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Design of Adaptive Constellations and Error Protection Coding for Wireless Network Coding in 5-node Butterfly Networks

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First of all, we would like to thank all the reviewers for their valuable comments and suggestions that have helped to significantly improve our manuscript. We first reply to the most common and important questions and then we answer the individual questions and comments individually.

1 Common Questions and Corresponding Answers

- CQ1: *Lacking novelty compared to [2].*
- A1: Compared with the conference paper [2], the major contributions and differences of this submitted manuscript are summarized as follows:
    1. We introduce additional performance analysis results for constellations in an uncoded system and an in-depth discussion of the observed results.
    2. We extend the section dealing with the adaptive constellation design in an uncoded system and we supplement additional HW evaluation results for the adaptive system in the whole range of observed channel SNRs. Again, close agreement between the analytic and measurement results is shown.
    3. We show how the channel coding can be integrated into the proposed constellation design, including the cut-set bound analysis of proper source transmission rates, which provides a hint for the setup of all channel encoders' rates in the system.
    4. We evaluate numerically the performance of the resulting adaptive modulation-coding scheme for a wide range of channel conditions in the WBN and we emphasise the performance gains with respect to the uncoded system.
    5. We perform a simple robustness analysis, demonstrating that the proposed modulation and coding strategy is viable even in the case when real-world conditions induce some deviations from the mathematical system model assumed in the paper.
    6. We conducted a comparison with the state of the art reference scenarios (traditional network coding and routing) for the proposed channel coded adaptive constellation design.
- CQ2: *Better reference scenario.*
- A2: We definitely agree that the zero throughput uncoded QPSK reference scenario is not ideal for the performance gain demonstration of the proposed constellation design. There are no equivalent 2-step state of the art strategies, so we decided to consider a comparison with traditional network coding and routing strategies. These strategies require 3 steps and therefore some attention is required to provide a fair comparison with the proposed 2-step framework. We added a completely new section, 7.4, into the manuscript dedicated to this comparison with the conventional techniques.

  In this new section, we show that the HW implementation of the proposed adaptive constellation design outperforms the reference scenarios even with the relaxed assumption (pre-rotation off). The good performance of the proposed design without pre-rotation is very important, because the pre-rotation represents a serious implementation challenge, requiring channel feedback. Finally we shown that the performance of the proposed framework is even above the corresponding 3-step reference theoretical limits.

- CQ3: *Typos and Formatting Issues*
- A3: The manuscript was carefully proofread by native speaker for typos. Regarding the formatting issues, we searched and corrected the issues we found. Nevertheless, we should stress that the manuscript will be transformed to the EURASIP template prior to publishing and there will be time for fine-tuning.
- CQ4: *Motivation beyond the proposed Adaptive Constellation Design and its Generalization*
- A4: We answer this question in two parts. We split the problem to 1) wireless aware network coding, that is to determine the information flow within the network [3] and 2) the particular constellation design suited for a given information stream. Note that the motivation can be found also in [2].

  The network information flow within the butterfly network can be seen as a combination of the cases, when a) all information is passed through the relay b) maximal information is passed through the side links as is explained in [1]. Intuitively, the wireless network paradigm should be exploited as much as possible due to its higher spectral efficiency. To the best of our knowledge, no such approach is available for a general network in the current state of the art. Random network coding cannot be "wireless aware" due to its randomness. There remains scope for researching proper network information flow design within a general network.

  The second part of the design assumes a given network information flow and the goal is to find the best possible constellation design across the nodes within the network for the given flow. Within this design, we consider two building blocks for the multiple access channel, that is: i) orthogonal constellation design forming a non-overlapping superimposed constellation at the receiving node enabling joint (full) decoding and ii) a hierarchical constellation design that allows some overlaps in the received constellation, such that only a network function of the data can be recovered (not both individual data streams). Finally, one needs to properly combine the aforementioned building blocks by means of superposition coding.

  In case of the orthogonal design, we chose ASK source constellations mutually shifted by $\pi/2$ to form the QAM constellation in the received node. This assumes exactly two transmitting nodes. To generalize to more sources, some way to preserve join decodability must be found. The hierarchical design depends on a particular network function (exclusive OR in our case). The goal is a received constellation with maximal free distance between the *network coded data*, where overlaps within the network function are allowed. Actually these overlaps allow an improvement in the minimal distance compared to the orthogonal design. Since both ASK and the proposed hierarchical constellation can be written as a composition of properly scaled BPSK constellations, the constellations are fully determined by scaling levels[1] for individual bit streams.

