WNC 2-way relaying. Theoretically, the scheme with the highest achievable rate requires long codewords used by the terminals at the MA stage. From its superposition is obtained network coded data packet, re-encoded and broadcast to the final destinations. The processing of channel decoding and network coding should be performed jointly, see its concrete realization using Factor-Graph Sum-Product Algorithm (FG-SPA) with LDPC codes in [13]. A separate processing of these two operations is sub-optimal as claimed in [12] and [14]. The relay processing which uses channel decoding and network coding separately shows approximately 1 dB loss (Bit Error Rate (BER) at 10^{-4} using BPSK constellations and LDPC with interleaver size 1000 and code rate 0.4 at SNR 5 dB [13]) over the optimal processing. Similar performance loss suffers a sub-optimal relaying scheme where network coded symbols are obtained per-symbol and consecutively channel encoded. This approach is denoted as a *layered relay processing* [15]. It requires linearity of the used network coding function, but the processing is less demanding than the previous schemes.

2.4 Fading Channel Parametrization Effects

2.4.1 Relative-Fading of WNC Relay Processing with CSIR

Information theoretical analysis of WNC [10] assumes perfect knowledge of Channel State Information (CSI) at all the nodes which is used for an ideal time, phase and frequency synchronisation and power control. In a real system operating over wireless channel, the amount of feedback required for such a perfect synchronisation would be prohibiting. In order to bring WNC closer to real implementation, work [16] considers only local knowledge of CSI at the receiver side. In this setting, a new form of fading in the WNC relaying appears. We call it a *relative-fading* effect [17], because it happens when a ratio of channel gains is close to certain critical values (denoted as *singularities)* no matter what are the actual channel gain values. So it can happen, that the system performs very poorly even though both channel gains at the MA stage are strong enough. Figure 3 presents such a situation when 4QAM constellations are used by the terminals and the relay decodes a bit-wise XOR function. The reason why channel parametrisation is still an issue even when perfect Channel State Information at the Receiver side (CSIR) is available (which does not appear in standard P2P communication) is due to the following. The received signal is $x = h_A s_A + h_B s_B + w$, where s_A, s_B are constellation space signals, h_A, h_B are frequency-flat channel coefficients known by the relay and w denotes a complex AWGN sample with variance $2N_0$. The relay may work with an equivalent signal when one of the known coefficients is eliminated e.g. as

$$x' = {}^{x}/_{h_A} = s_A + {}^{h_B}/_{h_A} s_B + w' = s_A + \alpha s_B + w', \tag{2}$$

where w' is a sample of AWGN with variance ${}^{2N_0}/_{|h_A|^2}$ and α denotes a channel parameter ratio. We conclude that even with CSIR the superimposed constellation is still parametrized by channel ratio α which may have a significant impact as shown in Fig. 3.

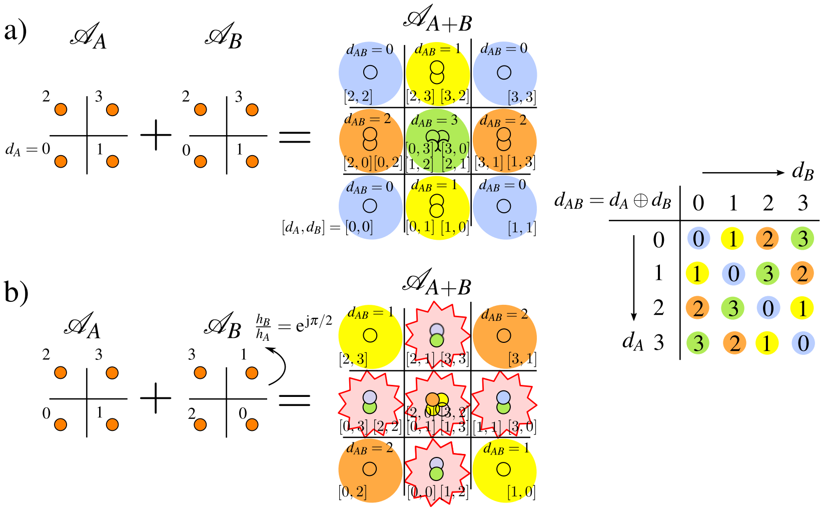

Figure 3: Example of the relative-fading at the WNC MA stage using 4QAM constellations and bit-wise XOR decoding. Case a) with $h_A = h_B = 1$ performs much better than case b) with $h_A = 1$, $h_B = e^{j\pi/2}$ although in both cases the magnitude of all channel coefficients are the same.

2.4.2 Adaptive WNC Method Eliminating the Relative-Fading

The authors of [16] proposes an adaptive relay processing where a network coding function decoded by the relay is adaptively chosen according to the actual channel ratio α in order to maximize minimal Euclidean distance and thus it eliminates the relative-fading. Surprisingly, the proposed network coding adaptation based on 4QAM alphabets requires network coding functions with higher cardinality than 4. Paper [9] analyses the adaptive WNC strategy using theory of Latin squares and proposes a simpler algorithm for the search of suitable network coding functions. Paper [16] also generalises the adaptive WNC strategy for 2-WRC with multiple antennas at the relay. Following works [18], [19] confirm that adaptive WNC strategy provides significant gains in the TCM coded system and in the system using multiple antennas at the relay and destinations. Our latest work [20] advices that there exist better constellations for adaptive WNC than 4QAM such as 4HEX constellation, where the relative-fading is eliminated by adaptive WNC without the use of network coding functions with cardinality higher than 4. The extended (higher than 4) cardinality network codes are undesirable since it introduces redundancy decreasing the data rates at the BC stage.

2.4.3 Elimination of the Relative-Fading Without any Adaptation

Our works [21], [22] reveal that the relative-fading may not appear for special type of modulation schemes and network coding functions (BPSK and bit-wise XOR being an important example) without any form of adaptation. Such modulations were denoted as Uniformly Most Powerful (UMP) alphabets due to the similarity with UMP parametric detectors which performs the best among all possible detectors for any parameter value. In our case, UMP alphabets are those having maximal (the best) minimal distance among all possible constellations with identical minimal distance of primary alphabet for any channel parameter α value. Paper [21] identifies some important features of UMP alphabets like a) bit-wise XOR network coding function is necessary but not sufficient condition for UMP alphabets, b) orthogonal and bi-orthogonal signalling is UMP and c) multi-dimensional constellations need to be used to fulfil UMP condition when alphabet cardinality is higher than binary. In the design of multi-dimensional UMP constellations we can beneficially consider naturally multi-dimensional schemes like frequency modulations Frequency Shift Keying (FSK) and CPM [21]. The numerically designed UMP multi-dimensional constellations using non-linear optimisation tools were proposed in [22]. It shows that UMP condition cannot be apparently achieved when constellation spectral efficiency is higher than $1\,[\text{bits}/\text{complex constellation dimension}]$. Ignoring the effect of the relative-fading leads to a serious performance degradation and even constellation alphabets which are not UMP but are resistant to the relative channel phase rotation provide considerable gains [22], [23]. According to the extensive performance evaluation in [17], we conclude that the relative-fading has much lower negative impact in a system with a reasonable level of diversity which is a usual assumption in reliable communication systems for wireless channel.

2.4.4 Non-Coherent WNC 2-Way Relaying

Another method dealing with wireless environment without any adaptation is a non-coherent “blind” approach. It requires no CSI neither on a transmitter nor a receiver side. Paper [24] develops a non-coherent WNC using orthogonal FSK signalling. The non-coherent WNC relay processing is very different from the canonical P2P non-coherent envelope detector. Another non-coherent WNC scheme using TCM and MIMO 2-way relaying has been recently presented in [25].

