Fairness-Aware Hybrid Precoding for mmWave NOMA Unicast/Multicast Transmissions in Industrial IoT

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- Due to rapid densification of industrial devices, wired connections become less appealing for factories of the future.

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- Wired connections hinder automation deployment and constrain the mobile robotics mechanics.
- Due to rapid densification of industrial devices, wired connections become less appealing for factories of the future.
- Wireless information transmission is a viable alternative for these environments.

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- In factories, multiple industrial devices are inherently hyper-connected via hard-wiring to ensure safety.
- Wired connections hinder automation deployment and constrain the mobile robotics mechanics.
- Due to rapid densification of industrial devices, wired connections become less appealing for factories of the future.
- Wireless information transmission is a viable alternative for these environments.
- However, guaranteeing high performance in terms of fairness, spectral efficiency and reliability is a challenging task.

Problem Overview

We investigate dual-layer non-orthogonal transmissions for industrial IoT millimeter-wave communications.
Primary layer: ubiquitous multicast signal devised to serve all the devices with a common message
Secondary layer: composite signal consisting of private unicast messages.
We jointly optimize the *hybrid precoder*, *analog combiners*, *power allocation*, and *fairness*. The performance is evaluated in terms of the spectral efficiency, fairness, and bit error rate.

Solution Overview

We propose two solutions:

PLDM−1: designs independently the multicast precoder from the unicast precoders

PLDM−2: the multicast precoder is obtained as a combination of the unicast precoding vectors

Non-Orthogonal Unicast/Multicast System

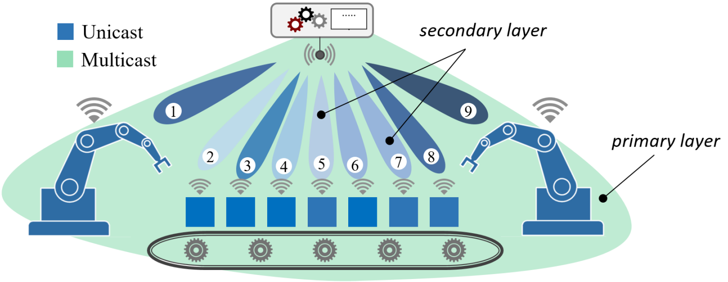

Figure: K-user Non-Orthogonal Unicast/Multicast System

Hybrid Precoder

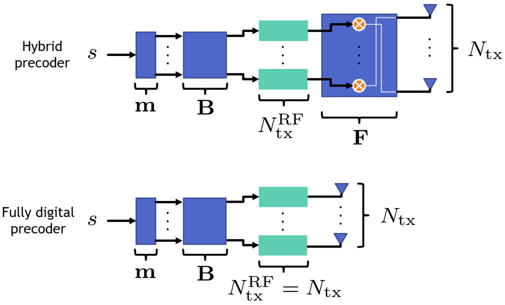

Figure: Hybrid and fully-digital precoders

$\mathbf{m} \in \mathbb{C}^{N_{\text{tx}}^{\text{RF}} \times 1}$: multicast digital precoder

$\mathbf{B} \in \mathbb{C}^{N_{\text{tx}}^{\text{RF}} \times N_{\text{tx}}^{\text{RF}}}$: unicast digital precoder

$\mathbf{F} \in \mathcal{F}^{N_{\text{tx}} \times N_{\text{tx}}^{\text{RF}}}$: analog precoder

$\mathcal{F} = \left\{ \sqrt{\delta_{\text{tx}}}, \dots, \sqrt{\delta_{\text{tx}}} e^{\frac{2\pi(L_{\text{tx}}-1)}{L_{\text{tx}}}} \right\}$: set of phase shifts

N_{tx}: number of transmit antennas

$N_{\text{tx}}^{\text{RF}}$: number of RF chains

L_{tx}: number of phase shifts

System Model

The downlink signal is

$$\mathbf{x} = \mathbf{F}\left[\mathbf{B}|\mathbf{m}\right]\left[\mathbf{s}|z\right]^T \quad (1)$$

where

$\mathbf{F} = [\mathbf{f}_1, \mathbf{f}_2, \ldots, \mathbf{f}_K] \in \mathbb{C}^{N_{\text{tx}} \times K}$: analog precoder

$\mathbf{B} = [\mathbf{b}_1, \mathbf{b}_2, \ldots, \mathbf{b}_K] \in \mathbb{C}^{K \times K}$: digital unicast precoder

