Detection Schemes for 6G Wireless Systems

Berna Özbek

Department of Electrical and Electronics Engineering

Izmir Institute of Technology

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Outline

- Introduction
- RECENT Project
- Detection schemes for PNC-based NOMA systems
- Detection schemes for PNC-enabled Cell-Free systems
- Conclusion

Introduction

- The sixth generation (6G) wireless networks have greatly increased density and scale compared to current networks, resulting in massive interaction between nodes.
- The conventional networking paradigm is severely limited by interference, greatly reducing efficiency.
- Physical Layer Network Coding (PNC) is capable of resolving this situation: allow relay nodes/base station to extract useful information from all combined received signals, rather than treating them as deleterious interference.

RECENT Project

- Ultra-Dense Unsupervised Heterogeneous Wireless Cloud Coded Networks for 5G/B5G (RECENT) http://recent-project.eu
- The project has been funded by Horizon2020 Marie Skłodowska-Curie Actions (H2020MSCA) Research Innovation Exchange Programme (RISE) (GA-823903)

H2020-MSCA-RECENT-Project

H2020-MSCA-RECENT-Project

Project Partners

- GS LDA, Averio, Porto, Portugal (SME) (Project Coordinator)
- University of Essex, Colchester, UK.
- YL-VERKOT OY,Tampere,Finland (SME).
- Izmir Institute of Technology, Türkiye
  - Prof.Dr.Berna Özbek
  - Dr.S.Simay Yılmaz
  - İrem Cumalı (PhD Student)
  - Mert İlgüy (PhD Student)

Project Objectives

- PNC schemes in sub 6GHz/mmWave Massive MIMO for unsupervised, asynchronous and heterogeneous networks via physical layer security features.
- An enhanced fully equipped system level simulation platform for validating a wide range of wireless technology algorithms and architectures for 6G.
- Hardware in Loop (HIL) prototype incorporating new features with regards to advanced autonomous PNC cloud coding.

Research Topics

RESEARCH TOPICS

This project will focus on the following technical topics:

NETWORK CODED MODULATION FOR WPNC

Network Coded Modulation for WPNC

PHYSICAL LAYER SECURITY

Physical Layer Security

RECENT

STOCHASTIC NETWORK THEORY

Stochastic Network Theory

SYSTEM LEVEL SIMULATION

System Level Simulation

PNC Scheme

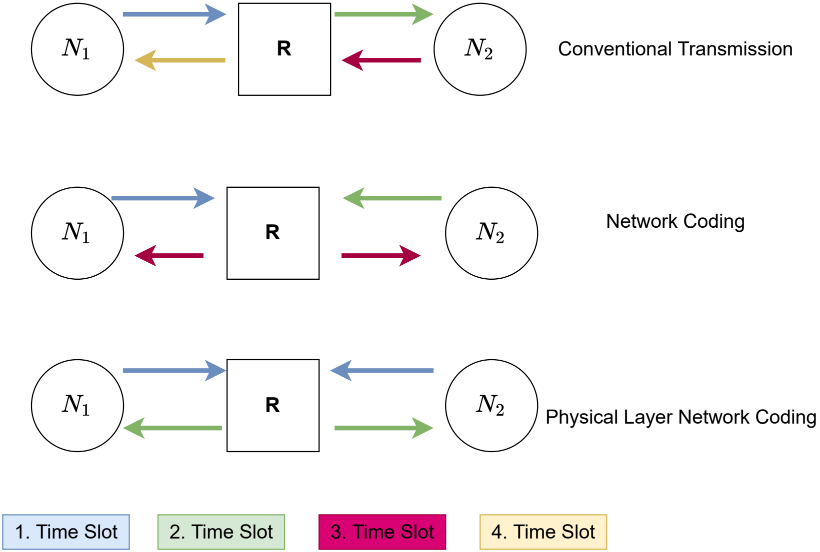

Figure 1: Conventional schemes, NC and PNC for two users.

PNC Scheme in Testbed

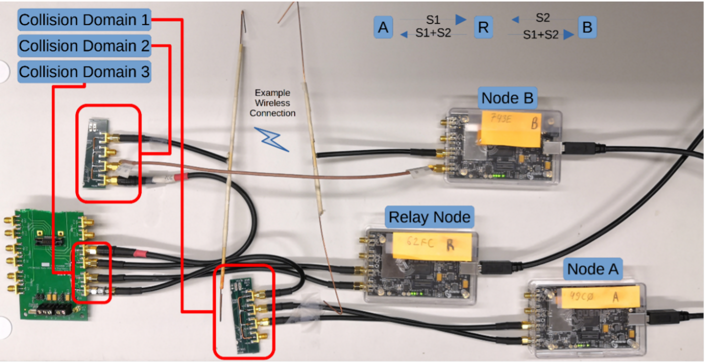

Figure 2: Testbed implementation for 2-user PNC scheme.