2.5 Constellation Design for WNC in an AWGN 2-WRC

WNC possesses several unique features in comparison to canonical P2P communication. We have already mentioned the effect of relative-fading. As another feature, we present a problem of constellation design optimising minimal Euclidean distance. WNC error performance does not depend only on channel coding & modulation but also on which network coding function is decoded at the relay and what type of symbol indexing is used by the terminals. For instance, 8PSK constellation has minimal distance $\delta^2_{\min} = 0.59$, but when used at WNC MA stage, the minimal distance of bit-wise XOR decoding is only $\Delta^2_{\min} = 0.34$. It can be even shown that there is no network coding function which would result in a higher minimal distance. So, even if the relative-fading is not an issue due to e.g. CSI available at the receiver as well at the transceiver. It is generally not obvious what type of constellation, indexing and network coding function leads to the highest minimal distance. Our paper [26] focuses on this issue. It shows, that constellations taken from a common lattice structure which are indexed in a special way (indices form an arithmetic progression along each lattice dimension; such indexing is denoted as Affine-Indexing (AI)) has a minimal distance equal to the minimal distance in a P2P channel. It works under the condition that modulo-sum network coding function is decoded at the relay. Paper [26] also presents some additional features like that not every lattice-constellation is indexable by AI and it presents a list of constellations with the maximal possible minimal distances. Paper [27] is focused on a joint constellation and network coding function design. It allows unequal channel gains and alphabet cardinalities. The approach considers combination of different canonical constellations like 2-, 4-, 8-QAM etc. finding a combination of constellations, its precoding coefficients and network coding functions leading to the highest minimal distance. This design of network coding functions uses the greedy clustering algorithm trying to cluster the closest superimposed-constellation points (as long as the network coding function is invertible) into the same cluster in order to maximize the minimal distance. The clustering algorithm is the same one introduced in [16].

2.6 WNC in other than 2-WRC Network Topology

The concept of WNC 2-way relaying is theoretically as well as practically quite well understood for cases with both CSIR & Channel State Information at the Transceiver side (CSIT), CSIR only and no CSI at all, including imperfect time synchronisation [28] and assuming current state-of-art communication approaches such as MIMO, TCM, turbo codes and principles of adaptation. Despite relatively good knowledge of WNC 2-way relaying, the optimal WNC strategy in a more complex network topology is the big unknown. From this point of view is the NC approach at the link-layer much more practical since it scales well into more complex topologies (although it does not provide such capacity gains as WNC). Strategies like the Compress-and-Forward (CF) strategy which designs PHY layer as to match the standard link-layer NC seems to be very promising. So far, WNC has been successfully generalised for a *chain topology* [7] (i.e. a bidirectional network with one source-destination pair and multiple serially connected relays between them) and for a wireless butterfly network [8]. Certainly, we could separate a complex general network topology into several 2-WRCs or other understood topologies, but the resulting scheme would be suboptimal as noticed e.g. in [29], [30]. Paper [29] shows that WNC strategy tailored for *a star topology* (i.e. two source-destination pairs bidirectionally communicating via a relay with reasonably strong cross channel links) substantially increases achievable rates over the strategy based on WNC for twice 2-WRC. In a star topology, the cross channel links deliver more information to the final destination, even though the information is not intended to the final destination, it enables higher network coding compression at the BC stage. Similarly as [29], our approach [30] proposes WNC strategy for a *3-terminal 1-relay multicast network.* The gain is obtained w.r.t. the strategy that considers the 3-terminal 1-relay multicast network (3T-1R) as a two 2-WRC. Particularly, paper [30] proposes a joint constellation prerotation & terminal constellation & its indexing & network coding function that allows compression of two orthogonal MA stages (corresponding to $2\times$ WNC in a 2-WRC) into the single MA stage where multiple network coded data symbols are decoded at once.

2.7 WNC in a General Network Topology

The WNC strategies presented in the preceding subsection are based on an optimisation constrained to a given network topology. So far, no general rule how the optimal solution should look like is known. The generalisation of WNC for a general multi-source multi-destination network is still an open challenge. The situation is very complicated due to a huge number of parameters which influence the optimal solution (e.g. every node may have different form of CSI and level of synchronisation, cooperation and knowledge of the overall network topology, etc.). Development of WNC strategy that is robust to the substantial portion of imperfectness is likely to be more important than the WNC strategy achieving the maximal sum-rates but under unrealistic conditions requiring tremendous data overhead. A WNC design for general wireless network is also challenging due to the lack of information-theoretical knowledge, i.e. there is no paper like [10] for the 2-WRC saying that WNC is the optimal relaying strategy in a general wireless multi-source multi-node network. This fact is demonstrated in unidirectional Multiple Access Relay Channel (MARC) where decoding of a function of the incoming data is not always the best solution [31].

2.8 Real Implementation of WNC

There are a few real verifications of WNC gains in a practically implemented system. The reason is a) the same as in case of NC, i.e. the overall network architecture needs to be completely revamp and it is difficult to simply extend the existing concept by WNC processing, b) several new challenges need to be solved such as an impact of wireless channel and synchronisation issues and generalisation for a general multi-node multi-source network. Recently, paper [32] presents a real implemented solution in a 2-WRC. The authors selected OFDM and Cyclic-Prefix (CP) strategy to combat time asynchronisation and frequency-selective fading. The gain of WNC is confirmed in Ettus Universal Software Radio Peripheral (USRP) scenario based on modification of the 802.11a/g standard. It assumes BPSK terminal constellations, bit-wise XOR network coding function and standard convolutional channel codes. Related work [33] introduced an AF network coding based relying called ANC. Although ANC non-optimaly amplifies also AWGN noise, it still provides a SNR gain $\sim 30\%$ over the NC based solution (implemented in COPE protocol [34]). ANC scheme combats time, phase and frequency asynchronisation by a special signal processing using a non-coherent Minimum-Shift Keying (MSK) modulation implemented in the GNU-radio. We conclude that current state-of-the-art of WNC implementation does not go much further then in the 2-WRC.

3 Summary of Main Contributions

3.1 Design of Lattice-Constellations and Constellation-Indexing for WNC 2-Way Relaying using Modulo-Sum Decoding

Problem. Let us consider a WNC 2-way relaying where both terminals use constellations curved from a common lattice structure and the relay node decodes a modulo-sum function of transmitted data symbols at the MA stage. Performance of such a system with AWGN is strongly determined by the used constellation indexing. For some indexing, the minimal distance of modulo-sum decoding is 0 (some points of superimposed-constellation are equal despite correspondence to unequal modulo-sum of data symbols) as shown in Fig. 4 b). It causes a considerable loss in the error performance as well as in the alphabet-constrained capacity.

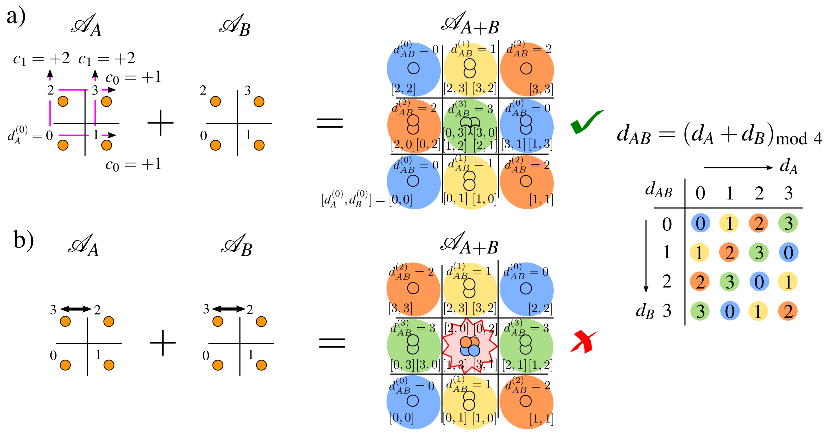

Figure 4: Minimal distance of the modulo-sum decoding with constellation indexing a) equals to the minimal distance of primary constellations since all identical superimposed-constellation points lie in the decoding region with the identical modulo-sum data symbol d_{AB}. Indexing b) implies that some superimposed points of modulo-sum decoding will be decoded erroneously.

