CZECH TECHNICAL UNIVERSITY IN PRAGUE

DOCTORAL THESIS STATEMENT

CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Electrical Engineering

Department of Radioelectronics

Wireless (Physical Layer) Network Coding Design for Parametric Channels and Systems with Partial Hierarchical Side-Information

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

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Ph.D. study at the Department of Radioelectronics of the Faculty of Electrical Engineering of the CTU in Prague.

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Chairman of the Board for the Defence of the Doctoral Thesis
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Contents

1 Introduction

The main purpose of this thesis statement is to provide a general overview of my own research work as a PhD candidate at the Czech Technical University in Prague. The introductory section specifies the scope of the main thesis, it provides a list of my publications related to the scope of the thesis[1)] and it also summarizes my other research-related activities (e.g. grants etc.). The second section provides a brief overview of the current state-of-the-art in the two specific fields of Wireless (physical layer) Network Coding (WNC) research, namely the WNC processing in *parametric wireless channels* and WNC processing with *imperfect/partial side information*. Our original contributions to the research in these interesting WNC research areas form the core of the thesis. The most important results of our research activities in these fields are summarized in Section 3.

1.1 Aims and scope of the thesis

The scope of the thesis is basically three-fold:

1. It serves as a very brief overview of the basic PHY techniques and principles applicable in wireless cooperative networks
2. It introduces the fundamental principles of WNC processing in context of relevant scientific publications and provides some important references for a more in-depth study of the WNC-related problems
3. It provides a detailed overview of my up-to-date research work as a PhD candidate at the Czech Technical University in Prague and summarizes my original results on:
   (a) *WNC processing in parametric channel*
   (b) *WNC processing with imperfect/partial side information*

1.2 Publications related to the scope of the thesis

Journals ranked by impact:

- T. Uricar and J. Sykora, "Design criteria for hierarchical exclusive code with parameter-invariant decision regions for wireless 2-way relay channel," *EURASIP J. on Wireless Comm. and Netw.*, vol. 2010, pp. 1–13, 2010. ***(TU 60%, JS 40%; cited by [1])***
- T. Uricar and J. Sykora, "Non-uniform 2-slot constellations for bidirectional relaying in fading channels," *IEEE Commun. Lett.*, vol. 15, no. 8, pp. 795–797, 2011. ***(TU 65%, JS 35%)***
- T. Uricar and J. Sykora, "Non-uniform 2-slot constellations for relaying in butterfly network with imperfect side information," *IEEE Commun. Lett.*, vol. 16, no. 9, pp. 1369–1372, 2012. ***(TU 65%, JS 35%)***
- T. Uricar, B. Qian, J. Sykora and W.H. Mow, "Wireless (Physical Layer) Network Coding with Limited Side-Information: Maximal Sum-Rates in 5-Node Butterfly Network", *submitted for publication*, 2013. ***(TU 25%, QB 25%, JS 25%, WHM 25%)***

1) Author's contribution to the core publications are emphasized by the red colour.

Refereed journals:

- T. Uricar, “Parameter-invariant hierarchical eXclusive alphabet design for 2-WRC with HDF strategy,” *Acta Polytechnica*, vol. 50, no. 4, pp. 79–86, 2010. ***(TU 100%)***

Conference papers (indexed by WoS/Scopus):

- T. Uricar, B. Qian, J. Sykora, and W.H. Mow, “Superposition coding for wireless butterfly network with partial network side-information,” in *Proc. IEEE Wireless Commun. Network. Conf. (WCNC)*, (Shanghai, China), pp. 1–6, Apr. 2013. ***(TU 25%, QB 25%, JS 25%, WHM 25%)***
- T. Uricar, T. Hynek, P. Prochazka, and J. Sykora, “Wireless-aware network coding: Solving a puzzle in acyclic multi-stage cloud networks,” in *Proc. Int. Symp. of Wireless Communication Systems (ISWCS)*, (Ilmenau, Germany), pp. 612–616, Aug. 2013. ***(TU 25%, TH 25%, PP 25%, JS 25%)***

Other conference papers

- T. Uricar and J. Sykora, “Systematic design of hierarchical network code mapper for butterfly network relaying,” in *Proc. European Wireless Conf. (EW)*, (Poznan, Poland), pp. 1–8, Apr. 2012. ***(TU 65%, JS 35%)***
- T. Uricar, “Rateless codes and network coding in two-way wireless relay channels,” in *Proc. POSTER 2009 - 13th International Student Conference on Electrical Engineering*, (Prague, Czech Republic), pp. 1–6, May 2009. ***(TU 100%)***
- T. Uricar and J. Sykora, “Extended design criteria for hierarchical eXclusive code with pairwise parameter-invariant boundaries for wireless 2-way relay channel,” in *COST 2100 MCM*, (Vienna, Austria), pp. 1–8, Sept. 2009. TD-09-952. ***(TU 50%, JS 50%)***
- 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), pp. 1–8, Feb. 2010. TD-10-10088. ***(TU 50%, JS 30%, MH 20%)***
- T. Uricar, “Parameter-invariant hierarchical eXclusive alphabet design for 2-WRC with HDF strategy,” in *Proc. POSTER 2010 - 14th International Student Conference on Electrical Engineering*, (Prague, Czech Republic), pp. 1–8, May 2010. ***(TU 100%)***
- T. Uricar and J. Sykora, “Hierarchical eXclusive alphabet in parametric 2-WRC - Euclidean distance analysis and alphabet construction algorithm,” in *COST 2100 MCM*, (Aalborg, Denmark), pp. 1–9, June 2010. TD-10-11051. ***(TU 70%, JS 30%)***
- T. Uricar, “Constellation alphabets for hierarchical relaying in multiple-access relay channel,” in *Proc. POSTER 2011 - 15th International Student Conference on Electrical Engineering*, (Prague, Czech Republic), pp. 1–5, May 2011. ***(TU 100%)***
- T. Uricar and J. Sykora, “Hierarchical network code mapper design for adaptive relaying in butterfly network,” in *COST IC1004 MCM*, (Barcelona, Spain), pp. 1–9, Feb. 2012. TD-12-03048. ***(TU 65%, JS 35%)***
- T. Uricar and J. Sykora, “Non-uniform 2-slot constellations: Design algorithm and 2-way relay channel performance,” in *COST IC1004 MCM*, (Lyon, France), pp. 1–7, May 2012. TD-12-04041. ***(TU 65%, JS 35%)***

- T. Uricar, B. Qian, J. Sykora and W.H. Mow, "Wireless (Physical Layer) Network Coding in 5-node butterfly network: Superposition coding approach," in *COST IC1004 MCM*, (Malaga, Spain), pp. 1–9, Feb. 2013. TD-13-06026. ***(TU 25%, QB 25%, JS 25%, WHM 25%)***

1.3 Grants

International grants

- 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 Ultra-WideBand Radio Technology**, 2010-2011
- FP7-ICT-2011-8/ICT-2009.1.1: DIWINE — **Dense Cooperative Wireless Cloud Network**, 2013-2015
- EU COST 2100: **Pervasive Mobile & Ambient Wireless Communications**, 2006-2010
- EU COST IC1004: **Cooperative Radio Communications for Green Smart Environments**, 2011-2014

National/local grants

- Grant Agency of Czech Republic (GACR 102/09/1624): **Mobile radio communication systems with distributed, cooperative and MIMO processing**, 2009-2012
- Ministry of Education, Youth and Sports (OC 188): **Signal Processing and Air-Interface Technique for MIMO radio communication systems**, 2007-2010
- Ministry of Education, Youth and Sports (LD12062): **Wireless Network Coding and Processing in Cooperative and Distributed Multi-Terminal and Multi-Node Communications Systems**, 2012-2015
- Grant Agency of the Czech Technical University in Prague (SGS10/287/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
- Grant Agency of the Czech Technical University in Prague (SGS13/083/OHK3/1T/13): **Wireless Network Coding based Multi-node Dense Networks**, 2013

1.4 Awards and recognitions

- **Exemplary reviewer of the *IEEE Communications Letters*** (2012)
- **Dean award for the best paper in section *Communications***: (T. Uricar, "Parameter-invariant hierarchical eXclusive alphabet design for 2-WRC with HDF strategy," in *Proc. POSTER 2010 - 14th International Student Conference on Electrical Engineering*, (Prague, Czech Republic), pp. 1–8, May 2010)

