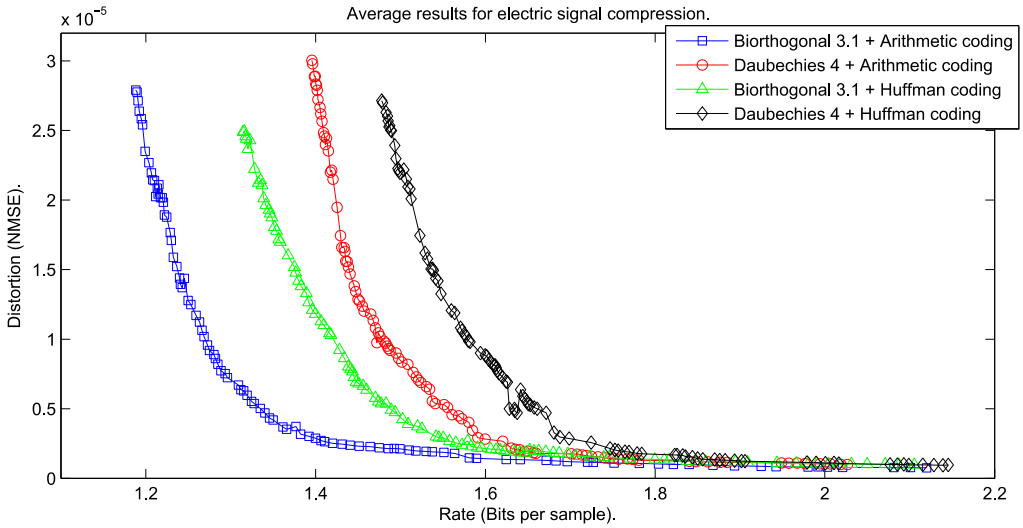

Figure 5: Performance comparison.

5. Conclusion

This paper demonstrated that jointly designing the PQ signal compression modules of wavelet transforms, non-uniform quantizers and entropy coding, using a genetic algorithm based optimization framework, resulted in significant improvement in PQ signals compression. Contrary to current approaches, which deploy ``off the shelf'' compression modules that were designed for other applications, the proposed approach leverages the ability to automatically classify the disturbances and designs the modules jointly while accounting for actual data statistics adapted to each category of disturbance. As a result of this joint optimization, Biorthogonal 3.1 emerged as the better choice of wavelet transform, in contrast with the currently employed Daubechies 4 wavelets. The overall experimental results demonstrate the significant performance improvement obtained by the proposed approach. Future research directions include, extending the adaptivity to hyper-local statistics, e.g., quantizers and entropy coders adapted to individual frequency components, and designing the modules for more categories of disturbances and their combinations.

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References

[1] M. H. J. Bollen, I. Y. H. Gu, S. Santoso, M. F. Mcgranaghan, P. A. Crossley, M. V. Ribeiro and P. F. Ribeiro, "Bridging the gap between signal and power," *IEEE Signal Processing Magazine*, pp. 12-31, 2009.

[2] L. Liboni, R. Flauzino, I. da Silva, E. Costa and M. Suetake, "Efficient signal processing technique for information extraction and its applications in power systems," *Electric Power Systems Research*, vol. 141, pp. 538-548, 2016.

[3] A. Vaccaro, I. Pisica, L. L. Lai and A. F. Zobaa, "A review of enabling methodologies for information processing in smart grids," *International Journal of Electrical Power & Energy Systems*, vol. 107, pp. 516-522, 2019.

[4] F. Samie, L. Bauer and J. Henkel, "Edge computing for smart grid: An overview on architectures and solutions," *Power Systems*, pp. 21-42, 2019.

[5] P. F. Ribeiro, C. A. Duque, P. M. Ribeiro and A. S. Cerqueira, Power systems signal processing for smart grids, New York: John Wiley & Sons, 2013.

[6] M. P. Tcheou, L. Lovisolo, E. A. B. d. Silva, M. A. M. Rodrigues and P. S. R. Diniz, "Optimum Rate-Distortion Dictionary Selection for Compression of Atomic Decompositions of Electric Disturbance Signals," *IEEE Signal Processing Letters*, vol. 14, no. 2, pp. 81-84, 2007.