Contribution. We show that if indices form a modulo-arithmetic progression along each lattice (real) dimension (denoted as Affine Indexing (AI)), the minimal distance of modulo-sum decoding equals to the minimal distance of primary terminal constellations as shown in Fig. 4 a). We also find that some canonical constellation-shapes prevent existence of AI, therefore we propose a greedy-sphere packing algorithm for constellation-shape design which jointly maximizes minimal distance and

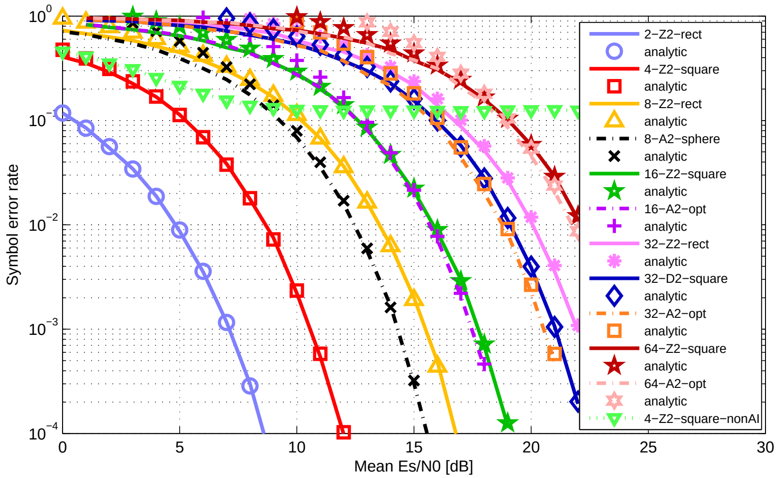

Figure 5: Uncoded symbol error performance curves of several canonical constellations and proposed constellations. The light-green line with triangular markers denotes 4-QAM performance. The dash-dotted curves denoted as 'analytic' are the pairwise symbol performance bounds.

keeps existence of AI [26]. In certain cases, we have found the constellations with the highest possible minimal distance of a network coding function decoding. The error performance curves are shown in Fig. 5.

3.2 Design of Constellations for Adaptive Minimum-Cardinality WNC utilising Hexagonal Lattice

Problem. Let us focus on a constellation design for adaptive WNC strategy in a wireless 2-way relay channel. It is well known that 4QAM constellation requires extended-cardinality network coding adaptation to avoid all singular channel parameters at the MA stage [16]. The cardinality extension is undesirable since it introduces the redundancy decreasing the data rates at the broadcast stage.

Contribution. We target a constellation design removing all the singularities without the cardinality extension [20]. We show that such a constellation is a 4-ary constellation taken from hexagonal lattice (4HEX)

$$\mathscr{A}_{4\mathrm{HEX}} = \sqrt{2}/4\left\{-3-\mathrm{j}\sqrt{3}, 1-\mathrm{j}\sqrt{3}, -1+\mathrm{j}\sqrt{3}, 3+\mathrm{j}\sqrt{3}\right\}, \tag{3}$$

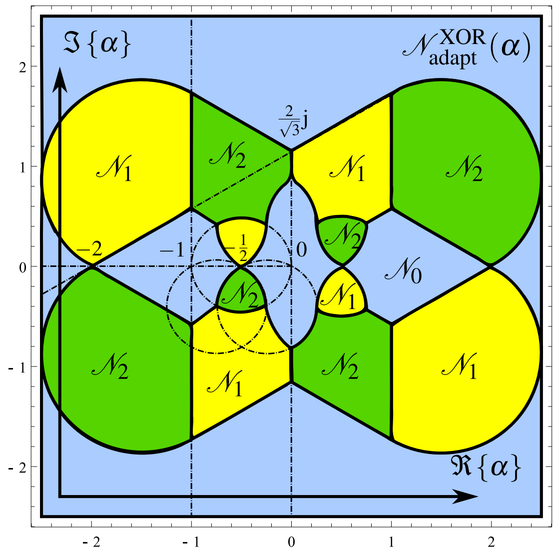

Figure 6: Adaptive network coding $\mathcal{N}_{\text{adapt}}^{\text{XOR}}(\alpha)$ based on the bit-wise XOR function for 4HEX.

which we present as a main contribution. The relay adaptively selects $\mathcal{N}_i(d_A, d_B) = [\mathbf{N}_i]_{d_A,d_B}$ according to adaptive network coding function $\mathcal{N}_{\text{adapt}}^{\text{XOR}}(\alpha)$ shown in Fig. 6 where $\mathbf{N}_i = P^i_{[0,2,3,1]}[\mathbf{N}_{\text{XOR}}]$, $i \in \mathbb{Z}_3$ and $\mathbf{N}_{\text{XOR}}$ is given by

$$\mathbf{N}_{\text{XOR}} = \begin{bmatrix} 0 & 1 & 2 & 3 \\ 1 & 0 & 3 & 2 \\ 2 & 3 & 0 & 1 \\ 3 & 2 & 1 & 0 \end{bmatrix}. \qquad (4)$$

Adaptive WNC using 4HEX and bit-wise XOR based network coding adaptation removes all singular channel parameters as shown in Fig. 7. It keeps comparable error performance at the MA stage as popular 4QAM (depicted in Fig. 8), however without the cardinality extension. The similar properties has been found also by unconventional 3HEX and 7HEX constellations.

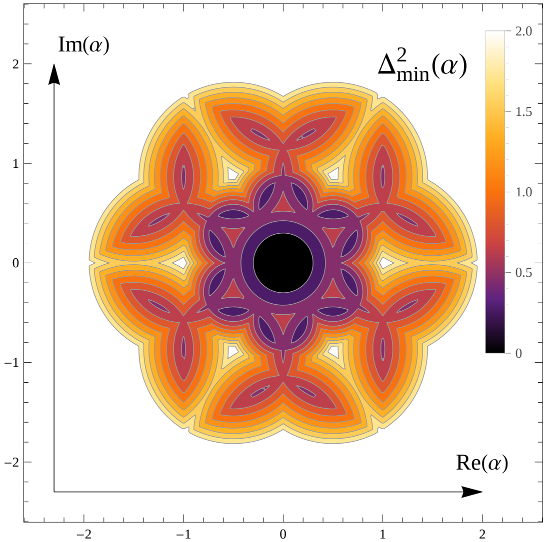

Figure 7: Parametric minimal distance of the adaptive WNC strategy using 4HEX.

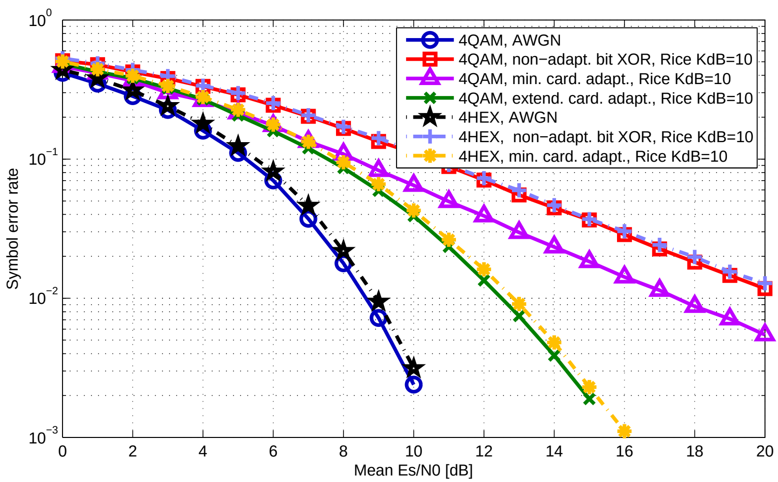

Figure 8: Network coded symbol error rate at the MA stage of the adaptive WNC strategy in Rician $K = 10\,\mathrm{dB}$ channel using 4QAM and 4HEX constellations.

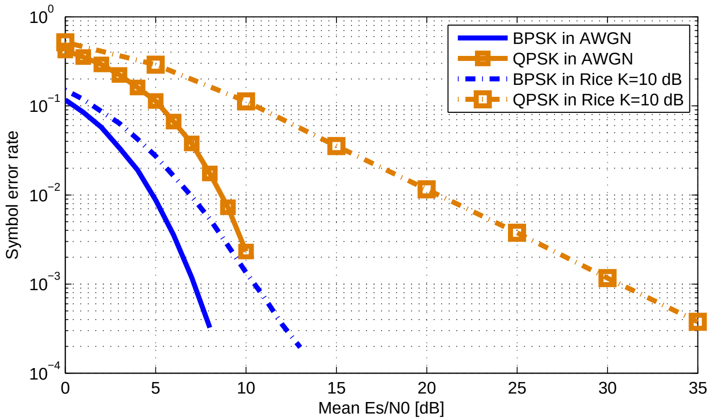

Figure 9: Symbol error rate of BPSK and QPSK in AWGN and Rice $K = 10\,\mathrm{dB}$ channel. Surprisingly, the performance of QPSK in the Rician channel (Rician factor $K = 10\,\mathrm{dB}$) is not a simple 3 dB shift of the BPSK performance as may suggest the performance in the AWGN channel, but it performs as it undergoes a stronger fading channel with smaller diversity order.