Within the butterfly network, the orthogonal stream is called the *superposed* stream and the hierarchical is called the *basic* stream. Since the basic stream is needed at the destinations, it is given a higher power level compared to the superposed stream. Please find Figures 3,4 in the manuscript for demonstration of this composition.

Regarding the generalization of the principle to a general network, one can of course consider the advantage of the proposed building blocks or even try to generalize them for more than two sources. A design of some useful rules for the proposed building block utilization in a generalized network is an open problem. In addition, one should also keep in mind that the severity of the real-world issues such as synchronization and pre-rotation would dramatically grow with network size.

Reviewer 1

- Q: *The weak aspect of this paper is that the current paper is a small variation of a previous paper by the authors. The authors should further highlight the difference of this paper.*
- A: See A1
- *The authors should edit the paper more carefully. For example, in Figure 5, the references are missing. Please go over the whole the paper and make sure similar issues do not exist*
- A: See A3

Reviewer 2

- Q: *Since this work builds upon previous work on the application of wireless network coding to the WBN, novelty is slightly lacking*
- A: see A1
- Q: *The proposed scheme appears to be quite specific to the WBN, I wonder if it is possible to generalize to other similar networks where linear codes yield a good performance.*
- A: See A4.
- Q: *The authors should also provide more insight or intuition on the design of the constellation and explain why the challenges to apply to other linear networks.*
- A: See A4

[1] Determination of those levels can be found in Algorithm 1, line 3 for superposed part and lines 6,7 for basic part.

- Q: *It might be useful to the reader to add a figure for the butterfly network in the setting of algebraic network coding for comparison.*
- A: see A2 and the new section 7.4 in the manuscript
- Q: *Since real world networks are usually more complicated, I think it would be really interesting if this systematic design can be generalized to all linear network coding schemes (e.g. random linear network coding).*
- A: see A4
- Q: *If it cannot be easily generalized, it could be helpful to explain what are the difficulties in applying it to other coding schemes.*
- A: see A4
- Q: *Might be helpful if mention beforehand that the nomenclature is given at the end of the paper (For example, HW is throughout the paper and its definition is only given at the end of the paper).*
- A: The nomenclature is placed according to the EURASIP-author's guidelines. The HW abbreviation was overlooked - it is now defined before its first appearance within the text.

Reviewer 3

- Q: *In figure 6, 7, 8, 9, the reference scheme using QPSK always has a zero throughput, which demonstrates that this reference modulation scheme does not work at all in WBN under the proposed SNRs. Then the proposed communication scheme is claimed to have performance enhancement for sure. However, logically, this only demonstrates that the proposed algorithm gives positive throughput in WBN instead of not working. But it is not enough to say it gives a "performance enhancement" comparing with a previous working scheme. So it would be better if the author can further compare some other modulation schemes which can also give some positive throughput in WBN.*
- A: See A2 for the coded case. Considering the two time slot communication schemes, there is indeed no state of the art solution for joint decoding, whereby the constellation design at the sources is such that the relay would reliably jointly resolve data[2] from both sources. We thus decided to claim the performance of the proposed $N_b = 0$, $N_s = 2$ compared to the zero throughput QPSK as the throughput gain.

  Nevertheless, the reviewer has a point that it is unfair to claim the performance of the proposed $N_b = 1$, $N_s = 1$ constellation as throughput gain compared to the zero-throughput QPSK, because the proposed constellation design uses the side link and it should be rather compared with some reference that is able to use the side link as well. For this purpose, the conventional wireless network coding with a BPSK constellation with non-zero throughput can be considered for instance. However, to keep the figure readable, we decided not to add another curve into the plot, because

[2] We assume uncoded data in this context only.

BPSK performs similarly to the $(N_b = 2, N_s = 0)$ strategy already shown in the figures. Therefore the performance gain statement between $N_b = 1$, $N_s = 1$ and the zero-throughput reference QPSK is omitted in Figures 6-9 in the revised manuscript. Check Figure 1) in this response letter.

