Wireless Network Coding with Intelligent Reflecting Surfaces

Amanat Kafizov

KAUST, Saudi Arabia

Outline

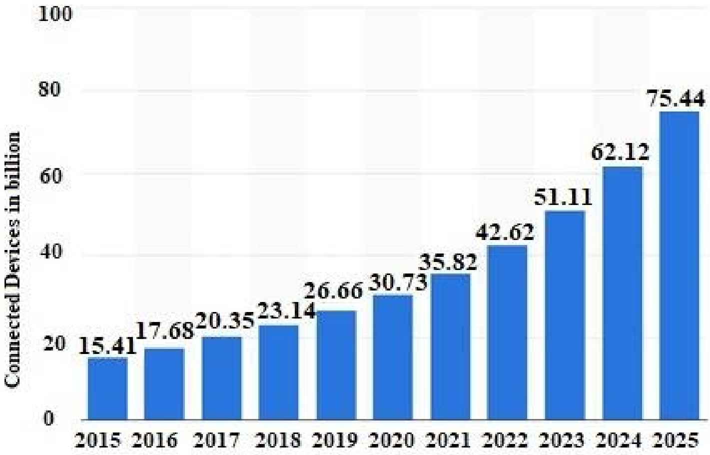

Figure: Predicted number of IoT devices connected to wireless networks

Introduction

Motivation

- Massive machine type communication (mMTC)
- Federated learning
- Ultra-fast wireless data aggregation
- Excessive network latency and low spectrum utilization efficiency
- Increase the capacity of wireless networks

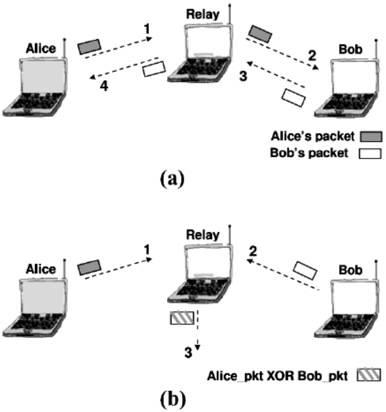

Figure: Practical Network Coding Approach: XOR in the air

- Exploiting the physical broadcast nature of wireless links
- Broadcasting can cause interference
- Takes advantage of broadcasting
- Increases throughput
- Requires higher bandwidth, millimeter wave (mm-Wave) band
- High path loss, susceptible to blockages
- Future sustainable networks

Introduction

IRS

- Flat surface comprising many small passive elements
- Can change phase of the incident signals [Wu and Zhang, 2019], [Subrt and Pechac, 2012]
- Doesn't need any dedicated energy source and doesn't consume any transmit power
- Can be integrated in the walls, ceilings and building facades [Nadeem et al., 2019], [Wu and Zhang, 2019]
- Improve the bit error rate (BER) performance of over-air-computation (OAC)

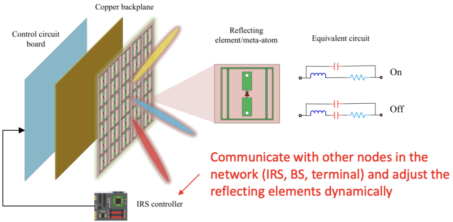

Figure: Hardware architecture [Wu and Zhang, 2019]

- PNC in an IRS-assisted environment
- Butterfly network model
- Propose algorithms for finding optimal phases of IRS and propose PNC scheme
- Derive theoretical BER of IRS-aided butterfly network
- Traditional multiple-input multiple-output (MIMO) network coding approach
- Analytical and simulation results

PNC in an IRS-assisted environment

System Model

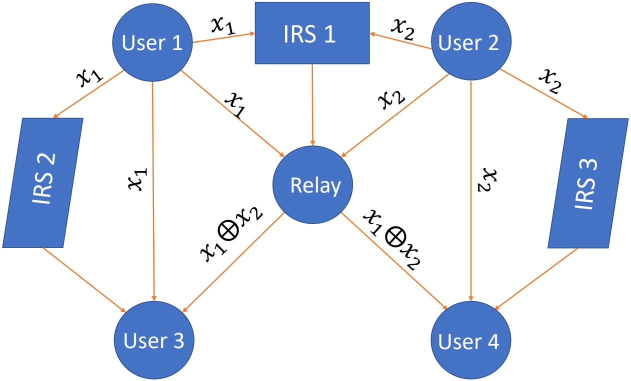

Figure: IRS-Aided Butterfly Network

The received signal at the relay node can be written in a matrix form as:

$$\boldsymbol{r} = \left(\boldsymbol{H}_{irs}^{re}\boldsymbol{\Theta}\boldsymbol{H}_{u}^{irs} + \boldsymbol{H}_{u}^{re}\right)\boldsymbol{x} + \boldsymbol{n} \triangleq \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n}, \quad (1)$$

where $\boldsymbol{\Theta} = \text{diag}\left(e^{j\theta_1}, e^{j\theta_2}, \ldots, e^{j\theta_M}\right)$ is the diagonal phase shift matrix of IRS with $\theta_m \in [0, 2\pi]$, $\boldsymbol{x} = [x_1, x_2]^T$ is the signal vector, and $\boldsymbol{n} = [n_1, n_2, \ldots, n_{N_r}]^T$ is the noise vector. We assume full channel state information (CSI) at the relay.
The received signal in (1) can be re-written in the following form:

$$\boldsymbol{r} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n} = \left(\boldsymbol{H}\boldsymbol{D}^{-1}\right)\left(\boldsymbol{D}\boldsymbol{x}\right) + \boldsymbol{n} = \widehat{\boldsymbol{H}}\widehat{\boldsymbol{x}} + \boldsymbol{n}, \quad (2)$$

where $\boldsymbol{D} = 2\boldsymbol{D}^{-1} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$ is the sum-difference matrix, and $\widehat{\boldsymbol{x}}$ is

$$\widehat{\boldsymbol{x}} = \begin{bmatrix} \widehat{x}_1 \\ \widehat{x}_2 \end{bmatrix} = \begin{bmatrix} x_1 + x_2 \\ x_1 - x_2 \end{bmatrix}. \quad (3)$$