3.3 UMP Alphabets: UMP Multi-Dimensional Frequency Modulations and UMP General Multi-Dimensional Alphabets

Problem. WNC is a promising 2-way relaying strategy due to its potential to operate outside of the classical MAC capacity region when CSI is available at all network nodes. Assuming a practical scenario with CSI at the receiver side and no channel adaptation, there exist modulations and network coding functions for which even non-zero channel parameters (denoted as singular) cause zero minimal distance – significantly degrading its performance as shown in Fig 9. The reason of the QPSK diversity loss is well explained by analysis of parametric minimal distance

$$\Delta^2_{\min} = \min_{\mathcal{N}_{\mathrm{adapt}}(d_A, d_B) \neq \mathcal{N}_{\mathrm{adapt}}(d'_A, d'_B)} \left\| \Delta s_A^{(d_A, d'_A)} + \alpha \Delta s_B^{(d_B, d'_B)} \right\|^2, \tag{5}$$

where $\Delta s_A^{(d_A,d'_A)} = s_A^{(d_A)} - s_A{}^{(d'_A)}$, $\Delta s_B^{(d_B,d'_B)} = s_B^{(d_B)} - s_B^{(d'_B)}$ and $\alpha = {}^{h_B}/_{h_A}$. The minimal distances are depicted in Fig. 10 and 11. The minimal distance of BPSK has a parabolic type of parametrization which is zero only for $\alpha = 0$ (i.e. $h_B = 0$), while QPSK indicates zero minimal distances also for some non-zero parameter ratios α which we call *singular channel parameters*. They effectively represent additional deep fading which appears as a diversity-loss in the error curves in Fig 9.

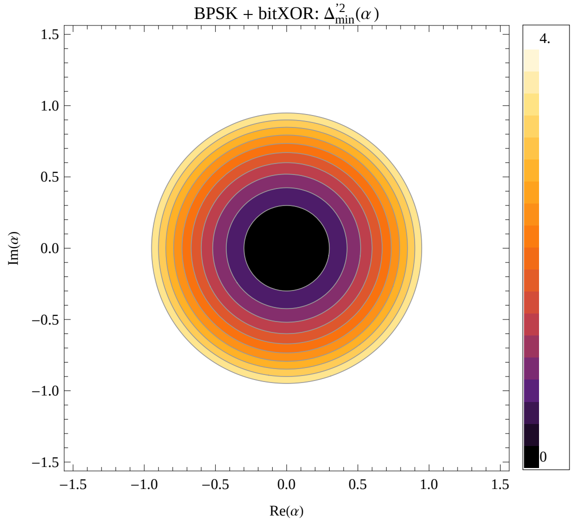

Figure 10: Minimal distance $\Delta'^2_{\text{min}}(\alpha)$ of BPSK showing no singularities.

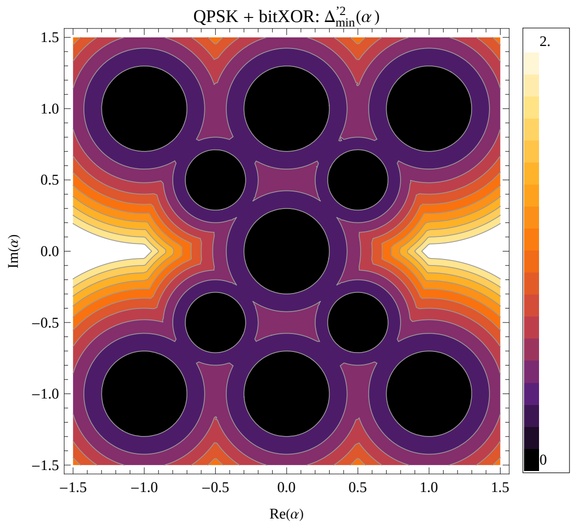

Figure 11: Minimal distance $\Delta'^2_{\text{min}}(\alpha)$ of QPSK showing singular parameters $\{\pm j, \pm 1 \pm j, \pm 1/2 \pm j/2\}$.

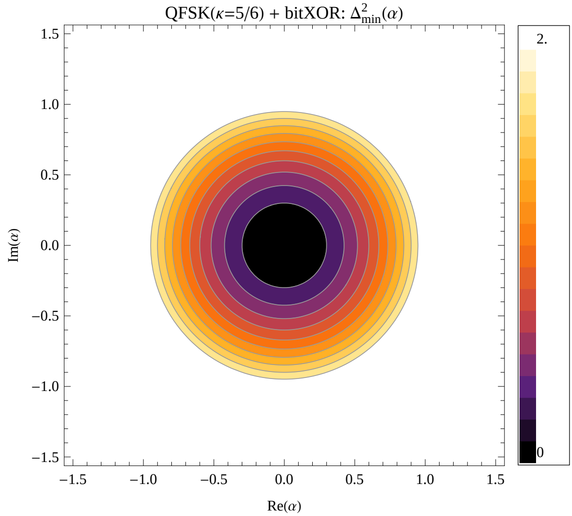

Figure 12: Minimal distance $\Delta'^2_{min}(\alpha)$ of UMP-QFSK with optimized $\kappa = 5/6$ showing no singularities.

Contribution (Design of UMP Frequency Modulations). We have proved that non-binary linear alphabets cannot avoid these singular parameters. Moreover, some network coding functions even imply its existence. We show that such a function is not a bit-wise XOR. We define robust alphabets avoiding all singularities and achieving the minimal distance upper-bound for all parameter values. We denote these alphabets as Uniformly Most Powerful (UMP). We have found that any binary, any non-binary orthogonal and any bi-orthogonal modulation is always UMP when combined with the bit-wise XOR function [21]. Apparently, non-binary UMP alphabets are multi-dimensional and so we optimize naturally multi-dimensional modulations such as Frequency Shift Keying (FSK) and full-response Continuous Phase Modulation (CPM) to yield UMP alphabets as shown in Fig. 12 and Fig. 13. In case of FSK, we optimise its modulation index κ and in case of full-response CPM, we optimise its frequency pulse shape $\beta(t)$. UMP alphabets provide considerable error performance gains as shown in Fig. 14, although they require always more bandwidth than in the P2P case. The extended-bandwidth alphabets may still have comparable benefits when we demand e.g. alphabets with the constant envelope property.

Contribution (Design of General UMP Alphabets). We formulate a UMP alphabet design as a bi-quadratically constrained linear optimisation problem on which the standard non-linear optimization methods are applied [22]. We design a list of

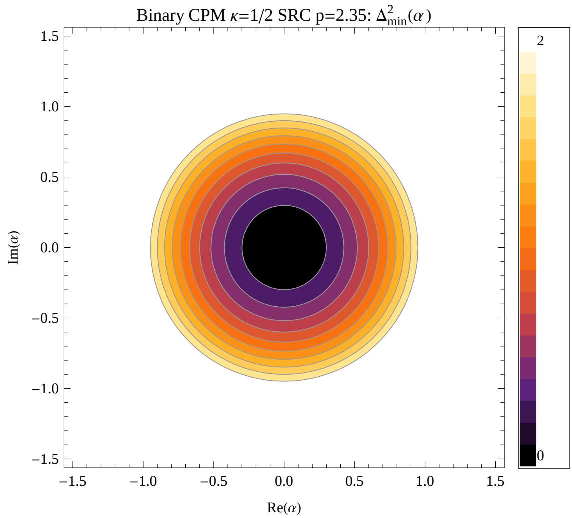

Figure 13: Minimal distance $\Delta'^2_{\min}(\alpha)$ of binary full-response CPM with $\kappa = 1/2$ and SRC phase pulse $\beta(t,p) = \frac{1}{2}\left(t - p\frac{\sin 2\pi t}{2\pi}\right)$ with $p \simeq 2.35$ showing no singularities.