- Q: *As far as we know, according to the 3GPP protocol, there is a Channel Quality Index (CQI) vs. modulation format table, which suggests the modulation scheme with respect to difference SNR range. According to this table, for example, for the SNR varying from 6dB to 20dB, the protocol suggests using 16QAM and 64QAM instead of QPSK. In WBN, it could be different from 3GPP, but I suggest the author to test some other reference modulation format and compare the difference.*

- A: The channel quality index is 3-dimensional (MAC, BC and HSI) in our model. Although its evaluation can be easily done according to the theoretical analysis, its practical impact is questionable, because of more degrees of freedom that comes into consideration in real scenarios, like a particular channel code, violation of the idealistic symmetry assumption, strength of the direct link, etc. Within our experiment, we manually found some "optimal" table values for a small collection of SNR tuples in the new section 7.4 (Figures 20, 21), but care should be taken before applying the parameters (N_b, N_s, r_b, r_s) directly to other experimental setups.

- Q: *Although, in the future work, the authors have mentioned the fading channel case, it would still be better that the case of fading channels or of longer communication distance could be simulated and experimented. AWGN channel seems to be too ideal. If some initial results on the fading channel case can be added into the paper, it would be better.*

- A: We agree that the investigation of the behavior of fading channels is an important step. We already have some initial results available for a fading channel without pre-rotation (check green line in Figures 20, 21), where the amplitude of the fading coefficients related to the sources to relay links is almost (but not completely) equal[3]. A more detailed analysis of the proposed constellation design in fading channels is an area for further work.

- Q: *The robustness analysis is important, and the authors have done some simulations on this aspect. However, it would be more appreciated if a hardware experiment can be done on this aspect.*

- A: We fully understand and agree that the robustness analysis deserves further deep investigation. Nevertheless, we provided some basic analysis including the hardware experiment within our work (check Figure 17 in manuscript) giving quite promising results. A more detailed investigation is suited rather for a standalone work than for this resubmission.

- Q: *In Fig. 15, the throughput enhancmence for the coding scheme is shown. It is interesting to see that the throughput enhancment has some*

[3]It can be not intuitive that the superimposed constellation is determined by relative fading given by the ratio $h = h_A/h_B$ in the 2-step setup. The absolute value of fading coefficients can be equally modelled by a corresponding SNR value modification.

"peak" and "valley" as the Îş_MAC increases. If possible, please give some explanation. Or this is just a random instance that happens to be shown by the hardware experiment, that is also fine.

- A: The explanation here is quite straightforward, as it follows from the steep gradients of the uncoded throughput as function of SNRs shown in Figure 10. On the other hand the coded throughput as a function of SNRs is much smoother (Figure 14) and therefore their difference induces peaks and valleys
- Q: *There are also some minor context error or typos found*
- A: See A3

References

[1] Pavel Prochazka. Wnc tutorial - constellation design for butterfly network. `http://pavel.prochazka.info/tutorial/const_design_WNC`. Accessed: 2016-12-28.

[2] Pavel Prochazka, Tomas Uricar, David Halls, and Jan Sykora. Relaying in butterfly networks: Superposition constellation design for wireless network coding. In *Proc. IEEE Int. Conf. on Commun. (ICC)*, pages 1–7, London, UK, to appear 2015.

[3] Tomas Uricar, Tomas Hynek, Pavel Prochazka, and Jan Sykora. Wireless-aware network coding: solving a puzzle in acyclic multi-stage cloud networks. In *Wireless Communication Systems (ISWCS 2013), Proceedings of the Tenth International Symposium on*, pages 1–5. VDE, 2013.