$\mathbf{m} = [m_1, m_2, \ldots, m_K]^T \in \mathbb{C}^{K \times 1}$: digital multicast precoder

$\mathbf{s} = [s_1, s_2, \ldots, s_K]^T \in \mathbb{C}^{K \times 1}$: unicast symbols

$z \in \mathbb{C}$: multicast symbol

Throughout the paper we assume that $N_{\text{tx}}^{\text{RF}} = K$

System Model

The received signal at user $k \in \mathcal{K}$ is

$$y_k = \underbrace{\mathbf{w}_k^H \mathbf{H}_k \mathbf{F} \mathbf{m} z}_{\text{common multicast signal}} + \underbrace{\mathbf{w}_k^H \mathbf{H}_k \mathbf{F} \mathbf{b}_k s_k}_{\text{unicast signal for device } k} + \underbrace{\mathbf{w}_k^H \mathbf{H}_k \mathbf{F} \sum_{j \neq k} \mathbf{b}_j s_j}_{\text{interference at device } k} + \underbrace{\mathbf{w}_k^H \mathbf{n}_k}_{\text{noise}}, \quad (2)$$

$\mathbf{w}_k$: combiner of the k-th user
$\mathbf{H}_k$: channel between the gNodeB and the k-th user
$\mathcal{K} = \{1, \dots, K\}$: set of users
K: number of users

System Model

The multicast and unicast SINRs at $k \in \mathcal{K}$ are

$$\tilde{\gamma}_k = \frac{\left|\mathbf{w}_k^H \mathbf{H}_k \mathbf{F} \mathbf{m}\right|^2}{\sum_j \left|\mathbf{w}_k^H \mathbf{H}_k \mathbf{F} \mathbf{b}_j\right|^2 + \sigma^2 \left\|\mathbf{w}_k\right\|_2^2} \tag{3}$$

$$\gamma_k = \frac{\left|\mathbf{w}_k^H \mathbf{H}_k \mathbf{F} \mathbf{b}_k\right|^2}{\sum_{j \neq k} \left|\mathbf{w}_k^H \mathbf{H}_k \mathbf{F} \mathbf{b}_j\right|^2 + \sigma^2 \left\|\mathbf{w}_k\right\|_2^2}. \tag{4}$$

$\tilde{\gamma}_k$: multicast SINR at the k-th user
γ_k: unicast SINR at the k-th user

Problem Formulation

$$\mathcal{P}: \max_{\{\mathbf{w}_k\}_{k=1}^K, \{\mathbf{f}_k\}_{k=1}^K, \{\mathbf{b}_k\}_{k=1}^K, \mathbf{m}, \Delta} \sum_k \log_2(1+\tilde{\gamma}_k) + \log_2(1+\gamma_k) - C'\Delta \quad (5a)$$

$$\text{s.t.} \quad |\tilde{\gamma}_k - \gamma_{\min}| \leq \Delta, \forall k \in \mathcal{K}, \quad (5b)$$

$$\tilde{\gamma}_1 \geq \tilde{\gamma}_2 \geq \ldots \geq \tilde{\gamma}_K \geq \tilde{\gamma}_1, \quad (5c)$$

$$\|\mathbf{F}\mathbf{m}\|_2^2 / \sum_k \|\mathbf{F}\mathbf{b}_k\|_2^2 \geq \beta, \quad (5d)$$

$$\|\mathbf{F}\mathbf{m}\|_2^2 + \sum_k \|\mathbf{F}\mathbf{b}_k\|_2^2 \leq P_{\text{tx}}, \quad (5e)$$

$$[\mathbf{F}]_{q,r} \in \mathcal{F}, q \in \mathcal{Q}, r \in \mathcal{R}, \quad (5f)$$

$$[\mathbf{w}_k]_n \in \mathcal{W}, n \in \mathcal{N}, \forall k \in \mathcal{K}, \quad (5g)$$

$$\Delta \geq 0, \quad (5h)$$

$\mathcal{F}$: allowed phase shifts at the precoder
$\mathcal{W}$: allowed phase shifts at the combiners