Today's Research Topics

- PNC-based NOMA with multiple antennas:
  - In the power-domain NOMA, the BS exploits the power difference to serve more than one user while using successive interference cancellation (SIC) at the receiver side to eliminate the inter-user interference.
- PNC-enabled Cell-Free systems:
  - In Cell Free networks, the users can receive data through multiple APs to achieve much higher data rates with lower variations compared to the cellular system.

Detection Schemes for PNC based NOMA

System Model

- The composite transmit symbol vector is defined by,

$$\mathbf{s} = \left[s_1, s_2\right]^T \tag{1}$$

where s_n; $n = 1, 2$ are the BPSK modulated symbols.

- The composite uplink channel matrix is given by,

$$\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2] \tag{2}$$

where $\mathbf{h}_n \in \mathbb{C}^{M \times 1}$; $n = 1, 2$ are the uplink channel vectors between the users and the base station (BS) in which is modelled by Rayleigh fading.

Uplink SIMO-PNC

- The received signal at the BS is expressed by,

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{n} \tag{3}$$

  where $\mathbf{n}$ is AWGN whose elements are Gaussian distributed random variable with zero mean and σ^2 variance.

- The sum-difference matrix is [1]:

$$\mathbf{D} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{4}$$

- The manipulated composite transmit symbol vector whose elements are the sum and difference of the users' transmit symbols is:

$$\hat{\mathbf{s}} = \mathbf{D}\mathbf{s} = \begin{bmatrix} s_1 + s_2 \\ s_1 - s_2 \end{bmatrix}. \tag{5}$$

[1] S.Zhang , S.C.Liew "Physical Layer Network Coding with Multiple Antennas" , *IEEE Wireless Communication and Networking Conference*, pp. 1-6, January 2010.

Uplink SIMO-PNC

- The manipulated composite channel matrix $\hat{\mathbf{H}}$ is:

$$\hat{\mathbf{H}} = \mathbf{H}\mathbf{D}^{-1} \tag{6}$$

- Then, the received vector in (3) is re-written by,

$$\mathbf{r} = \hat{\mathbf{H}}\hat{\mathbf{s}} + \mathbf{n} = \mathbf{H}\mathbf{D}^{-1}\mathbf{D}\mathbf{s} + \mathbf{n} \tag{7}$$

- Then, the received signal is equalized by,

$$\mathbf{y} = \mathbf{G}\mathbf{r} \tag{8}$$

where $\mathbf{G} = (\hat{\mathbf{H}}^H\hat{\mathbf{H}})^{-1}\hat{\mathbf{H}}^H$ is the ZF equalization matrix.

Uplink SIMO-PNC

- The LLR based detection can be utilized to detect the Network Coded Symbol (NCS) (that is ex-or between s_1 and s_2) [1]:

$$\mathrm{LLR} = \log\left(\frac{\exp\left(-\frac{2}{\sigma_2^2}\right)\left(\exp\left(\frac{2y_2}{\sigma_2^2}\right)+\exp\left(-\frac{2y_2}{\sigma_2^2}\right)\right)}{\exp\left(-\frac{2}{\sigma_1^2}\right)\left(\exp\left(\frac{2y_1}{\sigma_1^2}\right)+\exp\left(-\frac{2y_1}{\sigma_1^2}\right)\right)}\right) \quad (9)$$

where $\sigma_k^2; k = 1, 2$ are variances after equalization:

$$\sigma_k^2 = \{\mathbf{G}\mathbf{G}^H\}_{k,k}\sigma^2, \quad k \in \{1, 2\} \quad (10)$$

- The NCS is determined:

$$s_R = \begin{cases} 1 & \mathrm{LLR} \geq 0 \\ -1 & \text{otherwise} \end{cases} \quad (11)$$

[1] S.Zhang , S.C.Liew "Physical Layer Network Coding with Multiple Antennas" , *IEEE Wireless Communication and Networking Conference*, pp. 1-6, January 2010.

Uplink PNC-based SIMO-NOMA

- Uplink PNC-based NOMA system with multiple antennas through user selection has been introduced in [2] where the same modulation scheme for all users in a NOMA pair is employed.
- Uplink NOMA based PNC with multiple antennas scheme employing the LLR detection where different modulation schemes are used for strong and weak users in a NOMA pair [3].