1.5 International experience

- **Visiting postgraduate internship** at the Department of Electronic and Computer Engineering, School of Engineering, *Hong Kong University of Science and Technology* – HKUST (Oct. 2012 – Dec. 2012)

1.6 Other professional activities

Reviewer – Journals

- IEEE Communications Letters
- Radioengineering

Conference Technical Program Committee

- IEEE Student Conference on Research and Development (SCOReD), 2012
- IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 2013

Reviewer – Conferences

- IEEE Global Communications Conference (GlobeCom)
- IEEE Vehicular Technology Conference (VTC spring/fall)
- IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)
- International Conference on Computer Communications and Networks (ICCCN)
- International Symposium on Wireless Communications Systems (ISWCS)

2 Overview of the current state-of-the-art

2.1 Wireless (physical layer) Network Coding

During the last decade researchers over the world demonstrated that allowing a *non-orthogonal sharing* of channel resources (time/frequency/space) and implementation of *cooperative processing* directly at Physical Layer (PHY) can substantially improve the performance of wireless networks (see e.g. [2, 3]). *Wireless (physical layer) Network Coding (WNC)* [4, 5] represents one of the emerging PHY techniques, being capable to double the throughput in the wireless 2-Way Relay Channel (2-WRC), while having a potential to provide similar (or even larger) gains in more complicated wireless networks.

In 2-WRC (see Fig. 1), both nodes have knowledge about their own (previously sent) data (visualized as Hierarchical Side Information (HSI) [6, 7] in Fig. 1), which in turn allows to exploit this (inherently available) *side-information* to implement the WNC-based processing in the system. The original idea of *WNC relaying techniques* [8–10]) was inspired by the observation that it is unnecessary for the relay to decode the exact source information [9, 11–13], as it is not the final destination of the communication. This observation allows to select the source data rates *outside the relay MAC sum-rate region* and thus to improve markedly the spectral efficiency.

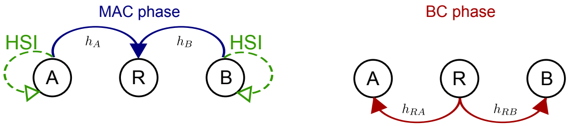

Figure 1: 2-WRC with HSI.

Two general WNC relaying strategies can be found in the literature (see e.g. [12]). In the first strategy the relay only amplifies the received analog signal and hence this strategy is called *Amplify and Forward* (AF) (see e.g. [8, 12, 14–16]) or Analog Network Coding [17]. The second strategy, whose principles were independently introduced in [9, 11] is usually called *Denoise and Forward* (DNF) [11], *Hierarchical Decode and Forward* (HDF) [7] or *Compute and Forward* (CaF) [5], although some less common names like *Partial Decoding* [18] can be found in the literature as well. A rigorous description of the HDF, DNF and CaF strategies can be found in the excellent papers [2, 4, 5, 7].

Although the fundamental idea of HDF processing is relatively straightforward, there is still a great number of research challenges which quickly arise when more complicated models of channels and networks are to be analysed. In the following section we briefly overview two specific open problems in the WNC research, namely the HDF processing in *parametric channels* and HDF processing with *partial/imperfect HSI*.

2.2 Selected open research problems in HDF processing

2.2.1 HDF in parametric channels

While the HDF strategies are already quite mature in the traditional AWGN channel, their performance in *fading channels* can be seriously degraded due to the inherent wireless channel *parametrization* (e.g. complex channel gain) [7, 10]. This performance degradation is a direct consequence of the undesired phase and amplitude offset between the source-relay channels [19, 20] and it was identified as a *major problem* of the WNC-based bi-directional relaying strategies already in [9, 11].

Channel coefficients in the MAC stage of HDF strategy determine how the two source signals overlap in the compound constellation (see an example in Fig. 2) observed at the relay node [10]. If the eXclusive mapping operation is kept fixed at the relay, some specific values of channel parameters can directly invoke *failures of the eXclusive law* [7, 21], resulting in a decreased performance of the overall system[2)].

There are several possible ways how to avoid this performance degradation in parametric HDF systems, including the phase pre-rotation (and power control) of both source node transmissions [10, 13, 22] and the adaptation of the relay output eXclusive mapping operation [10]. The design of adaptive relay mapping was originally proposed in the paper by

2)The detrimental effect of channel parametrization affects the performance of the system even if the relay has perfect estimates of source-relay channels available.

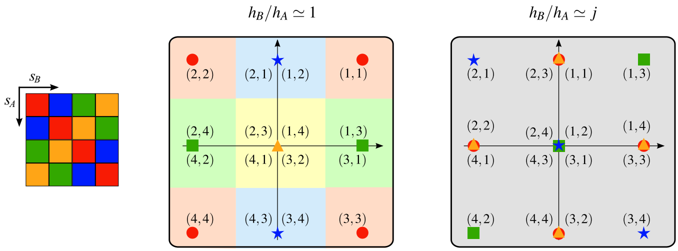

Figure 2: Impact of channel parametrization: 2-WRC with uncoded QPSK.

Koike et al. [20], where a brute-force search algorithm (identifying optimal mapping operation for a particular *channel parametrization*) was presented[3)].

Koike's design of adaptive mapping was revised later in [23], where a novel construction of adaptive mapping operation (based on the Latin squares) was introduced. The Latin squares-based design of adaptive mapping was further extended to the 2-WRC scenario with multiple source/relay node antennas [24]. An analytical treatment of the eXclusive law failure events (singular fade states) is presented in [21], where the fact that in Rician channels only some singular fade states contribute dominantly to the average Symbol Error Rate (SER) is emphasized. Even though most of the authors focus only on the *uncoded parametric 2-WRC*, there are already some results available for convolutionally-coded [25] and LDPC-coded [18] 2-WRC systems.

Unfortunately, the aforementioned techniques face several drawbacks, including a practical infeasibility of the (synchronized) multi-node transmission phase pre-rotation or a sensitivity to channel estimation errors of the adaptive solutions (inaccurate channel estimates results in an improper choice of the relay eXclusive symbol mapper) [26]. Due to these drawbacks, some authors try to attack the problem from a different angle. A simple multi-level coding scheme over QPSK modulation (allowing to adapt the relay decoding operation to actual channel conditions) is presented in [27]. However, this approach is limited only to the QPSK modulation scheme, and moreover, it avoids the performance degradation only for some specific values of channel parameters. In [28] the authors try to avoid the occurrence of *singular fade states* (eXclusive law failures) by the design of a distributed space-time coding technique (single antenna at both sources and relay node is assumed).

Another approach is based on the design of new modulation schemes which can essentially avoid (or at least decrease) the impact of channel parametrization on the system performance. Some novel *non-linear modulation schemes* for parametric HDF systems are introduced in [29,30]. The design of *linear modulation schemes* for parametric HDF systems represents one of the two major areas of our own research. The core of our results in this field has been already published in [31–38].

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3) The goal was to find the mapping which has the best Euclidean distance profile of the compound constellation received at the relay (unocoded QPSK modulation is assumed at both sources).

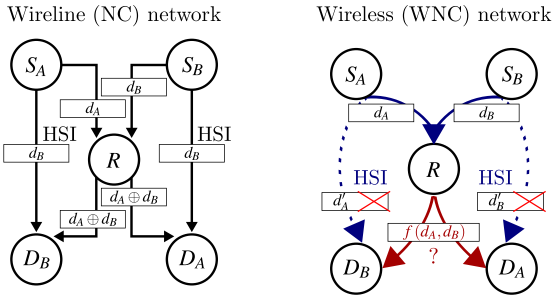

Figure 3: Wire-line vs. wireless 5-node Butterfly Network.

2.2.2 Partial HSI processing

Even though the principles of WNC profit from the specific nature of wireless channels (inherent combining of electromagnetic waves and its broadcast nature), they still remain partially grounded in the essentials of conventional Network Coding (NC) [39, 40].