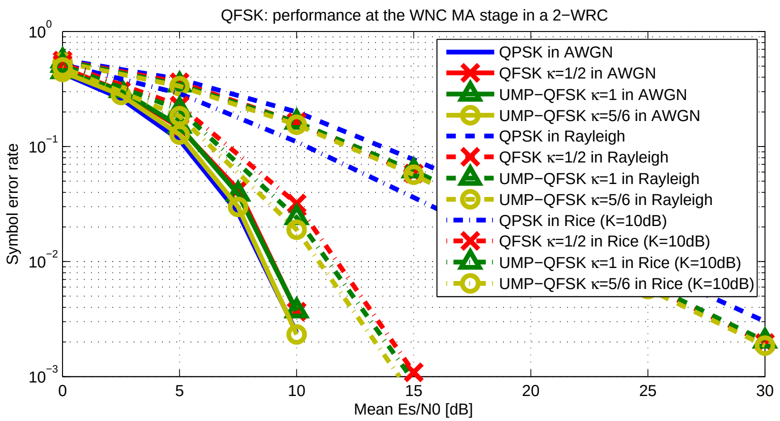

Figure 14: Symbol error rate in AWGN, Rayleigh/Rice fading channel for modulations QPSK, QFSK $\kappa = 1/2$, UMP-QFSK $\kappa = 1$ and UMP-QFSK $\kappa = 5/6$ showing the advantage of UMP alphabets (especially in Rician channels).

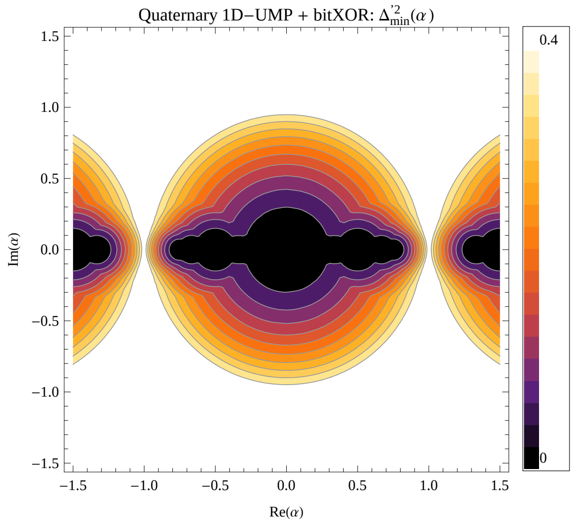

Figure 15: Minimal distance $\Delta'^2_{\min}$ of 4-ary 1-D weak UMP alphabet.

UMP multi-dimensional modulations for several alphabet cardinalities and dimensions. It seems that every found UMP alphabet has its rate-per-dimension upper-bounded by 1 bit/complex dimension (i.e. the rate-per-dimension of standard BPSK alphabet). Therefore, we propose a different type of alphabets called weak UMP alphabets which have unlimited rate-per-dimension but fulfil the UMP condition only for parameter ratios $|\alpha| = 1$ Minimal distance of 4-ary and 8-ary weak UMP alphabets

$$\mathscr{A}_{\text{4ary weak UMP}} = \sqrt{2/5}\{-2,-1,1,2\}, \tag{6}$$

$$\mathscr{A}_{\text{8ary weak UMP}} = \sqrt{1/91}\{-13,-11,-7,-5,5,7,11,13\} \tag{7}$$

depicted in Fig. 15 and Fig. 16 illustrate that all singularities do not occur for $|\alpha| = 1$ which implies robustness to the phase rotation and the Rician-type of fading. As expected and shown in Fig. 17, weak UMP alphabets perform several dB gain over canonical alphabets in the Rice channel.

3.4 Impact of Relative-Fading in WNC 2-Way Relaying with Diversity Reception

Problem. We identify two distinct sources of fading significantly degrading the performance of the WNC 2-way relaying with CSI at the receiver: Absolute-Fading (AF)

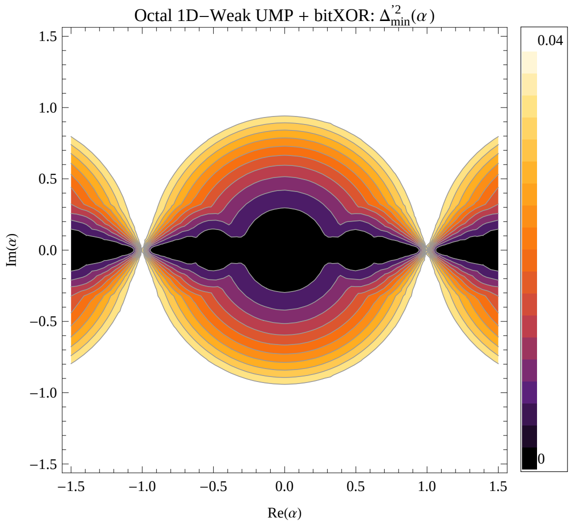

Figure 16: Minimal distance Δ'^2_{min} of 8-ary 1-D weak UMP alphabet.

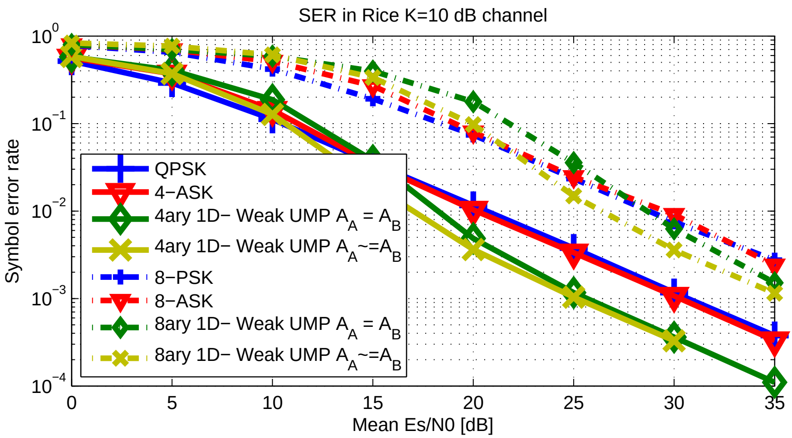

Figure 17: Symbol error rate of 4-ary and 8-ary Weak UMP alphabets in Rice $K = 10\,\text{dB}$ channel.

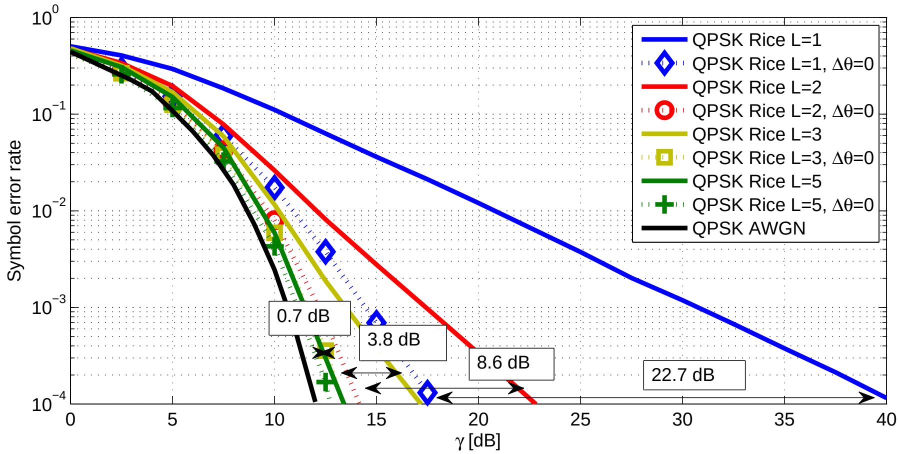

Figure 18: Symbol error rate of QPSK in a SIMO Rice channel.

and Relative-Fading (RF). AF corresponds to a standard small-scale fading of a wireless point-to-point channel when absolute values of the channel parameters are insufficiently strong. RF is a unique paradigm of WNC occurring when certain critical data symbols are transmitted and a ratio of channel parameters is close to certain critical values. The negative impact of RF is well demonstrated on QPSK performance in Rician channel as shown in Fig. 9.