[2] S.S.Yılmaz, B.Özbek, M.İlgüy, B.Okyere, L.Musavian and J.Gonzalez, "User Selection for NOMA-Based MIMO With Physical-Layer Network Coding in Internet of Things Applications", *IEEE Internet of Things Journal, vol. 9, no. 16, pp. 14998-15006, Aug. 2022.*

[3] M. İlgüy, B. Özbek, B. Okyere, L. Musavian, A. Pereira, "Physical Layer Network Coding Enabled NOMA with Multiple Antennas", *IEEE Conference on Standards for Communications and Networking (CSCN), Thessaloniki, Greece, 2022, pp. 176-180.*

Uplink PNC based SIMO-NOMA

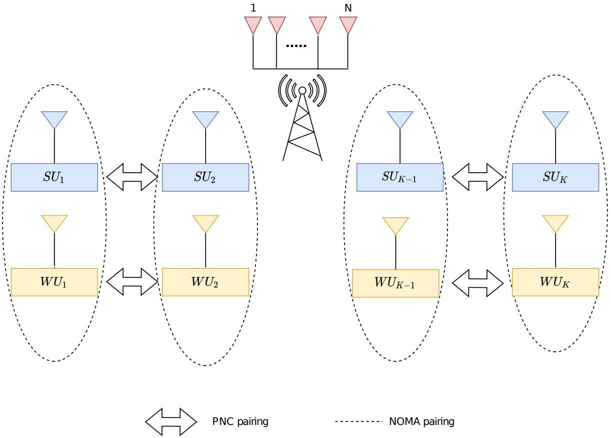

Figure 3: System model for uplink NOMA-PNC with multiple antennas.

Performance Results

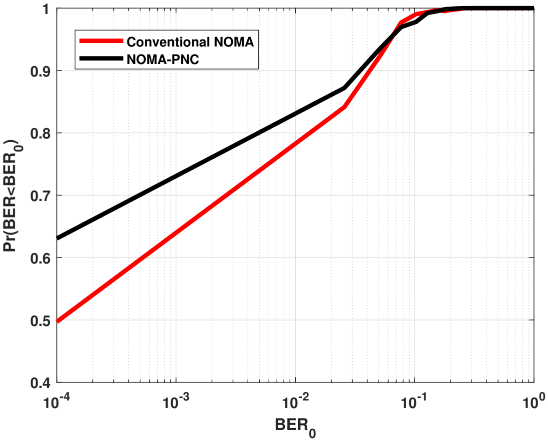

Figure 4: Comparison of the proposed PNC-NOMA and conventional NOMA with $N = 2, K_u = 4$, 16-QAM for SUs and 4-QAM for WUs.

Detection Schemes for PNC-enabled Cell Free

System Model for Cell Free (CF) MIMO

CF-MIMO network contains

- massive number of ubiquitous access points (APs), M
- less number of user equipments (UEs), K where $M \gg K$
- one or more central processing units (CPUs) to coordinate the APs.

✓ APs are cooperatively serving UEs in the same time/frequency band.

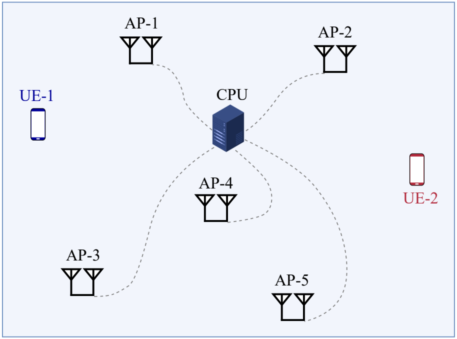

Figure 5: CF-MIMO Network

Uplink Transmission of CF-MIMO

- The received signal at the m^{th} AP is defined as

$$\mathbf{y}_m^{\mathrm{UL}} = \sum_{i=1}^{K} \mathbf{h}_{m,i} s_i + \mathbf{n}_m, \tag{12}$$

where $s_i \in \mathbb{C}$ is the signal transmitted by the i^{th} UE with the power $p_i = \mathbb{E}\{|s_i|^2\}$, and $\mathbf{n}_m \sim \mathcal{CN}(\mathbf{0}_N, \sigma_{\mathrm{UL}}^2 \mathbf{I}_N)$ is the receiver noise.

- The channel vector for m^{th} AP and k^{th} UE, $\mathbf{h}_{m,k} \in \mathbb{C}^{N\times 1}$ is defined by an uncorrelated Rayleigh fading, which is

$$\mathbf{h}_{m,k} \sim \mathcal{CN}(\mathbf{0}_N, \beta_{m,k} \mathbf{I}_N), \tag{13}$$

where $\beta_{m,k}$ describes the large-scale fading coefficient.

