Improper Signaling Testbed Based on Software Defined Radio

Álvaro Pendás-Recondo, Jesús Alberto López-Fernández, and Rafael González Ayestarán
Group of Signal Theory and Communications, Universidad de Oviedo, Spain, {pendasalvaro, jelofer, rayestaran}@uniovi.es

***Abstract*—The design and implementation of an improper signaling testbed based on Software Defined Radio (SDR) are presented. While improper signalling has garnered interest in recent years, a real-world system implementation remains to be seen in the literature. The proposed system offers significant insights into challenges associated with the problem. It also illustrates how these challenges can be effectively addressed through the use of SDR, thereby laying the groundwork for future research testbeds for improper and other types of asymmetric signaling.**

I. INTRODUCTION

Proper Gaussian Signaling (PGS) is optimal for maximizing mutual information in circularly symmetric Additive White Gaussian Noise (AWGN) channels. Yet, the use of Improper Gaussian Signaling (IGS) has been shown to enhance capacity in several interference-limited scenarios. [1], [2]. While Gaussian signals are theoretically optimal, their application in real-world communication systems is constrained by their infinite peak-to-average power ratio. This limitation leads to the use of discrete signaling in practical applications.

The design of improper discrete constellations with a prescribed circularity coefficient has been recently addressed in the literature [3], [4], being their interest shown in contexts such as interference management [5], [6] and hardware impairments [7], [8]. However, to the best of our knowledge, the practical implementation of improper discrete signaling in real-world settings has yet to be explored.

In this paper, an experimental testbed based on Software Defined Radio (SDR) designed for conducting research on improper discrete signaling is presented. The setup includes a Single-Input-Single-Output (SISO) Orthogonal Frequency Division Multiplexing (OFDM) wireless link, implemented using two Universal Software Radio Peripheral (USRP) N210 devices and the open-source GNU Radio software. The system offers significant insights into the practical challenges of implementing improper constellations and paves the way for the experimental verification of their theoretical benefits.

II. DISCRETE IMPROPER SIGNALING

Let us consider a zero-mean complex random variable X, representing a discrete signal constellation, i.e., it can take a finite number of realizations. The complementary-variance and variance of X are defined as $\tilde{\sigma}_X^2 = \mathrm{E}\left\{X^2\right\}$, and $\sigma_X^2 = \mathrm{E}\left\{|X|^2\right\}$, respectively. Its circularity coefficient, which measures the degree of impropriety, is defined as

$$\kappa = \frac{\left|\mathrm{E}\left\{X^2\right\}\right|}{\mathrm{E}\{|X|^2\}} = \frac{\left|\tilde{\sigma}^2\right|}{\sigma^2}, \tag{1}$$

satisfying $0 \leq \kappa \leq 1$. The circularity coefficient measures the degree of impropriety since x is proper if $\kappa = 0$; improper if $\kappa > 0$; and maximally improper when $\kappa = 1$ [9].

The design of discrete constellations for a specific circularity coefficient, κ, has been previously addressed in the literature [3], [4]. The presented system employs the method described in [3], based on a Widely Linear Transformation (WLT) of standard M-ary quadrature amplitude modulation (M-QAM) constellations.

III. SOFWARED DEFINED RADIO IMPLEMENTATION

The proposed testbed, shown in Fig. 1, includes two USRP N210 devices connected to a single laptop via Gigabit Ethernet cables. A wireless link between both USRP has been designed by using the open-source GNU Radio software. The architecture of the communication link is based on OFDM, incorporating 64 carriers in alignment with the IEEE 802.11a specifications. The central frequency for the experiment is established at 2.4 GHz, and the sampling rate of both hardware devices is set to 10 Msps.

Data transmission is organized into packets, each consisting of a header and a payload. The payload comprises random bytes and a Cyclic Redundancy Check (CRC) code, which facilitates the measurement of the Bit Error Rate (BER) at the receiver. The selected modulation for the header is BPSK, while the payload constellation can be alternated among QPSK, 16-QAM and 64-QAM. Furthermore, the circularity coefficient, κ, of the payload constellation is introduced as a variable in the software program. Points are determined using the WLT method, as noted in Section II. Fig. 2 depicts the constellation points of the received signal, as visualized in GNU Radio when using 16-QAM with $\kappa = 0.8$. Fig. 3 presents a SER comparison for 16-QAM with $\kappa = 0$ and $\kappa = 0.8$ in an AWGN channel. Hardware results are obtained by adding a predistorision at the transmitter, which is connected with an SMA cable to the receiver. Differences between simulation and experimental results can be attributed to additional noise introduced by both the transmitter and receiver chains, and the cable.

It should be noted that adjusting the circularity coefficient, κ, requires changes not only in the transmitter but also in the receiver. Each time the constellation points are modified, the decision regions are accordingly adapted to align with minimum Euclidean distance criteria. Furthermore, the receiver includes a single-tap Decision Feedback Equalizer (DFE) for each subcarrier, which is configured to adapt to the selected constellation. On the other hand, time synchronization remains unaffected, as it is achieved through the periodic transmission

Fig. 1: Testbed consisting of two USRP N210 devices connected to a single laptop via Gigabit Ethernet cables.