Contribution. We show that the diversity reception techniques (essential to restrain AF) significantly suppresses RF as well [17]. We measure the impact of RF on the uncoded error performance (Fig. 18) and ergodic alphabet-constrained capacity (Fig. 19) of representative QPSK alphabet in a wireless Rician $K = 10\,\text{dB}$ channel. We conclude that RF is sufficiently suppressed by systems with a reasonable level of diversity which is typically assumed if only AF is present. In other words, RF is apparently not so detrimental in practice as may be concluded from an artificial model assuming uncoded performance with diversity $L = 1$.

3.5 Optimised Constellation-Prerotation for WNC Relaying in 3-Terminal 1-Relay Network

Problem. WNC method is an interference harnessing physical-layer concept combining network coding principles and broadcast nature of the wireless medium. Significant capacity gains of WNC were shown in a wireless 2-WRC. The extension of WNC to more complicated network topologies potentially offers even larger gains than in

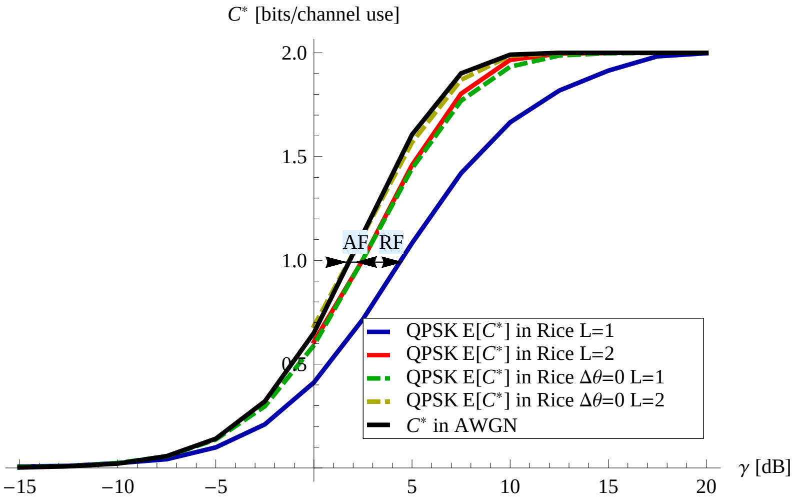

Figure 19: Alphabet-constrained capacity of QPSK in a SIMO Rice channel.

the 2-WRC. However, such an extension is generally non-trivial.

Contribution. We show that it is feasible to achieve additional considerable capacity gains in a 3-Terminal 1-Relay (3T-1R) network [30]. We focus on the constellation design for its uplink MA stage. The throughput maximisation is achieved by an optimised prerotation of carefully selected source constellations and corresponding network coding functions, effectively reducing the number of required MA stages. We propose ASK and modulo sum operation with $\pi/3$ prerotation (Fig. 20) which seems to be a favourable choice for 3T-1R since it keeps the same minimal distance as in the point-to-point case which results to the highest achievable rates as depicted in Fig. 21.

4 Conclusion

This thesis is concerned with a modulation design for the emerging wireless network architecture denoted as Wireless Network Coding (WNC). The modulation design topic is challenging and still sparsely investigated even in the simplest possible network scenario – a 2-Way Relay Channel (2-WRC) which is our most assumed scenario.

We see a great potential of our work considering affine-indexed lattice-constellations with modulo-sum relay decoding [26]. This contribution is rather theoretical one, but

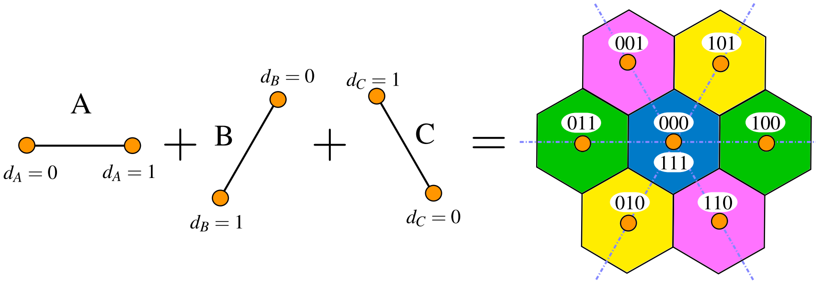

Figure 20: Composite constellation of three mutually $\pi/3$ prerotated BPSK modulations. The interfering signals at the point 0 in the signal space correspond to $[d_A, d_B, d_C] = [0,0,0]$ and $[1,1,1]$. Since these points lie in the region with identical $[d_{AB}, d_{BC}]$ (identical colour), it is not a source of errors.

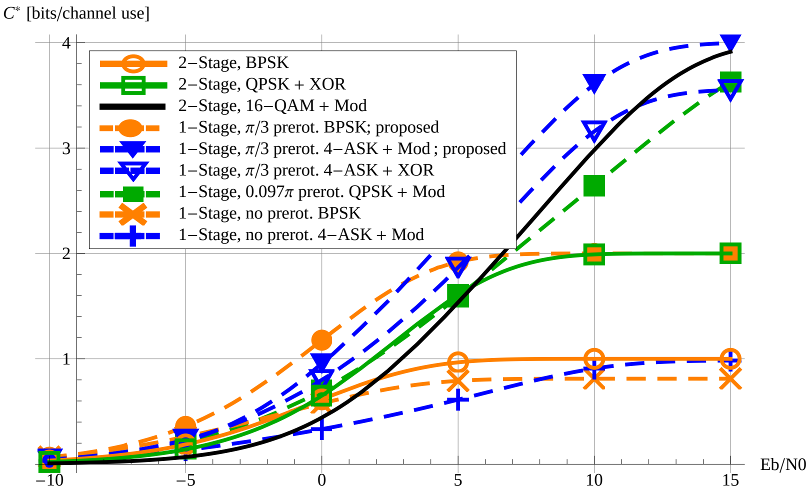

Figure 21: Alphabet-constrained capacity curves for several alphabets, network coding operations and mutual prerotations.

due to its simple analytical results, it provides a very useful designing tool. As far as we know, the modulations and network coding functions have been designed only numerically, particularly, by suboptimal greedy clustering algorithm [16] or by the NP hard algorithm filling a partially-filled Latin squares [9]. It can provide a solution only for reasonably large constellation alphabets. In our approach, we are always sure that the modulo-sum function is decodable at the relay as long as all lattice-constellations are affine-indexed. We believe that the lattice-constellations are naturally suitable for the modulo-sum decoding also in a general network topology because a superposition of any number of constellations taken from the same lattice is again a point in that lattice. It is very convenient that we can describe both domains mixed by WNC (i.e. the continuous signal space of physical-layer and the discrete integer space of network coding) by a common algebraic structure (by lattice-coordinate integer vectors).

We have successfully utilised the discovered properties of the affine-indexed lattice-constellations with modulo-sum relay decoding and based on them we find a 4HEX constellation suitable for adaptive WNC strategy using minimum-cardinality network coding adaptation [20]. Our proposed 4HEX constellation is probably the most practical contribution suitable for real implementation.

The considerable part of our work studies negative impact of relative-fading in wireless 2-WRC. We have found and proposed frequency multi-dimensional modulations robust to the relative-fading [21]. These modulations are beneficial especially when also the constant envelope property is demanded (e.g. in low-cost receivers or satellite communication). Our analysis of a general design of Uniformly Most Powerful (UMP) alphabets reveals that we cannot entirely eliminate the relative-fading by a suitable alphabet design when a spectral-efficiency is higher than 1 bit/dimension [22]. In that case, we can find alphabets (denoted as weak UMP) with better performance than standard QAM, PSK but still performing considerably worst than the utmost UMP scheme. The obstacle of the relative-fading seems to be practically solved when some level of diversity is assumed as shown in our paper [17]. Either the environment is so static that we can effort some form of adaptation eliminating the relative-fading or the environment is so dynamic that a rich source of temporal or frequency diversity is available. Our analysis shows that the relative-fading has significantly lower negative impact when enough diversity is provided which is usually fulfilled in practice.