In wire-line NC-based networks, the information packets are sent through orthogonal links with identical capacity and intermediate relay nodes combine the received packets before re-transmission (instead of purely relaying them) to boost the system performance. While this packet-based NC processing is natural in wire-line networks, in wireless networks the *inherent broadcast property* is to be exploited on channels with potentially *significantly different capacities*. Consequently, even though each node's transmission can be potentially overheard by several nodes in its vicinity, the same (perfect) information cannot be always retrieved by all these nodes due to the varying capacities of related wireless channels. The legacy of NC principles is hence partially broken in wireless (WNC-based) networks, yielding several significant and novel research challenges [6].

One example of this phenomenon can be demonstrated in a *5-node Butterfly Network* (BN) topology (see Fig. 3), where, similarly as in 2-WRC, HSI is required to decode the desired data from a common (NC/WNC-coded) data stream. While this information can be perfectly delivered to both destinations through orthogonal links in the wired BN, no dedicated orthogonal channels for transmission of HSI are required in the *Wireless BN (WBN)*, where both destinations can obtain HSI directly from the overheard source node transmission. Unfortunately, when channel conditions on such "overheard" HSI link(s) are not favourable, only *limited (partial/imperfect) HSI* could be received at destinations (due to an insufficient capacity of the corresponding wireless channels) and hence the WNC processing must be appropriately modified to cope with this situation [41–43].

To the best of our knowledge, there are still only very limited results considering the problem of *imperfect HSI processing*. As shown in [41], the performance of WBN with

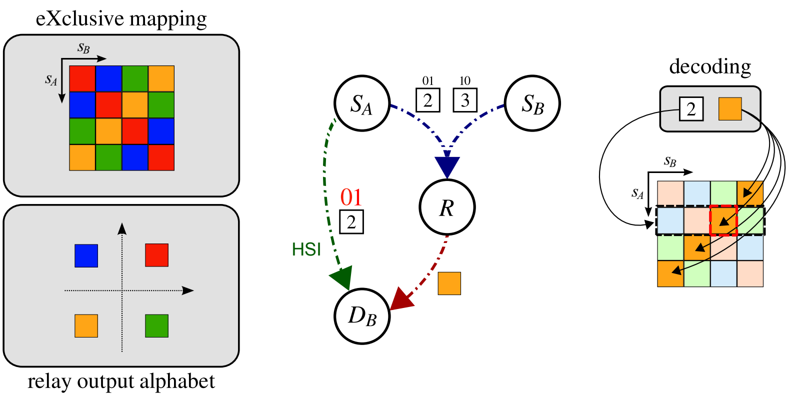

Figure 4: Perfect (full) HSI processing in WBN. Relay output has *minimal cardinality*.

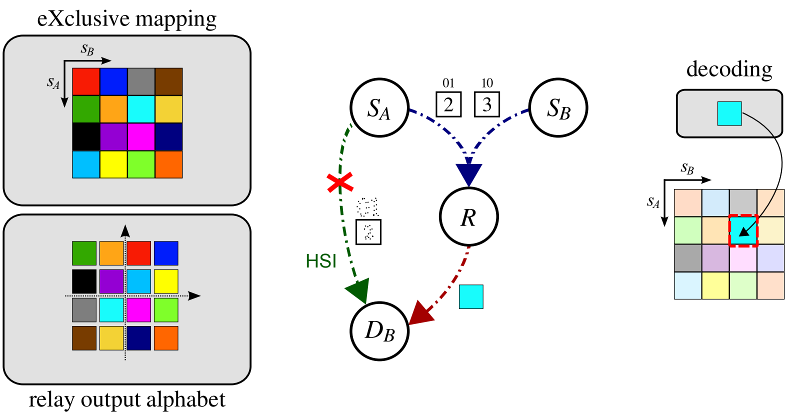

Figure 5: Zero HSI processing in WBN. Relay output has *full cardinality*.

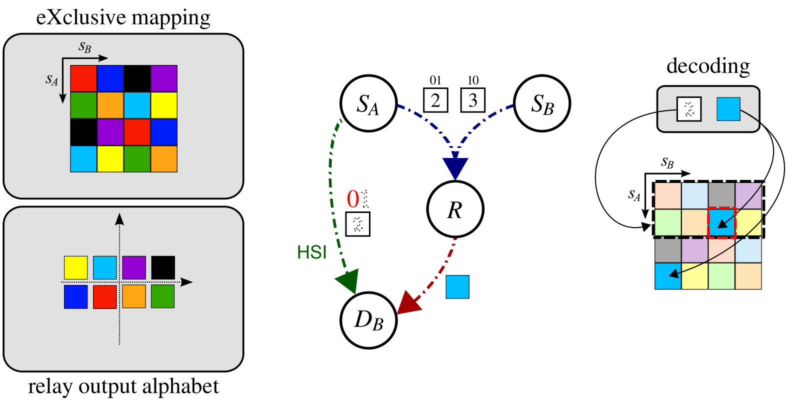

Figure 6: Partial HSI processing in WBN. Relay output has *extended cardinality*.

Algorithm 1 Higher-order codebook - Example design.

1. Choose $\mathbf{x},\mathbf{y} \in \mathbb{C}^2$ such that $\langle \mathbf{x};\mathbf{y}\rangle = 0$.
2. $\mathscr{A}_s^A = \{q^{i_A} \cdot \mathbf{x}\}_{i_A=0}^{M_s-1}; \quad q^{i_A} \in \mathbb{C}$
3. $\mathscr{A}_s^B = \{q^{i_B} \cdot \mathbf{y}\}_{i_B=0}^{M_s-1}; \quad q^{i_B} \in \mathbb{C}$

minimal cardinality HDF relaying[4)] is limited by the *HSI link capacity*. Fortunately, it is possible to overcome this limitation by employing the *extended cardinality* processing (see e.g. [42,43]). Even though an increased cardinality of the relay output is required in this case, only *partial HSI* becomes sufficient to guarantee a successful decoding at both destinations. As shown in [43], this approach can outperform (for some specific channel conditions) the conventional HDF relaying with minimal cardinality.

The basic principles of HDF processing in the *uncoded WBN system* with QPSK source alphabet constellation are summarized in Figs. 4 (perfect/full HSI), 5 (no HSI) and 6 (partial HSI). The decoding process is visualized only for destination D_B (for the sake of clarity).

The analysis of *partial/imperfect HSI* processing represents one of the two major areas of our own research. The core of our results in this field has been already published in [43–47], [6] has been submitted for publication.

[4)]The cardinality of the relay output alphabet $\mathscr{A}_s^R$ is given by $\left|\mathscr{A}_s^R\right| = \max\left\{\left|\mathscr{A}_s^A\right|, \left|\mathscr{A}_s^B\right|\right\}$ in the minimal cardinality HDF.

Algorithm 2 NuT constellation alphabet design.

1. Pick a base alphabet $\mathscr{A}_s$.
2. Choose a power scaling factor $s_f \in (0,2)$.
3. Source A alphabet: $\mathscr{A}_s^A = [\sqrt{s_f}\mathscr{A}_s, \sqrt{2-s_f}\mathscr{A}_s]$.
4. Source B alphabet: $\mathscr{A}_s^B = [\sqrt{2-s_f}\mathscr{A}_s, \sqrt{s_f}\mathscr{A}_s]$.

3 Summary of contributions

In the following sections we briefly summarize our most relevant original research results in the two specific research areas discussed in the previous section. Due to the limited extent of this thesis statement we introduce only the basic ideas behind our work and, where appropriate, we supplement the description with some relevant Figures, Tables or Algorithms.

3.1 HDF in parametric channels

In this section we overview our contributions to the design of *linear modulation schemes* for parametric HDF systems. The first attempts to design constellations resistant to the eXclusive law failure events (see [31, 33, 36]) have led only to multi-dimensional constellations in $\mathbb{C}^2$. An example design algorithm (see Algorithm 1) from [36] allows to design source constellations which have the Euclidean distance performance highly resistant to the effects of channel parametrization (see a comparison with conventional linear modulation constellations in Figs. 7, 8, 9).