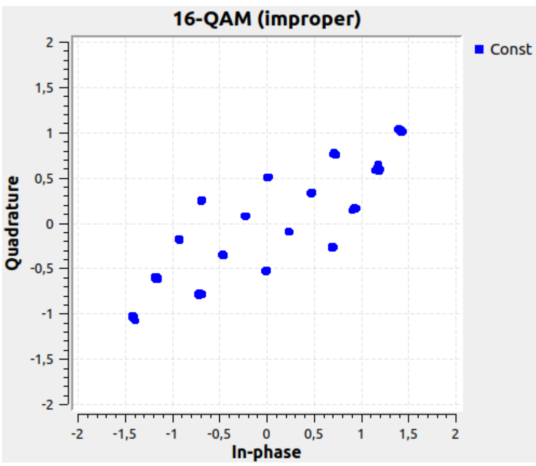

Fig. 2: Constellation points of the received signal using 16-QAM with $\kappa = 0.8$ in the payload, as visualized in GNU Radio.

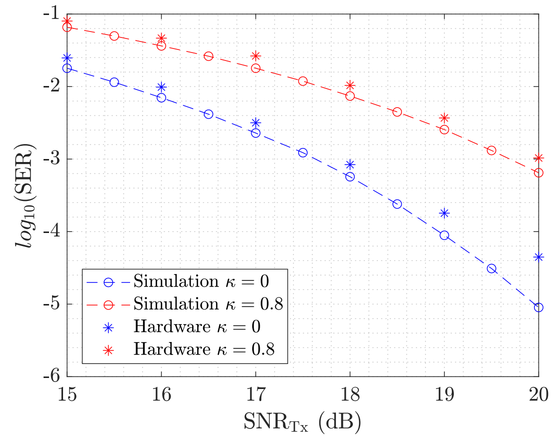

Fig. 3: SER comparison for 16-QAM with $\kappa = 0$ and $\kappa = 0.8$ in an AWGN channel. Hardware results are obtained by adding a predistorision at the transmitter, which is connected with an SMA cable to the receiver.

of known words, which are independent of the selected modulation scheme. The use of digital signal processing and SDR enables the automatic reconfiguration of the system to address the mentioned issues, thereby emphasizing the utility of the proposed system for research and experimental applications.

IV. Conclusion

The design and implementation of an improper signaling testbed based on SDR have been presented. The proposed system is based on an OFDM wireless link where the circularity coefficient of the constellation can be adjusted. Additionally, the paper outlines important design considerations, including the adaptation of equalizers and decision regions. The inherent flexibility of the SDR paradigm enables straightforward adjustments to these aspects without the need for hardware modifications. Future research directions include expanding the range of constellation options to include other types of asymmetric signaling, and obtaining figures of merit, such as error rate, for settings of interest. This approach could lead to the experimental validation of the theoretical benefits of these constellations in multiuser interference channels or scenarios requiring the correction of hardware impairments.

Acknowledgement

This work was supported in part by Ministerio de Ciencia e Innovación and Agencia Estatal de Investigación (MICIN)/(AEI)/10.13039/501100011033 within Project PID2020-114172RBC21 (ENHANCE-5G), and in part by Gobierno del Principado de Asturias under Project SV-PA-21 AYUD/2021/51706 and “Severo Ochoa” Program Grant PA-22-BP21-116.

References

[1] Z. K. Ho and E. Jorswieck, “Improper Gaussian Signaling on the Two-User SISO Interference Channel,” *IEEE Transactions on Wireless Communications*, vol. 11, no. 9, pp. 3194–3203, 2012.

[2] C. Lameiro, I. Santamaría, and P. J. Schreier, “Benefits of Improper Signaling for Underlay Cognitive Radio,” *IEEE Wireless Communications Letters*, vol. 4, no. 1, pp. 22–25, 2015.

[3] I. Santamaria, P. Crespo, C. Lameiro, and P. Schreier, “Information-Theoretic Analysis of a Family of Improper Discrete Constellations,” *Entropy*, vol. 20, no. 1, p. 45, 2018. [Online]. Available: http://dx.doi.org/10.3390/e20010045

[4] J. A. López-Fernández, R. G. Ayestarán, I. Santamaria, and C. Lameiro, “Design of Asymptotically Optimal Improper Constellations With Hexagonal Packing,” *IEEE Transactions on Communications*, vol. 67, no. 8, pp. 5445–5457, 2019.

[5] H. D. Nguyen, R. Zhang, and S. Sun, “Improper Signaling for Symbol Error Rate Minimization in K-User Interference Channel,” *IEEE Transactions on Communications*, vol. 63, no. 3, pp. 857–869, 2015.

[6] A. Pendás-Recondo, J. A. López-Fernández, and R. G. Ayestarán, “Study of SISO Superposition Coding Performance From Improper Discrete Signaling Perspective,” *IEEE Wireless Communications Letters*, pp. 1–1, 2024.

[7] S. Javed, O. Amin, B. Shihada, and M.-S. Alouini, “A Journey From Improper Gaussian Signaling to Asymmetric Signaling,” *IEEE Communications Surveys ‘I&’ Tutorials*, vol. 22, no. 3, pp. 1539–1591, 2020.

[8] S. Javed, O. Amin, S. S. Ikki, and M.-S. Alouini, “Asymmetric Modulation for Hardware Impaired Systems—Error Probability Analysis and Receiver Design,” *IEEE Transactions on Wireless Communications*, vol. 18, no. 3, pp. 1723–1738, 2019.

[9] P. J. Schreier and L. L. Scharf, *Statistical Signal Processing of Complex-Valued Data: The Theory of Improper and Noncircular Signals*. Cambridge, UK: Cambridge University Press, 2010.