WNC is both theoretically as well as practically quite well understood in the 2-WRC but the generalisation of WNC into a more complex network topology is still an open problem. We have identified another potential source of gains based on the optimisation of the multiple-access stage in a 3-terminal 1-relay network [30].

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5 Research Activities

My research activities were supported by the following grants on which I have actively participated. This activity includes regular project meetings, final deliverable publications and public presentations of our current contributions.

5.1 Projects

International Projects

- **FP7 ICT-2011-8/2009.1.1**: DIWINE - Dense Cooperative Wireless Cloud Network, 2013 – *present*
- **EU COST-IC1004**: Cooperative Radio Communications for Green Smart Environments, 2011 – *present*
- **FP7 ICT/STREP** (INFSO-ICT-248001): SAPHYRE — Sharing Physical Resources Mechanisms and Implementations for Wireless Networks, 2010 – 2012
- **FP7 ICT/STREP** (INFSO-ICT-215669): EUWB — Coexisting Short Range Radio by Advanced UWB Radio Technology, 2010 – 2011
- **EU COST 2100**: Pervasive Mobile & Ambient Wireless Communications, 2006 – 2010

Local Projects

- **Ministry of Education, Youth and Sports** (LD 12062): WNC and Signal Processing in Cooperative Distributed Multi-node Multi-source Communication Systems, 2012 – *present*
- **Grant Agency of the Czech Technical University in Prague** (SGS 13/083/-OHK3/1T/13): Wireless Network Coding based Multi-node Dense Networks, 2013 – *present*
- **Grant Agency of Czech Republic** (GACR 102/09/1624): Mobile radio communication systems with distributed, cooperative and MIMO processing, 2009 – 2012
- **Grant Agency of the Czech Technical University in Prague** (SGS 10/287/-OHK3/3T/13): Distributed, Cooperative and MIMO (Multiple-Input Multiple-Output) Physical Layer Processing in General Multi-Source Multi-Node Mobile Wireless Network, 2010 – 2012
- **Ministry of Education, Youth and Sports** (OC 188): Signal Processing and Air-Interface Technique for MIMO radio communication systems, 2007 – 2010

5.2 Publications

5.2.1 Publications Related to the PhD Thesis

Journals Ranked by Impact:

1. M. Hekrdla and J. Sykora. Hexagonal Constellations for Adaptive Physical-Layer Network Coding 2-Way Relaying. **In press IEEE Communication Letters**. 2013. **(MH 65%, JS 35%)**
2. M. Hekrdla and J. Sykora. Optimized Constellation Prerotation for 3-Terminal 1-Relay Network with Wireless Network Coding. In **IEEE Communication Letters**, pages 1200 - 1203, vol. 16, no. 8, August 2012. **(MH 65%, JS 35%)**
3. M. Hekrdla and J. Sykora. Design of Uniformly Most Powerful Alphabets for HDF 2-Way Relaying Employing Non-Linear Frequency Modulations. In **EURASIP Journal on Wireless Communications and Networking (J-WCN**), pages 1-18, no. 128/2011, October 2011. **(MH 65%, JS 35%)**

Refereed Journals:

1. M. Hekrdla. Numerically Optimized Uniformly Most Powerful Alphabets for Hierarchical-Decode-and-Forward Two-Way Relaying. In **Acta Polytechnica**, vol. 51, no. 5/ 2011. **(MH 100%)**

Conference Papers excerpt by WOS:

1. M. Hekrdla and J. Sykora. On Indexing of Lattice-Constellations for Wireless Network Coding with Modulo-Sum Decoding. In **Proc. IEEE Vehicular Technology Conf. (VTC)**, Dresden, Germany, 2013. **(MH 65%, JS 35%)**
2. M. Hekrdla and J. Sykora. Uniformly Most Powerful Alphabet for HDF Two-Way Relaying Designed by Non-linear Optimization Tools. In **IEEE International Symposium on Wireless Communication Systems (ISWCS)**, Aachen, Germany, 2011. **(MH 65%, JS 35%)**

Workshop Papers:

1. M. Hekrdla and J. Sykora. Lattice-Constellation Indexing for Wireless Network Coding 2-Way Relaying with Modulo-Sum Relay Decoding. In **COST IC1004 MCM**, Bristol, United Kingdom, 2012. **(MH 65%, JS 35%)**
2. M. Hekrdla and J. Sykora. Suppression of Relative-Fading by Diversity Reception in Wireless Network Coding 2-Way Relaying. In **COST IC1004 MCM**, Lyon, France, 2012. **(MH 65%, JS 35%)**

3. M. Hekrdla. Numerically Optimized Uniformly Most Powerful Alphabets for Hierarchical-Decode-and-Forward Two-Way Relaying. In **Poster 2011**, Prague, 2011. **(MH 100%) *** Dean award for the best paper in section Communications in Poster 2011 *****
4. M. Hekrdla and J. Sykora. Channel parameter invariant network coded FSK modulation for hierarchical decode and forward strategy in wireless 2-way relay channel. In **COST 2100 MCM**, Aalborg, Denmark, 2010. **(MH 70%, JS 30%)**
5. M. Hekrdla. On design of channel parameter invariant FSK in two-way relay channel. In **Poster 2010**, pages 1-7, Prague, May 2010. **(MH 100%)**
6. T. Uricar, J. Sykora and M. Hekrdla. Example design of multi-dimensional parameter-invariant hierarchical exclusive alphabet for layered HXC design in 2-WRC. In **COST 2100 MCM**, Athens, Greece, 2010. **(TU 50%, JS 30%, MH 20%)**

5.2.2 Other Publications

Refereed journals:

1. M. Hekrdla. Constellation space dimensionality reduced sub-optimal receiver for orthogonal STBC CPM modulation in MIMO channel. In **Acta Polytechnica**, vol. 49, no.2-3/ 2009. **(MH 100%)**

Conference Papers excerpt by WOS:

1. J. Sykora and M. Hekrdla. Determinant criterion optimizing linear subspace projector for burst orthogonal STC CPM modulation in MIMO channel. In **Proc. IEEE Vehicular Technology Conf. (VTC)**, Barcelona, Spain, 2009. **(JS 70%, MH 30%)**

Workshop Papers:

1. M. Hekrdla. Constellation space dimensionality reduced sub-optimal receiver for orthogonal STBC CPM modulation in MIMO channel. In **Poster 2009**, pages 1-6, Prague, 2009. **(MH 100%) *** Dean award for the paper in section Communications in Poster 2009 *****
2. M. Hekrdla and J. Sykora. CPM constellation subspace projection maximizing average minimal distance - sufficiency condition and comparison to PC analysis. In **COST 2100 MCM**, Valencia, Spain, 2009. **(MH 70%, JS 30%)**
3. J. Sykora and M. Hekrdla. Determinant maximizing and rank preserving waveform subspace linear projector for burst Alamouti STC MSK modulation. In **COST 2100 MCM**, Lille, France, 2008. **(JS 70%, MH 30%)**

5.3 Professional Service

I have participated as a technical program committee of the following conference:

- **IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)**, London, United Kingdom, 2013.

I have participated as a reviewer of the following conferences and local journal:

- **IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC),**
- **IEEE Global Telecommunications Conf. (GLOBECOM),**
- **IEEE Vehicular Technology Conf. (VTC),**
- **International Symposium on Wireless Communication Systems (ISWCS),**
- **Radioengineering.**

Summary

This thesis is focused on a modulation design for emerging Wireless Network Coding (WNC) relaying strategy respecting various practical and theoretical conditions. Our contributions concern three main topics.

The first topic is a constellation design for WNC in a simple AWGN 2-Way Relay Channel (2-WRC). The constellation design for WNC is generally challenging and sparsely investigated since the error performance of WNC processing at the relay (asymptotically determined by the minimal distance) does not depend only on a particular modulation alphabet but also on a network coding function used by the relay. Among other findings, we reveal the important property that *the constellations taken from a common lattice which are indexed in a suitable way* (indices form an arithmetic progression along each lattice dimension) *has the minimal distance equal to the minimal distance as in the point-to-point channel* (the important condition is that the modulo-sum network coding function is used by the relay). Based on this result, we have designed the constellations with the maximal possible minimal distance. The optimality of the proposed constellations are supported by error performance simulations as well as mutual information alphabet-constrained capacity curves.