Unfortunately, even though the design of multi-dimensional constellations in $\mathbb{C}^2$ appears to be the most simple solution, the increased alphabet cardinality is inherently accompanied with a reduction of achievable throughput. Naturally, the goal of the follow-up work was to find a suitable constellations in $\mathbb{C}^1$ to avoid this inherent drawback of multi-dimensional constellations. However, based on the analysis of (squared) *Euclidean distance properties* of hierarchical symbols, we have proved that only binary constellations can fully avoid the violation of the eXclusive law (for arbitrary parametrization), if the constellation dimensionality is limited to $\mathbb{C}^1$ (see [36] for details).

Even though the occurrence of eXclusive law failures cannot be prevented in case of conventional modulation schemes in $\mathbb{C}^1$ (excepting the binary alphabets), it can be shown that in *Rician fading channels* it is possible to at least suppress this harmful behaviour of channel parametrization by a design of novel 2-slot constellation alphabets. The proposed *Non-uniform 2-slot (NuT)* alphabets [32, 38] (see Algorithm 2) are robust to channel parametrization effects in Rician channels, outperforming the traditional linear modulation schemes without sacrificing the overall system throughput.

The NuT constellation (NuT $(\mathscr{A}_s; s_f)$) is generally a 2-source alphabet $(\mathscr{A}_s^A, \mathscr{A}_s^B)$, where the power is re-allocated *non-uniformly* among the 2-slots of the NuT super-symbol. The non-uniform allocation of power allows to *trade-off the vulnerability to eXclusive law failures with the alphabet distance properties*, resulting in an improved performance in the medium to high SNR region. A comparison of the overall Euclidean distance performance and SER

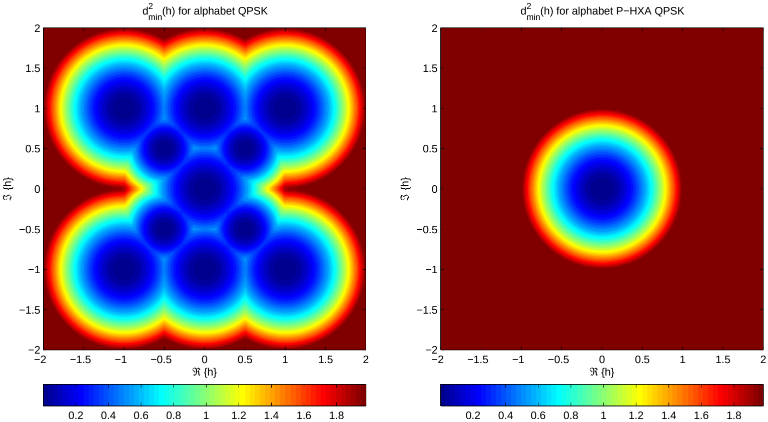

Figure 7: Minimum hierarchical distance performance for QPSK and 4-ary example alphabet.

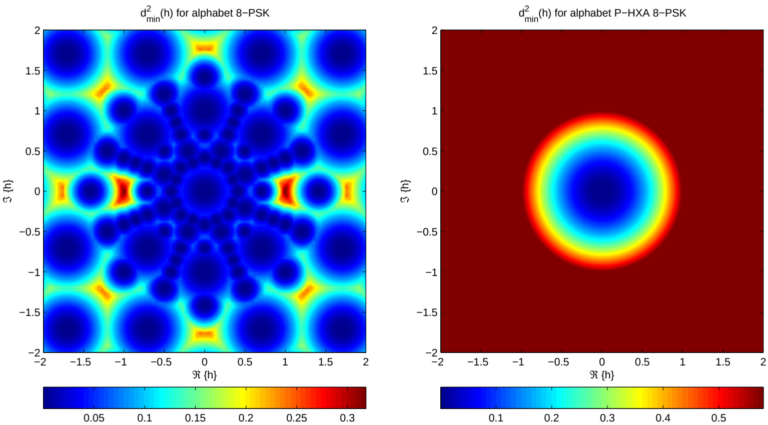

Figure 8: Minimum hierarchical distance performance for 8-PSK and 8-ary example alphabet.

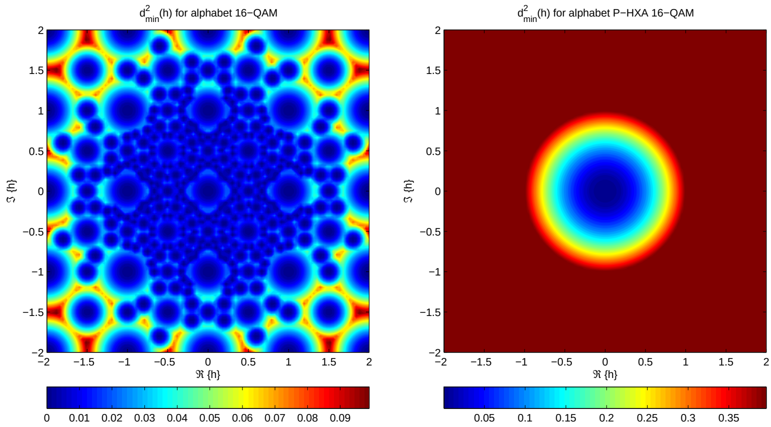

Figure 9: Minimum hierarchical distance performance for 16-QAM and 16-ary example alphabet.

performance of the proposed NuT alphabets (with variable s_f) and some conventional linear modulation constellations is in Figs. 10, 11, 12, 13.

Remarkable SNR gains of NuT alphabets ($\sim 10-15$dB in Fig. 12, $\sim 5-7$dB in Fig. 13) have been observed in moderately high SNR regions. Note again, that the overall system throughput is not sacrificed, since the cardinality of the NuT alphabet is $\left|\mathscr{A}_s^A\right| = \left|\mathscr{A}_s^B\right| = M^2$ for $|\mathscr{A}_s| = M$ (see Algorithm 2) and hence the promising parametric performance of NuT alphabets is not accompanied with a reduction of achievable throughput.

3.2 Partial HSI processing

In this section we summarize our original contributions in the field of *partial/imperfect HSI processing* in WNC networks. A Superposition Coding (SC) based scheme for relaying in WBN was introduced in [46, 47] as a scheme capable to adapt to arbitrary amount of HSI. The main idea of the SC-based scheme (see Fig. 14) is based on the splitting of source information into two separate data streams (and optimization of rate and power allocated to each particular stream), which in turn allows to adapt the WBN processing to the actual channel conditions (and hence the available HSI at destinations). As shown in Fig. 15, the SC-based scheme is capable to provide non-zero two-way rate for an arbitrary quality of HSI channels (given by the SNR of HSI channels γ_2).

In [6], the state-of-the-art bi-directional 3-step (Decode and Forward – DF) and 2-step (Amplify and Forward – AF, Joint Decode and Forward – JDF and Hierarchical Decode and Forward – HDF) relaying strategies were modified to guarantee that successful decoding at

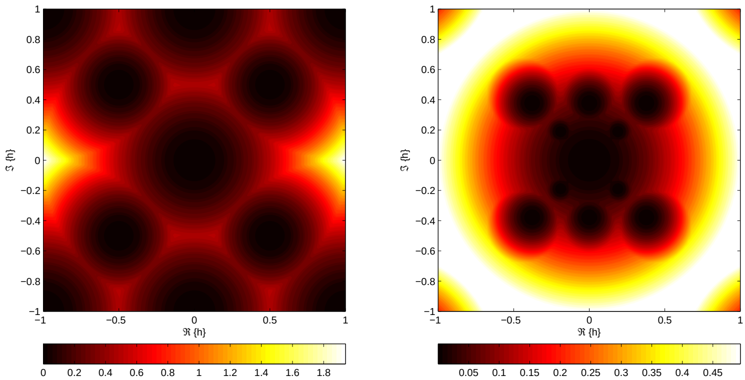

Figure 10: Minimum hierarchical distance $d^2_{\min}(h)$ of NuT(QPSK;1) and NuT(QPSK;0.25) alphabets as a function of channel parameter $h \in \mathbb{C}$.