[7] M. P. Tcheou, L. Lovisolo, M. V. Ribeiro, E. A. B. d. Silva, M. A. M. Rodrigues, J. M. T. Romano and P. S. R. Diniz, "The Compression of Electric Signal Waveforms for Smart Grids: State of the Art and Future Trends," *IEEE Transactions on Smart Grid*, vol. 5, no. 1, pp. 291-302, 2014.

[8] A. S. Spanias, "Speech coding: A tutorial review," *Proceedings of the IEEE*, vol. 82, no. 10, pp. 1541-1582, 1994.

[9] G. J. Sullivan, "Efficient scalar quantization of exponential and Laplacian random variables," *IEEE Transactions on Information Theory*, vol. 42, no. 5, pp. 1365--1374, 1996.

[10] J. Chung, E. J. Powers, W. M. Grady and S. C. Bhatt, "Variable rate power disturbance signal compression using embedded zerotree wavelet

transform coding," in *IEEE Power Engineering Society Winter Meeting*, New York, NY, USA, 1999.

[11] C. T. Hsieh and S. J. Huang, "Disturbance data compression of a power system using the Huffman coding approach with wavelet transform enhancement," *IEE Proceedings - Generation, Transmission and Distribution*, vol. 150, no. 1, pp. 7-14, 2003.

[12] S.-J. Huang and M.-J. Jou, "Application of arithmetic coding for electric power disturbance data compression with wavelet packet enhancement," *IEEE Transactions on Power Systems*, vol. 19, no. 3, pp. 1334-1341, 2004.

[13] F. Lorio and F. Magnago, "Analysis of data compression methods for power quality events," *IEEE Power Engineering Society General Meeting*, vol. 1, pp. 504-509, 2004.

[14] K. Deb, A. Pratap, S. Agarwal and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE Transactions on Evolutionary Computation*, vol. 6, no. 2, pp. 182-197, 2002.

[15] L. C. M. Andrade, M. Oleskovicz and R. A. S. Fernandes, "Adaptive threshold based on wavelet transform applied to the segmentation of single and combined power quality disturbances," *Applied Soft Computing*, vol. 38, pp. 967 - 977, 2016.

[16] M. Oleskovicz, D. V. Coury, O. D. Felho, W. F. Usida, A. A. F. M. Carneiro and L. R. S. Pires, "Power quality analysis applying a hybrid methodology with wavelet transforms and neural networks," *International Journal of Electrical Power & Energy Systems* , vol. 31, no. 5, pp. 206 - 212, 2009.

[17] M. Paez and T. Glisson, "Minimum mean-squared-error quantization in speech PCM and DPCM systems," *IEEE Transactions on Communications*, vol. 20, no. 2, pp. 225-230, 1972.

[18] R. Reininger and J. Gibson, "Distributions of the two-dimensional DCT coefficients for images," *IEEE Transactions on Communications*, vol. 31, no. 6, pp. 835-839, 1983.

[19] G. J. Sullivan, J. Ohm, W.-J. Han and T. Wiegand, "Overview of the high efficiency video coding (HEVC) standard," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 22, no. 12, pp. 1649-1668, 2012.

[20] M. F. Duarte, G. Shen, A. Ortega and R. G. Baraniuk, "Signal compression in wireless sensor networks," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 370, no. 1958, pp. 118-135, 2012.

[21] P. Murugan, S. Kannan and S. Baskar, "Application of NSGA-II Algorithm to Single-Objective Transmission Constrained Generation Expansion Planning," *IEEE Transactions on Power Systems*, vol. 24, no. 4, pp. 1790-1797, 2009.

[22] R. B. Agrawal and K. Deb, "Simulated Binary Crossover for Continuous Search Space," Indian Institute of Technology, Kampur, India, 1994.

[23] R. Hooshmand and A. Enshaee, "Detection and classification of single and combined power quality disturbances using fuzzy systems oriented by particle swarm optimization algorithm," *Electric Power Systems Research*, vol. 80, no. 12, pp. 1552-1561, 2010.

[24] L. C. M. Andrade, M. Oleskovicz and R. A. S. Fernandes, "Analysis of Wavelet Transform applied to the segmentation of disturbance signals with different sampling rates," in *IEEE Power Engineering Society General Meeting*, National Harbor, MD, USA, 2014.

[25] R. C. Dugan, M. F. McGranaghan, S. Santoso and H. W. Beaty, Electrical Power Systems Quality, Third Edition, New York, NY, USA: McGraw-Hill Education, 2012.