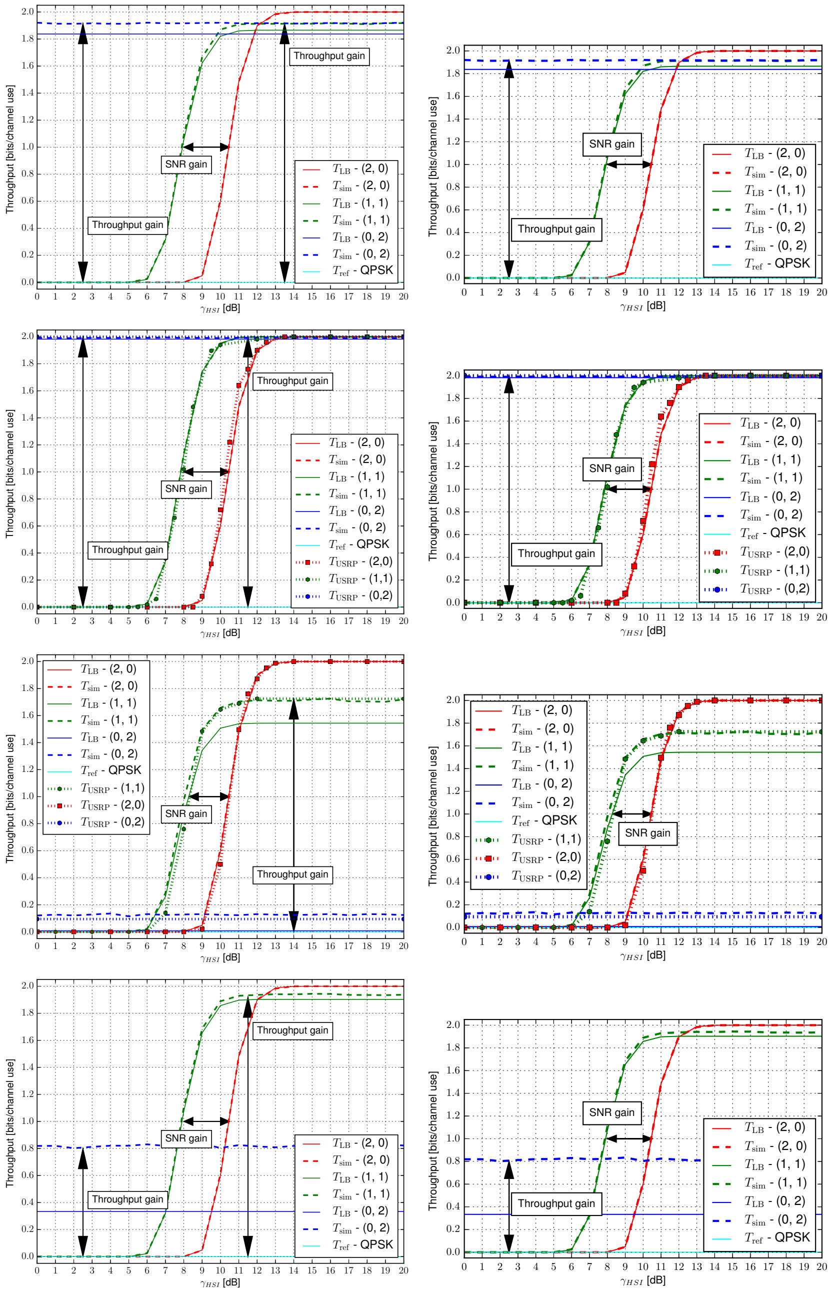

Figure 1: Uncoded throughputs (old versions left, new versions right).

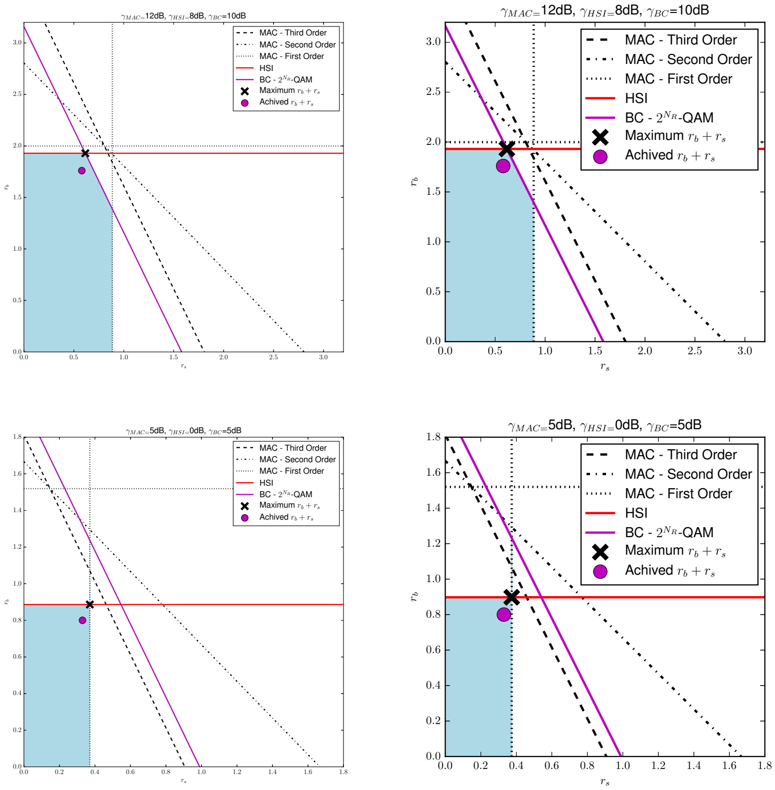

Figure 2: Enlarged fonts – Figure 13 in the manuscript (old versions left, new versions right).