Uplink Transmission of CF-MIMO

- The m^{th} AP can compute an estimate of the signal s_k for the k^{th} UE.
- The estimate $\widehat{s}_{m,k}$ can be defined as

$$\widehat{s}_{m,k} = \mathbf{v}_{m,k}^{H} \, \mathbf{y}_{m}^{\mathrm{UL}}, \tag{14}$$

where $\mathbf{v}_{m,k} \in \mathbb{C}^{N \times 1}$ is the receive combining vector.

- Zero-forcing (ZF) combining matrix at the m^{th} AP is

$$\mathbf{V}_m = \mathbf{H}_m \left(\mathbf{H}_m^H \mathbf{H}_m \right)^{-1}, \tag{15}$$

where $\mathbf{H}_m = [\mathbf{h}_{m,1}, \mathbf{h}_{m,2}, \ldots, \mathbf{h}_{m,K}] \in \mathbb{C}^{N \times K}$ is the composite channel matrix for the m^{th} AP and $\mathbf{V}_m = [\mathbf{v}_{m,1}, \mathbf{v}_{m,2}, \ldots, \mathbf{v}_{m,K}] \in \mathbb{C}^{N \times K}$.

Detection for Conventional CF-MIMO

- The CPU gathers the local estimates of the data signals to compute its estimate such that

$$\widehat{s}_k^{\mathrm{CF}} = \sum_{m=1}^{M} \widehat{s}_{m,k}. \tag{16}$$

- The maximum likelihood (ML) detection of symbols $\widetilde{s}_k^{\mathrm{CF}}$ are determined through $\widehat{s}_k^{\mathrm{CF}}$ for $k = 1, 2, \ldots, K$ based on

$$\widetilde{s}_k^{\mathrm{CF}} = \begin{cases} +1, & \widehat{s}_k^{\mathrm{CF}} \geq 0 \\ -1, & \widehat{s}_k^{\mathrm{CF}} < 0 \end{cases} \tag{17}$$

where BPSK symbols are transmitted.

System Model for PNC-based CF-MIMO

- $Q = K/2$ user pairs

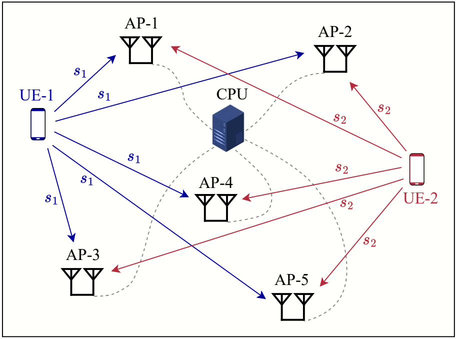

Figure 6: Uplink transmission of the PNC-based CF-MIMO system [5].

[5] İ. Cumalı, B. Özbek, and G. K. Kurt, "Detection Scheme for PNC-Based Cell-Free MIMO Systems", *2023 IEEE International Mediterranean Conference on Communications and Networking (MeditCom)*

Simulation Results

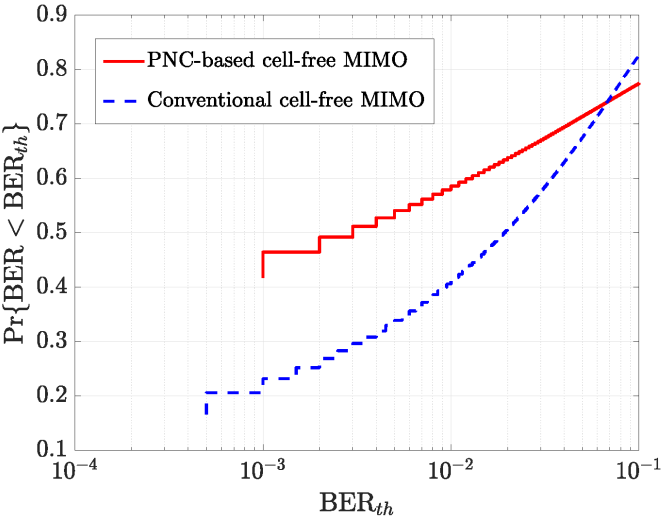

Figure 7: Uplink BER comparison for CF-MIMO with 5 APs.

Conclusion

- In the framework of RECENT project, the PNC schemes with multiple antennas are employed for 6G wireless systems.
- Novel detection schemes for **PNC-based SIMO-NOMA** and **PNC-based cell-free MIMO** for 6G wireless communication systems have been introduced.
- As future works, novel detection schemes for Reflective Intelligence Surface (RIS) enabled PNC schemes will be examined.

Thank you for your attention.