Full-Duplex Transmission Optimization for Bi-directional MIMO links with QoS Guarantees

Hiroki Iimori†, Giuseppe Thadeu Freitas de Abreu‡ and George C. Alexandropoulos*
† Dep. of EEE, Ritsumeikan University 1-1-1 Noji-higashi, Kusatsu, Shiga, 525-8577 Japan
E-mails: `h.iimori@ieee.org`
‡ Dep. of CS. & EE., Jacobs University Bremen Campus Ring 1, 28759, Bremen, Germany
E-mails: `g.abreu@jacobs-university.de`
* Mathematical and Algorithmic Sciences Lab, Huawei Technologies France SASU, 92100 Boulogne-Billancourt, France
E-mails: `george.alexandropoulos@huawei.com`

Abstract - **We consider a bi-directional Full-Duplex (FD) Multiple-Input Multiple-Output (MIMO) communication system in which nodes are capable of performing transitter (TX)-Receiver (RX) digital precoding/combining and multi-tap analog cancellation, and have individual Signal-to-Interference-plus-noise Ratio (SINR) requirements. We present an iterative algorithm for the TX powers minimization that includes closed-form expressions for the TX/RX digital beamformers at each algorithmic iteration step. Simulation results demonstrate that the proposed algorithm can reduce residual Self-Interference (SI) to below -110 dB and outperform relevant recent solutions proposed for 2-user MIMO systems in terms of both power efficiency and computational complexity.**

I. SYSTEM MODEL

Consider the two-way FD MIMO communication system illustrated in Figure 1. This system consists of two nodes in which each equipped with M TX and N RX antennas and both are assumed to transmit and receive simultaneously to/from one another in the same resource unit. A generic k-th node, with $k \in \{1,2\}$, is assumed to employ the digital TX precoding vector $\boldsymbol{v}_k \in \mathbb{C}^{M\times 1}$ and the digital RX Beamforming (BF) vector $\boldsymbol{u}_k \in \mathbb{C}^{1\times N}$, as well as the multi-tap analog cancellation matrix $\boldsymbol{C}_k \in \mathbb{C}^{N\times M}$ [1], [2].

Signal Model with TX-RX Beamforming

From all the above, the received signal and the corresponding estimated signal at the k-th node can be written as

$$\begin{aligned}\boldsymbol{y}_k &= \boldsymbol{H}_{\ell k}\boldsymbol{v}_\ell s_\ell + (\boldsymbol{H}_{kk} - \boldsymbol{C}_k)\,\boldsymbol{v}_k s_k + \boldsymbol{n}_k \\ &= \underbrace{\boldsymbol{H}_{\ell k}\boldsymbol{v}_\ell s_\ell}_{\text{Intended}} + \underbrace{\tilde{\boldsymbol{H}}_{kk}\boldsymbol{v}_k s_k}_{\text{SI}} + \underbrace{\boldsymbol{n}_k}_{\text{Noise}}, \qquad (1)\end{aligned}$$

$$\begin{aligned}\tilde{s}_\ell &= \boldsymbol{u}_k\boldsymbol{y}_k \qquad (2)\\ &= \boldsymbol{u}_k\boldsymbol{H}_{\ell k}\boldsymbol{v}_\ell s_\ell + \boldsymbol{u}_k\tilde{\boldsymbol{H}}_{kk}\boldsymbol{v}_k s_k + \boldsymbol{u}_k\boldsymbol{n}_k.\end{aligned}$$

where $\boldsymbol{C}_k$ consists of N_{tap} non-zeros and $MN - N_{\text{tap}}$ zeros with $k \neq \ell \in \{1,2\}$, $\boldsymbol{n}_k \sim \mathcal{CN}\left(0, \sigma^2\boldsymbol{I}_N\right)$, and $\tilde{\boldsymbol{H}}_{kk} = \boldsymbol{H}_{kk} - \boldsymbol{C}_k$.