The second topic targets a unique phenomenon of WNC in a wireless 2-WRC with perfect channel state information at the receiver – a new type of fading denoted as a *relative-fading*. Its name is derived by the fact that the relative-fading appears when a ratio of the channel gains is close to certain critical values no matter what are the actual

values of the channel gains. The well-known relay processing method (using popular 4QAM) eliminates the relative-fading by the extended-cardinality network coding adaptation (the cardinality extension is undesirable since it introduces redundancy decreasing the data rates). We design and propose *special constellations (e.g. 4HEX constellation) suitable for this method where the relative-fading is eliminated without the use of extended-cardinality adaptation*. As an alternative way how to combat the relative-fading, we introduce *constellations immune to the relative-fading without any adaptation* denoted as Uniformly Most Powerful (UMP). We identify some important features of the UMP systems like a) the use of bit-wise XOR network coding function is necessary but not a sufficient condition for the UMP condition, b) any orthogonal and bi-orthogonal alphabet is UMP and c) generally only multi-dimensional constellations can be UMP. We optimise naturally multi-dimensional modulations such as Frequency Shift Keying (FSK) and full-response Continuous Phase Modulation (CPM) to yield UMP alphabets. The found UMP alphabets provide considerable gains in a Rayleigh/Rice fading 2-WRC. Although they require always more bandwidth than in the point-to-point case, they serve well as a performance benchmark identifying the schemes which perform close to the utmost UMP case but do not require more bandwidth. In the next chapter, we use robust non-linear optimisation tools to design general multi-dimensional UMP constellations with the highest possible minimal distance for given available bandwidth. It turns out that the UMP condition cannot be apparently fulfilled when the constellation spectral-efficiency is higher than $1\,[\text{bits}/\text{dimension}]$. Therefore, we propose a different type of alphabets called weak UMP which possess an unlimited spectral-efficiency but fulfil the UMP condition only for parameter ratios with absolute value equal to 1. This implies robustness to the Rician-type of fading.

The third topic is focused on the widely unexplored area of *the extension of WNC to more complicated network topologies*. We show that it is feasible to achieve additional considerable capacity gains in a 3-terminal 1-relay network with the carefully optimised multiple-access stage. We propose the ASK modulation, the modulo-sum network coding function and the $\pi/3$ constellation prerotation for this scenario. It keeps the same minimal distance as in the point-to-point case providing the highest alphabet-constrained capacity performance among the other modulation, coding and prerotation types.

Anotace

Tématem mé disertační práce je návrh modulací pro nově vznikající a slibnou metodu komunikace v bezdrátových sítích zvanou Wireless Network Coding (WNC). Návrh modulací respektuje různorodé praktické a teoretické podmínky. Nové přínosy práce spadají do tří kategorií.

První část se zabývá návrhem konstelací pro WNC metodu v jednoduchém Additive White Gaussian Channel (AWGN) relay kanále. Návrh konstelací pro WNC metodu je obecně náročnější (a také méně prozkoumaný) než návrh konstelací pro komunikaci bod-bod (Point-to-Point (P2P)), protože kromě konstelace samotné ještě chybovost významným způsobem ovlivňuje výběr network coding funkce, kterou při detekci používá relay uzel. Kromě jiných vlastností systému se podařilo objevit důležitou skutečnost, že konstelace, které jsou vybrané z pravidelné mřížky (zvané lattice) a zároveň jejich indexy splňují jisté podmínky (indexy tvoří aritmetickou posloupnost v každé dimenzi lattice), pak mají minimální vzdálenost při dekódování network coding funkce rovnu minimální vzdálenosti konstelace samotné (důležitá podmínka platnosti tohoto tvrzení je předpoklad, že network coding funkce se dá popsat jako součet modulo). Na základě tohoto tvrzení se podařilo nalézt konstelace s maximální možnou minimální vzdáleností. Takovéto konstelace poté v porovnání se standardními konstelacemi vykazovaly nejmenší křivku chybovosti a největší křivku abecedou podmíněné kapacitě kanálu.

Druhé téma se týká unikátního jevu, který se vyskytuje u WNC metody v bezdrátovém dvoucestném relay kanále, a to je nový druh úniku (fading), který se nazývá Relativní Fading (RF). Jméno RF vychází ze skutečnosti, že k úniku dochází, když poměr koeficientů kanálu se blíží určitým kritickým hodnotám, bez ohledu na to, jak jsou jednotlivé koeficienty kanálu velké. Byla navržena relay strategie, která je schopná eliminovat RF tím, že adaptivně přizpůsobuje network coding funkci na relay uzlu. Jestliže tato metoda používá populární konstelaci 4QAM, pak mají network coding funkce větší kardinalitu než vstupní abeceda. Extenze kardinality je v tomto případě nežádoucí, protože představuje redundanci, která pak omezuje celkové dosažitelné datové rychlosti. V této oblasti se nám podařilo navrhnout speciální konstelace, které umožňují potlačit RF aniž by docházelo k extenzi kardinality. Další možností jak potlačit RF je návrh abecedy, který potlačuje RF aniž by se používala jakákoli forma adaptace. Takovéto abecedy jsme nazvali Uniformly Most Powerful (UMP) abecedy. Podařilo se nalézt několik důležitých vlastností UMP abeced jako: a) použití bit-wise XOR network coding funkce je nutná podmínka pro UMP abecedy, b) ortogonální a bi-ortogonální abecedy jsou UMP, c) nebinární abecedy mohou být UMP jen pokud jsou více dimenzionální. Proto jsme hledali UMP abecedy, které vychází z více dimenzionálních frekvenčních abeced jakými je Frequency Shift Keying (FSK) a Continuous Phase Modulation (CPM). Nalezené UMP abecedy vykazují

významný výkonový zisk na chybovostech v kanálech s Rayleigh-Rice únikem. Ačkoli UMP frekvenční abecedy vyžadují širší frekvenční pásmo (bandwidth), tak dobře poslouží jako horní odhad chybovosti, který umožní identifikaci abeced, které nevyžadují širší frekvenční pásmo, ale zároveň mají chybovost blízkou UMP maximu. V další části textu jsme se zabývali obecným návrhem UMP abeced, kde jsme pro návrh použili robustní nelineární numerické optimalizační algoritmy. Optimalizační úloha byla pak nalézt abecedu pro danou kardinalitu a počet dimenzí za podmínky UMP a maximální minimální vzdálenosti. Ukázalo se, že UMP podmínku zřejmě není možné splnit, pokud spektrální účinnost abecedy přesahuje 1 bit na komplexní dimenzi. Z tohoto důvodu jsme UMP kritérium změkčili, tak aby spektrální účinnost zůstala neomezená, ale UMP podmínka byla splněna jen pro absolutního hodnotu poměru kanálových koeficientů rovnou jedné, což implikuje dobré vlastnosti pro kanály se silnou Line-Of-Sight (LOS) složkou tj. kanály typu Rice.

Třetí téma se zaměřuje na široce neprobádanou úlohu zobecnění principů WNC pro komplikovanější sítě než je dvoucestný relay kanál. Podařilo se nám ukázat, že v komplikovanější síti se třemi terminály a jedním sdíleným relay uzlem metoda WNC nabízí nový další druh kapacitního zisku, který se neobjevuje ve dvoucestném relay kanále. Tento zisk souvisí s vhodnou volbou optimalizovaných abeced pro fázi s mnoho uživatelským přístupem (Multiple Access komunikace). Pro takovýto model doporučujeme použít vzájemně o $\pi/3$ před rotovanou ASK konstelaci, pro kterou minimální vzdálenost dekódování modulo-sum funkce je shodná s minimální vzdáleností abecedy samotné, což umožňuje mezi ostatními standartními modulacemi dosáhnout nejvyšší dosažitelné datové rychlosti.