Proposed Solution

$$\mathcal{P}_0: \max_{\substack{\{\mathbf{w}_k\}_{k=1}^K, \{\mathbf{f}_k\}_{k=1}^K, \\ \{p_k\}_{k=1}^K, \{\mathbf{v}_k\}_{k=1}^K, \mathbf{m}, \Delta}} \quad \sum_k \tilde{\gamma}_k + \gamma_k - C\Delta \tag{6a}$$

$$\text{s.t.} \quad \left|\tilde{\gamma}_k - \gamma_{\min}\right| \leq \Delta, \forall k \in \mathcal{K}, \tag{6b}$$

$$\tilde{\gamma}_1 \geq \tilde{\gamma}_2 \geq \ldots \geq \tilde{\gamma}_K \geq \tilde{\gamma}_1, \tag{6c}$$

$$\left\|\mathbf{F}\mathbf{m}\right\|_2^2 / \sum_k p_k \left\|\mathbf{F}\mathbf{v}_k\right\|_2^2 \geq \beta, \tag{6d}$$

$$\left\|\mathbf{F}\mathbf{m}\right\|_2^2 + \sum_k p_k \left\|\mathbf{F}\mathbf{v}_k\right\|_2^2 \leq P_{\mathrm{tx}}, \tag{6e}$$

$$\left[\mathbf{F}\right]_{q,r} \in \mathcal{F}, q \in \mathcal{Q}, r \in \mathcal{R}, \tag{6f}$$

$$\left[\mathbf{w}_k\right]_n \in \mathcal{W}, n \in \mathcal{N}, \forall k \in \mathcal{K}, \tag{6g}$$

$$\left\|\mathbf{v}_k\right\|_2^2 = 1, \forall k \in \mathcal{K}, \tag{6h}$$

$$p_k \geq 0, \forall k \in \mathcal{K}, \tag{6i}$$

$$\Delta \geq 0, \forall k \in \mathcal{K}, \tag{6j}$$

Proposed Solution

$$\mathcal{P}_1: \max_{\{\mathbf{w}_k\}_{k=1}^K, \{\mathbf{f}_k\}_{k=1}^K, \{\mathbf{v}_k\}_{k=1}^K} \quad \sum_k \gamma_k \tag{7a}$$

$$\text{s.t.} \quad [\mathbf{F}]_{q,r} \in \mathcal{F}, q \in \mathcal{Q}, r \in \mathcal{R}, \tag{7b}$$

$$[\mathbf{w}_k]_n \in \mathcal{W}, n \in \mathcal{N}, \forall k \in \mathcal{K}, \tag{7c}$$

$$\|\mathbf{v}_k\|_2^2 = 1, \forall k \in \mathcal{K}. \tag{7d}$$

$$\mathcal{P}_2: \max_{\{p_k\}_{k=1}^K, \mathbf{m}, \Delta} \quad \sum_k \tilde{\gamma}_k + \gamma_k - C\Delta \tag{8a}$$

$$\text{s.t.} \quad |\tilde{\gamma}_k - \gamma_{\min}| \leq \Delta, \forall k \in \mathcal{K}, \tag{8b}$$

$$\tilde{\gamma}_1 \geq \tilde{\gamma}_2 \geq \ldots \geq \tilde{\gamma}_K \geq \tilde{\gamma}_1, \tag{8c}$$

$$\|\mathbf{F}\mathbf{m}\|_2^2 / \sum_k p_k \|\mathbf{F}\mathbf{v}_k\|_2^2 \geq \beta, \tag{8d}$$

$$\|\mathbf{F}\mathbf{m}\|_2^2 + \sum_k p_k \|\mathbf{F}\mathbf{v}_k\|_2^2 \leq P_{\text{tx}}, \tag{8e}$$

$$p_k \geq 0, \forall k \in \mathcal{K}, \tag{8f}$$

$$\Delta \geq 0. \tag{8g}$$

Optimization of $\{\mathbf{w}_k\}_{k=1}^K$, $\{\mathbf{f}_k\}_{k=1}^K$, $\{\mathbf{v}_k\}_{k=1}^K$

$$\mathcal{P}_{1,1}: \max_{\{\mathbf{w}_k\}_{k=1}^K, \{\mathbf{f}_k\}_{k=1}^K} \sum_k p_k \left| \mathbf{w}_k^H \mathbf{H}_k \mathbf{F} \mathbf{v}_k \right|^2 \tag{9a}$$

$$\text{s.t.} \quad [\mathbf{F}]_{q,r} \in \mathcal{F}, q \in \mathcal{Q}, r \in \mathcal{R}, \tag{9b}$$

$$[\mathbf{w}_k]_n \in \mathcal{W}, n \in \mathcal{N}, \forall k \in \mathcal{K}. \tag{9c}$$

$$\mathcal{P}_{1,2}: \min_{\{\mathbf{v}_k\}_{k=1}^K} \sum_k \sum_{j \neq k} p_j \left| \mathbf{w}_k^H \mathbf{H}_k \mathbf{F} \mathbf{v}_j \right|^2 \tag{10a}$$

$$\text{s.t.} \quad \|\mathbf{v}_k\|_2^2 = 1, \forall k \in \mathcal{K}. \tag{10b}$$