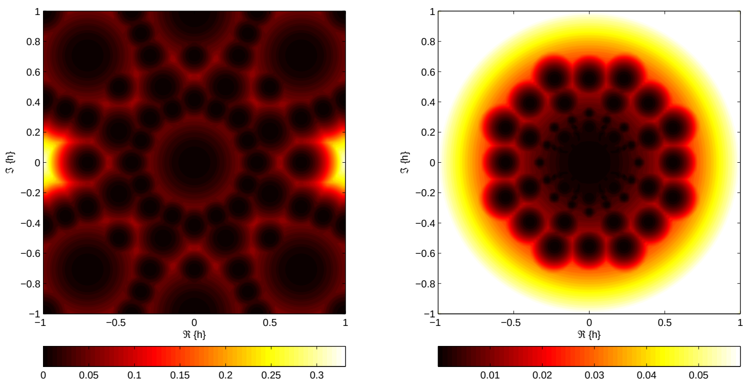

Figure 11: Minimum hierarchical distance $d^2_{\min}(h)$ of NuT(8PSK;1) and NuT(8PSK;0.1) alphabets as a function of channel parameter $h \in \mathbb{C}$.

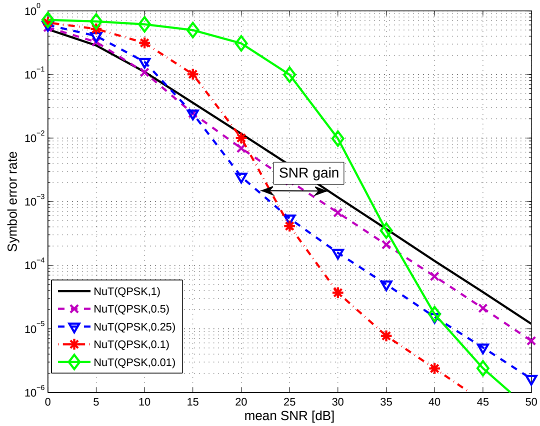

Figure 12: H-SER of NuT$(\text{QPSK};1)$ and NuT$\left(\text{QPSK};s_f\right)$ alphabets. It is obvious that a crucial part of the alphabet design (Algorithm 2) is a choice of the scaling factor s_f.

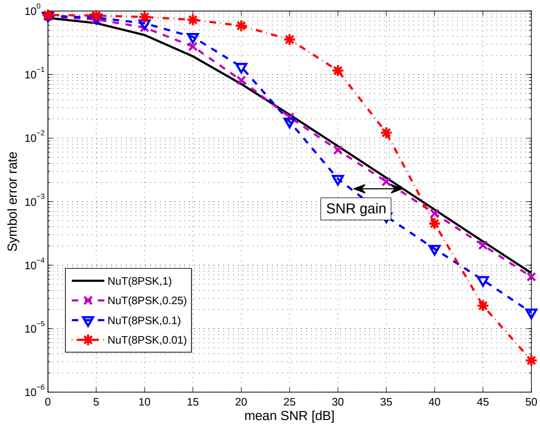

Figure 13: H-SER of NuT$(\text{8PSK};1)$ and NuT$\left(\text{8PSK};s_f\right)$ alphabets. It is obvious that the choice of the scaling factor s_f is again a crucial part of the alphabet design (Algorithm 2).

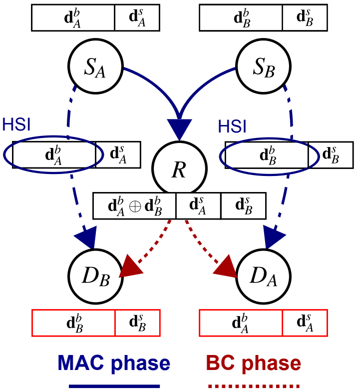

Figure 14: Principle of SC-based relaying in WBN.

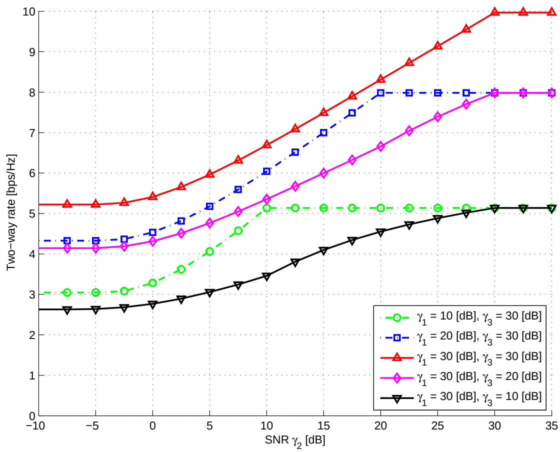

Figure 15: Comparison of maximal 2-way rates of the SC scheme (as a function of the HSI channel quality γ_2).

DF	$R_{\text{sum}}^{DF} = \begin{cases} \frac{C(\gamma_1)C(\gamma_3)}{C(\gamma_3)+0.5C(\gamma_1)}, & \gamma_2 \geq \gamma_1 \\ \max\left[\frac{C(\gamma_2)C(\gamma_3)}{C(\gamma_3)+0.5C(\gamma_2)}; \frac{C(\gamma_1)C(\gamma_3)}{C(\gamma_3)+C(\gamma_1)-0.5C(\gamma_2)}\right], & \gamma_2 < \gamma_1 \end{cases}$
AF	$R_{\text{sum}}^{AF} = \begin{cases} C\left(\frac{\gamma_1\gamma_3}{2\gamma_1+\gamma_3+1}\right), & \gamma_2 \geq \frac{\gamma_1\gamma_3}{2\gamma_1+\gamma_3+1} \\ C(\gamma_2), & \frac{\gamma_1\gamma_3}{2\gamma_1+\gamma_1\gamma_3+\gamma_3+1} \leq \gamma_2 < \frac{\gamma_1\gamma_3}{2\gamma_1+\gamma_3+1} \\ C\left(\frac{\gamma_1\gamma_3}{2\gamma_1+\gamma_1\gamma_3+\gamma_3+1}\right), & \gamma_2 < \frac{\gamma_1\gamma_3}{2\gamma_1+\gamma_1\gamma_3+\gamma_3+1} \end{cases}$
JDF	$R_{\text{sum}}^{JDF} = \begin{cases} \frac{C(2\gamma_1)C(\gamma_3)}{C(\gamma_3)+0.5C(2\gamma_1)}, & C(\gamma_2) \geq \frac{1}{2}C(2\gamma_1) \\ \max\left[\frac{2C(\gamma_2)C(\gamma_3)}{C(\gamma_3)+C(\gamma_2)}; \frac{C(2\gamma_1)C(\gamma_3)}{C(\gamma_3)+C(2\gamma_1)-C(\gamma_2)}\right], & C(\gamma_2) < \frac{1}{2}C(2\gamma_1) \end{cases}$
HDF	$R_{\text{sum}}^{HDF} = \begin{cases} \frac{2C(\gamma_1)C(\gamma_3)}{C(\gamma_1)+C(\gamma_3)}, & C(\gamma_2) \geq C(\gamma_1) \\ \frac{2C(\gamma_2)C(\gamma_3)}{C(\gamma_2)+C(\gamma_3)}, & \frac{1}{2}C(2\gamma_1) \leq C(\gamma_2) < C(\gamma_1) \\ \max\left[\frac{2C(\gamma_2)C(\gamma_3)}{C(\gamma_3)+C(\gamma_2)}; \frac{C(2\gamma_1)C(\gamma_3)}{C(\gamma_3)+C(2\gamma_1)-C(\gamma_2)}\right], & C(\gamma_2) < \frac{1}{2}C(2\gamma_1) \end{cases}$

Table 1: Maximal two-way rates of relaying strategies in WBN (symmetric channel SNRs: γ_1 (source$\to$ relay), γ_2 (HSI channel), γ_3 (relay$\to$ destination)).

extended cardinality map	minimal cardinality map
$\left[\begin{array}{cc\|cc} 0 & 2 & 4 & 6 \\ 1 & 3 & 5 & 7 \\ \hline 4 & 6 & 0 & 2 \\ 5 & 7 & 1 & 3 \end{array}\right]$	$\left[\begin{array}{c\|c\|c\|c} 0 & 1 & 2 & 3 \\ \hline 1 & 0 & 3 & 2 \\ \hline 2 & 3 & 0 & 1 \\ \hline 3 & 2 & 1 & 0 \end{array}\right]$

Table 2: eXclusive mapping operations (matrix representation) for sources with 4-ary alphabets.