We assume that the relay performs minimum mean square error (MMSE) estimation of $\widehat{\boldsymbol{x}}$ from $\boldsymbol{r}$. Hence, an estimate of $\widehat{\boldsymbol{x}}$ is $\boldsymbol{y}$, and it is derived as

$$\boldsymbol{y} = \boldsymbol{G}\boldsymbol{r} \tag{4}$$

with beamforming matrix $\boldsymbol{G} \in \mathbb{C}^{2\times N_r}$.

We derive the log likelihood ratio (LLR) to obtain $\widetilde{x_1 \oplus x_2}$ at the relay from both y_1 and y_2. Ignoring the noise dependencies in y_1 and y_2, the LLR is derived as:

$$\mathrm{LLR}\left(x_1 \oplus x_2 | y_1 y_2\right) = \log\left(\frac{\mathbb{P}\{y_1 y_2 | x_1 \oplus x_2 = 1\}}{\mathbb{P}\{y_1 y_2 | x_1 \oplus x_2 = -1\}}\right) \tag{5}$$

The corresponding decision rule is then:

$$\widetilde{x_1 \oplus x_2} = \begin{cases} 1 & \text{when } \mathrm{LLR}\left(x_1 \oplus x_2 | y_1 y_2\right) \geq 0 \\ -1 & \text{when } \mathrm{LLR}\left(x_1 \oplus x_2 | y_1 y_2\right) < 0 \end{cases}. \tag{6}$$

The optimization problem can be written as:

$$\underset{\boldsymbol{\Theta},\boldsymbol{G}}{\text{minimize}} \quad \text{MSE} \triangleq \mathrm{E}\left[\|\boldsymbol{y}(\boldsymbol{\Theta},\boldsymbol{G}) - \widehat{\boldsymbol{x}}\|^2\right] \tag{7a}$$

$$\text{subject to} \quad 0 \leq \theta_j \leq 2\pi,\ j \in 1, 2, \ldots, M \tag{7b}$$

- Propose an iterative algorithm
- Matrix lifting approach
- CVX in Matlab

Analytical and simulation results

Performance gain due to IRS

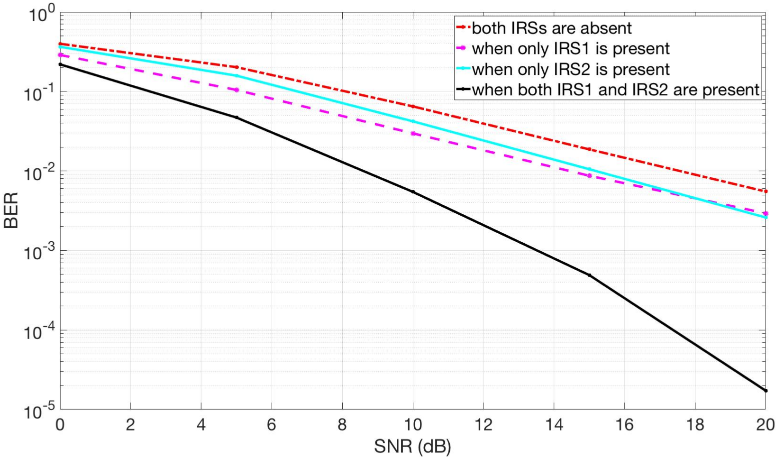

Figure: BER calculated at user 3 vs SNR for four different cases

Analytical and simulation results

Performance gain due to network coding

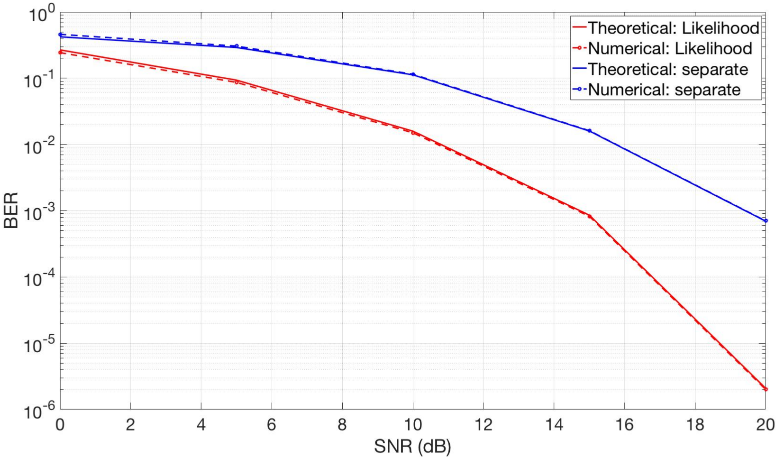

Figure: BER calculated at the relay for BPSK modulation

Conclusion

- Proposed IRS-aided PNC to improve network's capacity and BER performance
- Jointly optimizing the IRS phases and the beamforming matrix at the relay
- Better capacity and better performance in terms of BER
- more complicated network model


Questions?
Thanks for your attention!

References I

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