Optimization of $\{p_k\}_{k=1}^{K}$, $\mathbf{m}$, Δ

$$\mathcal{P}_2: \max_{\{p_k\}_{k=1}^{K},\mathbf{m},\Delta} \quad \sum_k \tilde{\gamma}_k + \gamma_k - C\Delta \tag{11a}$$

$$\text{s.t.} \quad |\tilde{\gamma}_k - \gamma_{\min}| \leq \Delta, \forall k \in \mathcal{K}, \tag{11b}$$

$$\tilde{\gamma}_1 \geq \tilde{\gamma}_2 \geq \ldots \geq \tilde{\gamma}_K \geq \tilde{\gamma}_1, \tag{11c}$$

$$\|\mathbf{Fm}\|_2^2 \,/ \sum_k p_k \|\mathbf{F}\mathbf{v}_k\|_2^2 \geq \beta, \tag{11d}$$

$$\|\mathbf{Fm}\|_2^2 + \sum_k p_k \|\mathbf{F}\mathbf{v}_k\|_2^2 \leq P_{\text{tx}}, \tag{11e}$$

$$p_k \geq 0, \forall k \in \mathcal{K}, \tag{11f}$$

$$\Delta \geq 0. \tag{11g}$$

Optimization of $\{p_k\}_{k=1}^{K}$, $\mathbf{m}$, Δ

$$
\begin{aligned}
\widetilde{\mathcal{P}}_2 : \max_{\{p_k\}_{k=1}^K, \{\mu_k\}_{k=1}^K, \{\upsilon_k\}_{k=1}^K, \mathbf{m}, \Delta} \quad & \sum_k \mu_k + \upsilon_k - C\Delta && \text{(12a)} \\
\text{s.t.} \quad & \left|\mathbf{h}_k^{\text{eff}} \mathbf{m}\right|^2 / \left(p_k \left|g_k\right|^2 + \sigma^2\right) \geq \mu_k, \forall k \in \mathcal{K}, && \text{(12b)} \\
& p_k \left|g_k\right|^2 / \sigma^2 \geq \upsilon_k, \forall k \in \mathcal{K}, && \text{(12c)} \\
& \|\mathbf{F}\mathbf{m}\|_2^2 / \sum_k p_k \|\mathbf{F}\mathbf{v}_k\|_2^2 \geq \beta, && \text{(12d)} \\
& \|\mathbf{F}\mathbf{m}\|_2^2 + \sum_k p_k \|\mathbf{F}\mathbf{v}_k\|_2^2 \leq P_{\text{tx}}, && \text{(12e)} \\
& \mu_1 \geq \mu_2 \geq \ldots \geq \mu_K \geq \mu_1, && \text{(12f)} \\
& \mu_k \leq \gamma_{\min} + \Delta, \forall k \in \mathcal{K}, && \text{(12g)} \\
& \mu_k \geq \gamma_{\min} - \Delta, \forall k \in \mathcal{K}, && \text{(12h)} \\
& \upsilon_k \geq 0, \forall k \in \mathcal{K}, && \text{(12i)} \\
& p_k \geq 0, \forall k \in \mathcal{K}, && \text{(12j)} \\
& \Delta \geq 0, && \text{(12k)}
\end{aligned}
$$

Optimization of $\{p_k\}_{k=1}^{K}$, $\mathbf{m}$, Δ

$$\widetilde{\mathcal{P}}_2^{(t)} : \max_{\mathbf{m},\mathbf{p},\boldsymbol{\mu},\boldsymbol{\upsilon},\Delta} \quad \mathbf{1}^T\boldsymbol{\mu} + \mathbf{1}^T\boldsymbol{\upsilon} - C\Delta \tag{13a}$$

s.t.