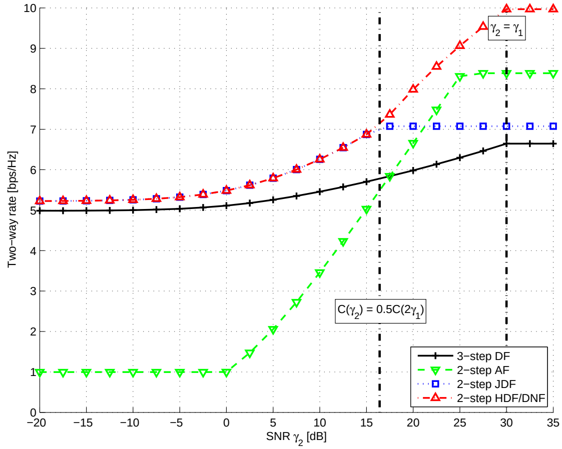

Figure 16: Comparison of the maximal sum-rates of DF, AF, JDF and HDF strategies in WBN ($\gamma_1 = 30$ dB, $\gamma_3 = 30$ dB).

destinations is made possible even if HSI is only partially available. We have shown that in all the strategies the so-called *partial HSI processing* usually provides a better sum-rate than the straightforward solution, where the availability of perfect HSI is secured by a decrease of the source transmission rate. The performance of all the modified strategies was compared in an information-theoretic investigation and the (modified) HDF strategy was found to provide the *best performance* among all the WNC strategies (even under the partial HSI condition). The results of this analysis are summarized in Table 1. An example comparison of the sum-rate performance of all the strategies (for a particular channel SNRs) is provided in Fig. 16.

One of the crucial steps in the design of particular HDF processing for partial HSI systems is the choice of a suitable eXclusive mapping operation at the relay. As noted in [43,44], the unreliable transmission of HSI can be overcome by increasing the cardinality of the relay output [7]. A design of eXclusive mapping operation is quite simple for the *minimal mapping* (perfect HSI assumption) operation, where it is usually given by a simple bit-wise XOR operation. However, in case of the *extended cardinality mapping* (see Fig. 6), a suitable eXclusive mapper must respect the amount of HSI at destinations to maximize the system throughput. A systematic approach to the design of a *set of eXclusive relay output mappers* for WBN was introduced in [43]. An example of suitable eXclusive mappers designed according to the Algorithm from [43] is presented in Table 2. As shown in Figure. 17, a feasible eXclusive mapping (with extended cardinality) guarantees that the BC phase capacity is no longer limited by the HSI link capacity.

The capability to design suitable eXclusive mappers for arbitrary quality of HSI channels

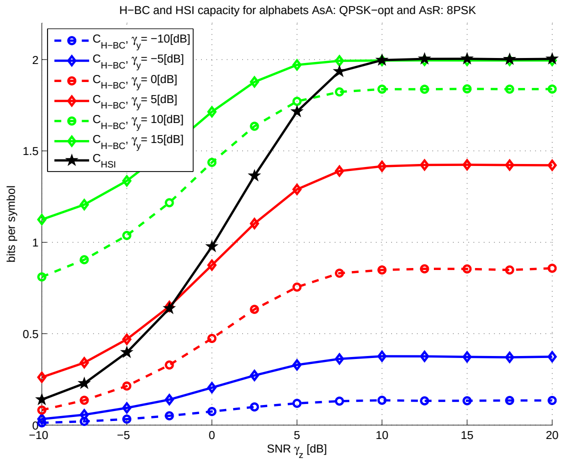

Figure 17: BC phase alphabet constrained capacity and capacity of the HSI link (extended mapping, $\mathscr{A}_s = \text{QPSK}$, $\mathscr{A}_s^R = \text{8PSK}$).

has enabled the possibility to exploit the promising parametric channel performance of *NuT source alphabets* in the WBN systems [45]. While the favourable parametric MAC channel performance of NuT alphabets induces a *lower error floor* in both minimal (Fig. 18) and extended (Fig. 19) cardinality relaying, the increased reliability of *partial one-slot HSI* transforms into an *additional SNR gain* in the extended cardinality case (Fig. 19), where the worse aggregate HSI performance is compensated by an increased cardinality of the relay output alphabet. The basic principle of extended cardinality relaying with NuT constellations in WBN is depicted in Fig. 20.

4 Conclusions

In this thesis statement I have summarized my own research work as a PhD candidate at the Czech Technical University in Prague. The scope of the thesis was specified in the introductory section, together with a list of my core publications related to the scope of the thesis and summary of my other research-related activities. Then, the current state-of-the-art in the two specific fields of WNC techniques research, namely the *WNC processing in parametric wireless channels* and *WNC processing with imperfect/partial side information* was discussed in section 2. Our original contributions to the research in these two specific WNC research areas, which form the core of the thesis, were summarized in Section 3.

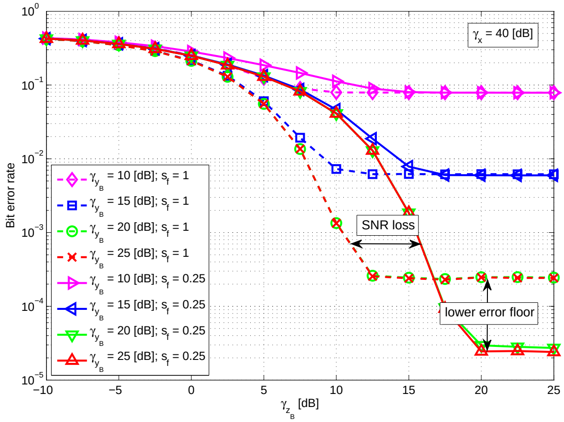

Figure 18: Minimal cardinality relaying ($M_R = 16$, $\mathscr{A}_s^R = 16\text{QAM}$), destination D_B BER (constellations $\text{NuT}(\text{QPSK};1)$ & $\text{NuT}(\text{QPSK};0.25)$).

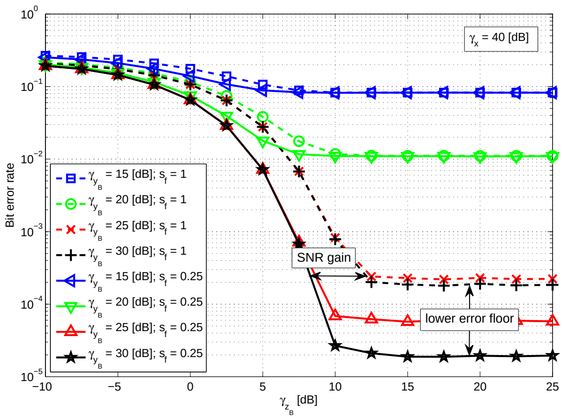

Figure 19: Extended cardinality relaying ($M_R = 64$, $\mathscr{A}_s^R = 64\text{QAM}$), destination D_B BER (constellations $\text{NuT}(\text{QPSK};1)$ & $\text{NuT}(\text{QPSK};0.25)$).

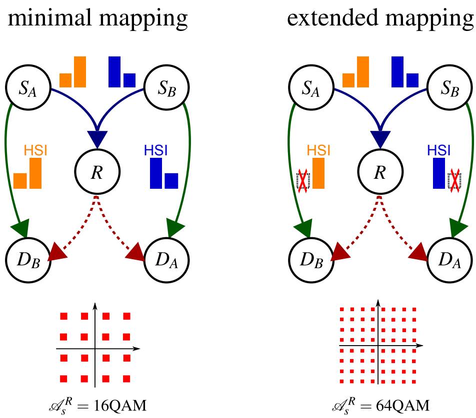

Figure 20: WBN with NuT source constellations and extended cardinality relaying.

References

[1] J. Jalden and T. J. Oechtering, "Distributed Bayesian detection for the butterfly network," in *Proc. IEEE Workshop on Signal Processing Advances in Wireless Communications*, pp. 61–65, 2013.

[2] B. Nazer and M. Gastpar, "Reliable physical layer network coding," *Proc. IEEE*, vol. 99, no. 3, pp. 438–460, 2011.