$$2\mathfrak{Re}\left\{\mathrm{diag}\left(\mathbf{A}\mathbf{p}^{(t)} + \mathbf{d}\right)\left(\mathbf{I}\otimes\mathbf{m}^{(t)\,H}\right)\mathbf{C}\left(\mathbf{1}\otimes\mathbf{m}\right)\right\}$$
$$-\,\mathrm{diag}\left(\mathbf{A}\mathbf{p} + \mathbf{d}\right)\left(\mathbf{I}\otimes\mathbf{m}^{(t)\,H}\right)\mathbf{C}\left(\mathbf{1}\otimes\mathbf{m}^{(t)}\right) -$$
$$\mathrm{diag}\left(\mathbf{A}\mathbf{p}^{(t)} + \mathbf{d}\right)\mathrm{diag}\left(\mathbf{A}\mathbf{p}^{(t)} + \mathbf{d}\right)\boldsymbol{\mu} \succcurlyeq \mathbf{0}, \tag{13b}$$

$$\left(\mathbf{A}\odot\left(\mathrm{diag}\left(\mathbf{d}\right)\right)^{-1}\right)\mathbf{p} \succcurlyeq \boldsymbol{\upsilon}, \tag{13c}$$

$$2\mathfrak{Re}\left\{\left(\mathbf{c}^T\mathbf{p}^{(t)}\mathbf{m}^{(t)\,H}\mathbf{F}^H\mathbf{F}\mathbf{m}\right)\right\} -$$
$$\mathbf{c}^T\mathbf{p}\mathbf{m}^{(t)\,H}\mathbf{F}^H\mathbf{F}\mathbf{m}^{(t)} - \left(\mathbf{c}^T\mathbf{p}^{(t)}\right)^2\beta \geq 0, \tag{13d}$$

$$\|\mathbf{F}\mathbf{m}\|_2^2 + \sum_k p_k\,\|\mathbf{F}\mathbf{v}_k\|_2^2 \leq P_{\mathrm{tx}}, \tag{13e}$$

$$\left(\mathbf{I} - \widetilde{\mathbf{I}}\right)\boldsymbol{\mu} \succcurlyeq \mathbf{0}, \tag{13f}$$

$$\boldsymbol{\mu} \preccurlyeq \left(\gamma_{\min} + \Delta\right)\mathbf{1}, \tag{13g}$$

$$\boldsymbol{\mu} \succcurlyeq \left(\gamma_{\min} - \Delta\right)\mathbf{1}, \tag{13h}$$

$$\boldsymbol{\upsilon} \succcurlyeq \mathbf{0}, \tag{13i}$$

$$\mathbf{p} \succcurlyeq \mathbf{0}, \tag{13j}$$

$$\Delta \geq 0. \tag{13k}$$

Simulation Results

Table: Simulation parameters

Description	Symbol	Value	Units
Number of users	K	6	-
Number of transmit antennas	N_{tx}	64	-
Number of receive antennas	N_{rx}	4	-
Number of RF chains (at the hybrid precoder)	$N_{\text{tx}}^{\text{RF}}$	6	-
Number of phase shifts at the precoder	L_{tx}	32	-
Number of phase shifts at the combiner	L_{rx}	4	-
Multicast QoS requirement	γ_{min}	5	dB

Simulation Results - Spectral Efficiency

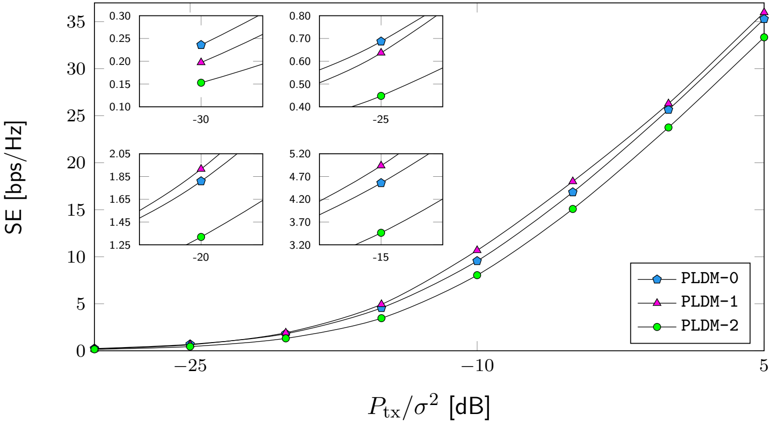

Figure: Overall SE of the system

Simulation Results - Spectral Efficiency

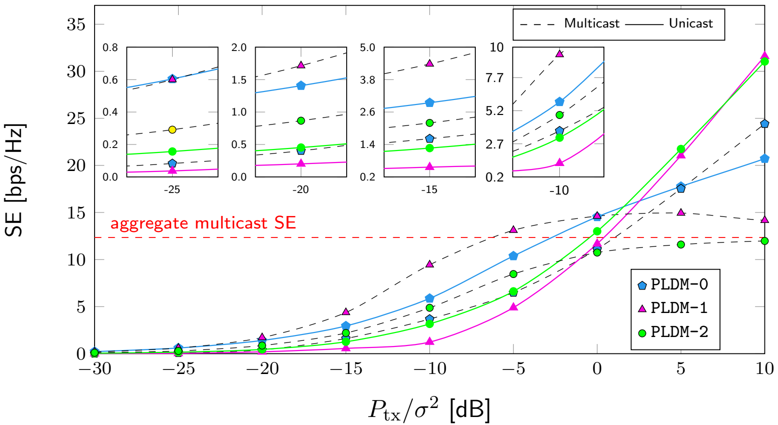

Figure: Disaggregated SE of the system

Simulation Results - Multicast Fairness

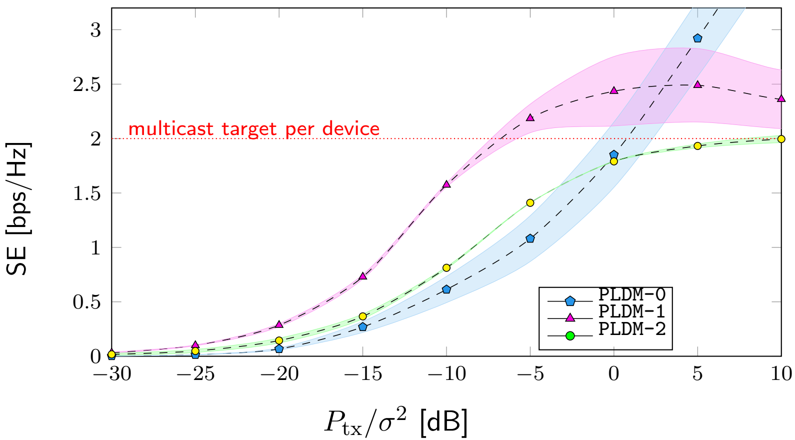

Figure: Multicast SE per device

Simulation Results - BER

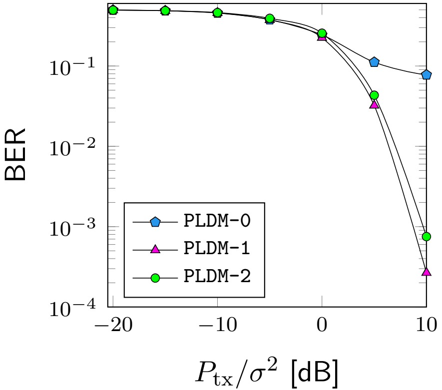

Figure: Aggregate

Simulation Results - Multicast BER

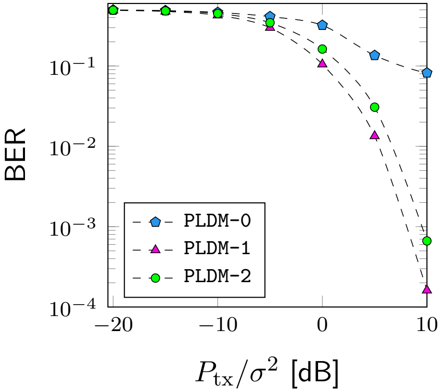

Figure: Multicast

Simulation Results - Unicast BER

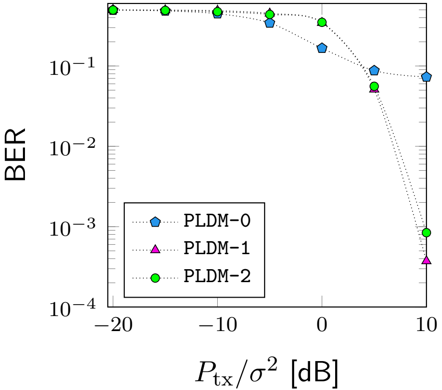

Figure: Unicast

Conclusions

- We investigated the joint optimization of hybrid precoding, fairness, and power splitting in NOMA-LDM superimposed transmissions for industrial IoT scenarios.
- We proposed two solutions: one of them regarded as the superposition of two distinct precoders with different spatial and power signatures. The second approach is designed as a purely power-domain NOMA scheme.
- Through simulations we show that both proposed schemes, `PLDM-1` and `PLDM-2`, are capable of providing remarkable fairness and high BER, which is relevant for the dissemination of critical control messages in this kind of scenarios.

Questions

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