[3] A. Goldsmith, M. Effros, R. Koetter, M. Médard, A. Ozdaglar, and L. Zheng, "Beyond Shannon: The quest for fundamental performance limits of wireless ad hoc networks," *IEEE Communications Mag.*, vol. 49, pp. 195–205, May 2011.

[4] S. Zhang, S.-C. Liew, and L. Lu, "Physical-layer network coding: Tutorial, survey, and beyond," *Physical Communication*, vol. 2012, pp. 1–39, 2012. doi:10.1016/j.phycom.2012.05.002.

[5] B. Nazer and M. Gastpar, "Compute-and-forward: Harnessing interference through structured codes," *IEEE Trans. Inf. Theory*, vol. 57, no. 10, pp. 6463–6486, 2011.

[6] T. Uricar, B. Qian, J. Sykora, and W. H. Mow, "Wireless (physical layer) network coding with limited side-information: Maximal sum-rates in 5-node butterfly network," Submitted for publication.

[7] J. Sykora and A. Burr, "Layered design of hierarchical exclusive codebook and its capacity regions for HDF strategy in parametric wireless 2-WRC," *IEEE Trans. Veh. Technol.*, vol. 60, pp. 3241–3252, Sept. 2011.

[8] P. Popovski and H. Yomo, "Physical network coding in two-way wireless realy channels," in *Proc. IEEE Internat. Conf. on Commun. (ICC)*, 2007.

[9] S. Zhang, S.-C. Liew, and P. P. Lam, "Hot topic: Physical layer network coding," in

Proc. Annual International Conference on Mobile Computing and Networking (MobiCom), (Los Angeles, CA, USA), 2006.

[10] T. Koike-Akino, P. Popovski, and V. Tarokh, "Optimized constellations for two-way wireless relaying with physical network coding," *IEEE J. Sel. Areas Commun.*, vol. 27, pp. 773–787, June 2009.

[11] P. Popovski and H. Yomo, "The anti-packets can increase the achievable throughput of a wireless multi-hop network," in *Proc. IEEE Internat. Conf. on Commun. (ICC)*, 2006.

[12] S. Zhang, S.-C. Liew, and L. Lu, "Physical layer network coding schemes over finite and infinite fields," in *Proc. IEEE Global Telecommunications Conf. (GlobeCom)*, 2008.

[13] S. Zhang and S.-C. Liew, "Applying physical-layer network coding in wireless networks," *EURASIP J. on Wireless Comm. and Netw.*, vol. 2010, pp. 1–12, 2010. doi:10.1155/2010/870268.

[14] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, 2004.

[15] P. Popovski and H. Yomo, "Bi-directional amplification of throughput in a wireless multi-hop network," in *Proc. IEEE Vehicular Technology Conf. (VTC)*, Spring 2006.

[16] B. Rankov and A. Wittneben, "Spectral efficient protocols for half-duplex fading relay channels," *IEEE J. Sel. Areas Commun.*, vol. SAC-25, pp. 379–389, Feb. 2007.

[17] S. Katti, S. Gollakota, and D. Katabi, "Embracing wireless interference: Analog network coding," in *Proc. Annual SIGCOMM Conference*, (Kyoto, Japan), 2007.

[18] J. Liu, M. Tao, and Y. Xu, "Pairwise check decoding for LDPC coded two-way relay block fading channels," *IEEE Trans. Commun.*, vol. 60, no. 8, pp. 2065–2076, 2012.

[19] J. Liu, M. Tao, and Y. Xu, "Pseudo exclusive-OR for LDPC coded two-way relay block fading channels," in *Proc. IEEE Internat. Conf. on Commun. (ICC)*, pp. 1–5, 2011.

[20] T. Koike-Akino, P. Popovski, and V. Tarokh, "Denoising maps and constellations for wireless network coding in two-way relaying systems," in *Proc. IEEE Global Telecommunications Conf. (GlobeCom)*, 2008.

[21] V. T. Muralidharan and B. S. Rajan, "Performance analysis of adaptive physical layer network coding for wireless two-way relaying," *IEEE Trans. Wireless Commun.*, vol. 12, no. 3, pp. 1328–1339, 2013.

[22] A. Li, Y. Yan, and H. Kayama, "An enhanced denoise-and-forward relaying scheme for fading channel with low computational complexity," *IEEE Signal Process. Lett.*, vol. 15, 2008.

[23] V. T. Muralidharan, V. Namboodiri, and B. S. Rajan, "Wireless network-coded bidirectional relaying using latin squares for M-PSK modulation," *IEEE Trans. Inf. Theory*, in press.

[24] V. T. Muralidharan and B. S. Rajan, "Wireless network coding for MIMO two-way relaying," *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, pp. 3566–3577, 2013.

[25] T. Koike-Akino, P. Popovski, and V. Tarokh, "Denoising strategy for convolutionally-coded bidirectional relaying," in *Proc. IEEE Internat. Conf. on Commun. (ICC)*, 2009.

[26] K. Yasami, A. Razi, and A. Abedi, "Analysis of channel estimation error in physical layer network coding," *IEEE Commun. Lett.*, vol. 15, pp. 1029 –1031, Oct. 2011.

[27] D. Fang and A. Burr, "Rotationally invariant coded modulation for physical layer network coding in two-way relay fading channel," in *Proc. European Wireless Conf. (EW)*, pp. 1–6, 2012.
[28] V. T. Muralidharan and B. S. Rajan, "Distributed space time coding for wireless two-way relaying," *IEEE Trans. Signal Process.*, vol. 61, no. 4, pp. 980–991, 2013.
[29] M. Hekrdla and J. Sykora, "Design of uniformly most powerful alphabets for HDF 2-way relaying employing non-linear frequency modulations," *EURASIP J. on Wireless Comm. and Netw.*, vol. 128, pp. 1–18, Oct. 2011.
[30] M. Hekrdla and J. Sykora, "Uniformly most powerful alphabet for HDF two-way relaying designed by non-linear optimization tools," in *Proc. Int. Symp. of Wireless Communication Systems (ISWCS)*, pp. 594 –598, Nov. 2011.
[31] T. Uricar and J. Sykora, "Design criteria for hierarchical exclusive code with parameter-invariant decision regions for wireless 2-way relay channel," *EURASIP J. on Wireless Comm. and Netw.*, vol. 2010, pp. 1–13, 2010. doi:10.1155/2010/921427.
[32] T. Uricar and J. Sykora, "Non-uniform 2-slot constellations for bidirectional relaying in fading channels," *IEEE Commun. Lett.*, vol. 15, no. 8, pp. 795–797, 2011.
[33] T. Uricar, "Parameter-invariant hierarchical eXclusive alphabet design for 2-WRC with HDF strategy," *Acta Polytechnica*, vol. 50, no. 4, pp. 79–86, 2010.
[34] T. Uricar and J. Sykora, "Extended design criteria for hierarchical eXclusive code with pairwise parameter-invariant boundaries for wireless 2-way relay channel," in *COST 2100 MCM*, (Vienna, Austria), pp. 1–8, Sept. 2009. TD-09-952.
[35] 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), pp. 1–8, Feb. 2010. TD-10-10088.
[36] T. Uricar and J. Sykora, "Hierarchical eXclusive alphabet in parametric 2-WRC - Euclidean distance analysis and alphabet construction algorithm," in *COST 2100 MCM*, (Aalborg, Denmark), pp. 1–9, June 2010. TD-10-11051.
[37] T. Uricar, "Constellation alphabets for hierarchical relaying in multiple-access relay channel," in *Proc. POSTER 2011 - 15th International Student Conference on Electrical Engineering*, (Prague, Czech Republic), pp. 1–5, May 2011.
[38] T. Uricar and J. Sykora, "Non-uniform 2-slot constellations: Design algorithm and 2-way relay channel performance," in *COST IC1004 MCM*, (Lyon, France), pp. 1–7, May 2012. TD-12-04041.
[39] R. W. Yeung, S.-Y. R. Li, N. Cai, and Z. Zhang, *Network Coding Theory*. NOW Publishers, 2006.
[40] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung, "Network information flow," *IEEE Trans. Inf. Theory*, vol. 46, pp. 1204–1216, July 2000.
[41] J. Sykora and A. Burr, "Network coded modulation with partial side-information and hierarchical decode and forward relay sharing in multi-source wireless network," in *Proc. European Wireless Conf. (EW)*, (Lucca, Italy), 2010.
[42] A. Burr and J. Sykora, "Extended mappings for wireless network coded butterfly network," in *Proc. European Wireless Conf. (EW)*, (Vienna, Austria), 2011.
[43] T. Uricar and J. Sykora, "Systematic design of hierarchical network code mapper for butterfly network relaying," in *Proc. European Wireless Conf. (EW)*, (Poznan, Poland),

pp. 1–8, Apr. 2012.

[44] T. Uricar and J. Sykora, “Hierarchical network code mapper design for adaptive relaying in butterfly network,” in *COST IC1004 MCM*, (Barcelona, Spain), pp. 1–9, Feb. 2012. TD-12-03048.

[45] T. Uricar and J. Sykora, “Non-uniform 2-slot constellations for relaying in butterfly network with imperfect side information,” *IEEE Commun. Lett.*, vol. 16, no. 9, pp. 1369–1372, 2012.

[46] T. Uricar and J. Sykora, “Wireless (Physical Layer) Network Coding in 5-node butterfly network: Superposition coding approach,” in *COST IC1004 MCM*, (Malaga, Spain), pp. 1–9, Feb. 2013. TD-13-06026.

[47] T. Uricar, B. Qian, J. Sykora, and W. H. Mow, “Superposition coding for wireless butterfly network with partial network side-information,” in *Proc. IEEE Wireless Commun. Network. Conf. (WCNC)*, (Shanghai, China), pp. 1–6, Apr. 2013.

Summary

The up-and-coming *Wireless (Physical layer) Network Coding (WNC) techniques*, implemented directly at Physical Layer (PHY), possess undoubtedly a great potential to harness all the performance benefits accompanied with the *non-orthogonal* sharing of wireless medium. The power of WNC lies mainly in an efficient exploitation of the *inherent properties of wireless channels* (broadcast nature and inherent combining of electromagnetic waves at receiver antenna(s)), which provide a fertile ground for an extension of conventional (wire-line) *network-coding principles* to wireless channels. The interference is no longer considered as harmful in WNC-based systems, and hence it is exploited rather than avoided. Since WNC operates directly at PHY, huge performance gains can be achieved, when compared to conventional routing (e.g. doubled throughput in a simple bi-directional relay channel). Unfortunately, the specific properties of wireless channels are not always only beneficial, as they introduce many novel research problems which makes a direct implementation of WNC in wireless systems quite challenging.

First, the *inherent parametrization* of wireless channels (e.g. channel gain) significantly influences the achievable performance of WNC systems, and hence the PHY processing algorithms must take the channel parametrization inherently into account, providing solutions robust to parametrization effects. Secondly, the inherent broadcast nature is to be exploited on channels with *potentially significantly different capacities*, forcing the PHY processing to cope with the problems associated with an *imperfect/partial transmission of information*. In the doctoral thesis we focused on these two specific open problems in WNC research, namely the WNC processing in *parametric channels* and WNC processing with *partial/imperfect Hierarchical Side Information* (HSI).

We have shown that even though only multi-dimensional constellations are capable to fully avoid the detrimental effects of channel parametrization, these constellations suffer from an inherent reduction of achievable throughput. To avoid this inherent drawback of multi-dimensional constellations, we introduced a design of novel Non-uniform 2-slot (NuT) constellations, which proved to be able to suppress the harmful behaviour of channel parametrization if the 2-WRC system operates in Rician fading channels. The proposed NuT constellations outperform the traditional linear modulation schemes (in the sense of SER performance) without sacrificing the overall system throughput.

An attempt to extend the WNC processing to more complex network structures (e.g. Wireless Butterfly Network – WBN) has revealed the issues associated with the limited availability of HSI at receiving nodes. We have shown that the state-of-the-art bi-directional 3-step and 2-step relaying strategies can be modified to guarantee that successful decoding at destinations is made possible even if HSI is only partially available and we have proposed a novel WNC scheme, which is capable to adapt to any amount of HSI at destinations. To provide a practical design tool for a construction of relay processing for networks with imperfect HSI links we have introduced a systematic algorithm for a design of relay output mapping operations. The availability of suitable relay output mapping operation has enabled to exploit the promising parametric channel performance of NuT constellations in WBN, transforming the increased reliability of *partial one-slot HSI* into an *additional SNR gain* in BER performance of the system.

Anotace

Technika *bezdrátového síťového kódování* (WNC) nabízí nepochybně velký potenciál k využití příznivých jevů spojených s neortogonálním přístupem ke sdílení radiového kanálu. Tato perspektivnost WNC technik spočívá zejména v efektivním využití *specifických vlastností radiových kanálů* (všesměrové šíření signálu či samočinné kombinování/sčítání interagujících elektromagnetických vln na anténě přijímače), poskytujích příznivé podmínky pro implementaci (modifikovaných) principů *síťového kódování* (NC) v bezdrátových sítích. V systémech založených na WNC není interference považována za nežádoucí jev, ale dochází zde naopak ke snaze o její efektivní využívání. Jelikož je WNC implementováno přímo na fyzické vrstvě, umožňuje dosáhnout mnohem lepších přenosových vlastností než konvenční přístup založený na směrování individuálních datových toků v síti. Bohužel, výše zmíněné specifické vlastnosti radiových kanálů s sebou přináší také řadu nových výzkumných problémů, které znesnadňují přímou implementaci WNC v bezdrátových systémech.

První z problémů, kterým musí návrh WNC zpracování čelit, souvisí s *parametrizací* (např. komplexní zisk) radiového kanálu. Druhým problémem je pak samotné *všesměrové šíření radiového signálu*, které je ve WNC systémech využíváno k přenosu informace radiovými kanály s potenciálně významně odlišnými přenosovými kapacitami. Tato skutečnost vyžaduje, aby bylo zpracování signálu přizpůsobeno možným problémům souvisejícím s částečným/neperfektním přenosem informace. Ve své dizertační práci jsem se změřil na tyto dva výše zmíněné problémy ve WNC systémech, konkrétně tedy návrh zpracování signálu ve WNC systémech s *parametrickým kanálem* a WNC systémech s *neperfektním přenosem hierarchické postranní informace* (HSI).

V dizertační práci jsme ukázali že pouze více-dimenzionální konstelace jsou schopné úplně zabránit nežádoucím jevům souvisejícím s parametrizací kanálu. Bohužel, s vícedimenionální povahou těchto konstelací je rovněž spojeno významné snížení dosažitelné propustnosti sítě. Abychom předešli tomuto nežádoucímu jevu, představili jsme návrh nových *neuniformních 2-slotových konstelací* (NuT), které jsou v případě kanálů s Riceovým rozložení schopny významně potlačit důsledky parametrizace kanálu. Navržené NuT konstelace tak překonávají tradiční konstelace ve smyslu odolnosti vůči chybám při přenosu, aniž by tyto výhodné vlastnosti byly spojeny s jakýmkoliv omezením dosažitelné propustnosti sítě.

Pokusy o rozšíření WNC zpracování do složitějších sítí (např. 5-terminálová 2-zdrojová síť – WBN) poodhalily problémy spojené s omezenou dostupností postranní informace (HSI) na přijímači. Jak uvádíme v dizertační práci, stávající 2 a 3-krokové WNC strategie mohou být upraveny pro použití ve WBN sítích, přičemž jsou všechny tyto (modifikované) strategie schopny zajistit dekódovatelnost požadované informace na přijímači při libovolném množství dostupné HSI. Dalším významným krokem k rozšíření WNC zpracování do složitějších sítí byl návrh systematického algoritmu pro výstupní (mapovací) operace vnitřního uzlu sítě (tzv. relay), který v konečném důsledku umožnil také znovuobjevení NuT konstelací pro aplikaci ve WBN sítích. Typická odolnost NuT konstelací vůči nežádoucím vlivům parametrizace kanálu zde tak opět umožňuje dosáhnout lepší odolnosti vůči chybám při přenosu (ve srovnání s tradičními konstelacemi), a to i v případě neperfektní HSI.