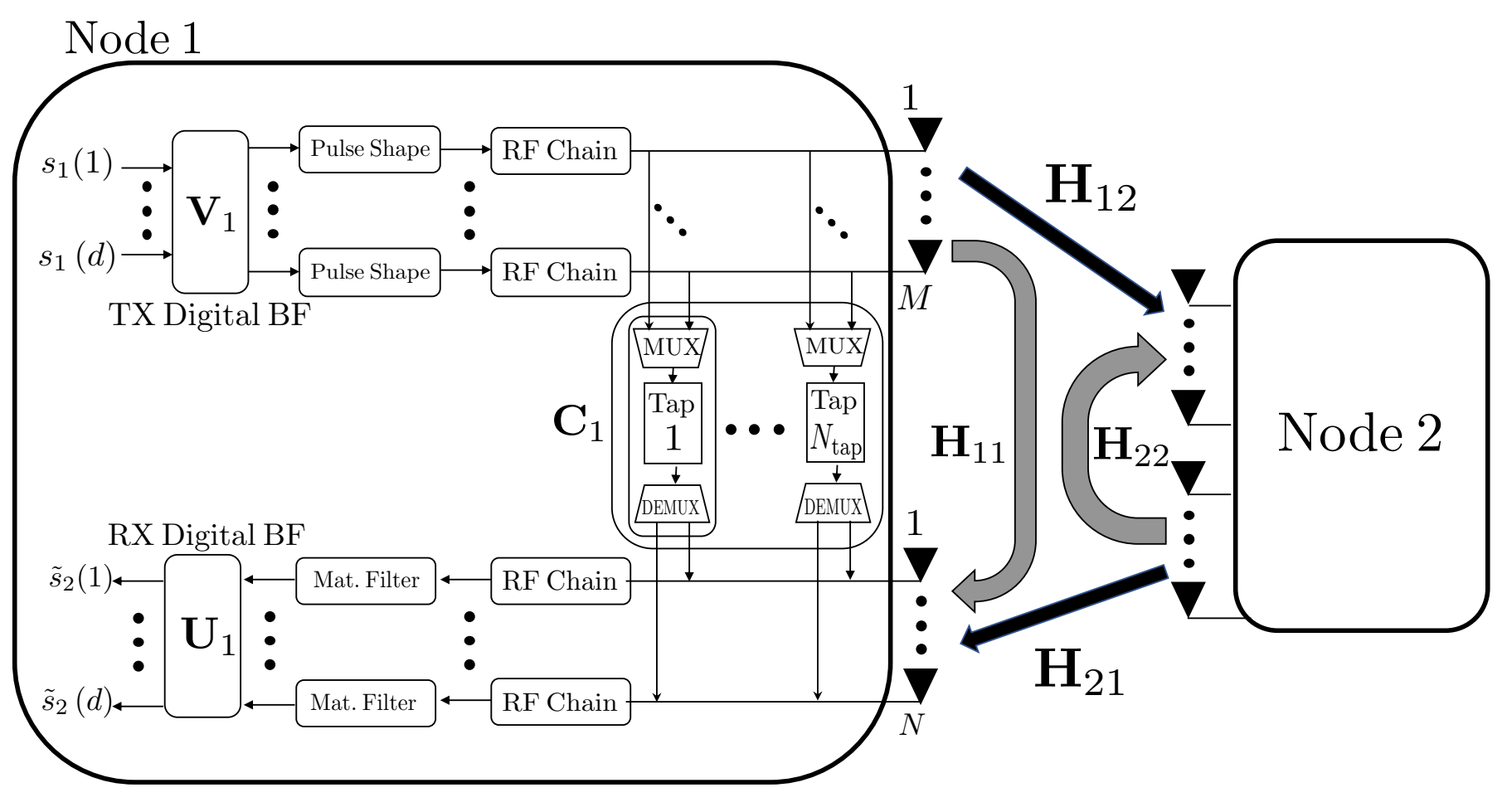

Fig. 1. System model of two-way full duplex MIMO with reduced hardware multi-tap analog cancellation.

From equations (2), it follows that the average SINR estimates at k-th node is given as follows.

$$\gamma_k = \frac{|\boldsymbol{u}_k\boldsymbol{H}_{\ell k}\boldsymbol{v}_\ell|^2}{\left|\boldsymbol{u}_k\tilde{\boldsymbol{H}}_{kk}\boldsymbol{v}_k\right|^2 + \sigma^2} \qquad (3)$$

where we assume that the channel matrices in equation (3) are constant for a number of signal transmissions and the RX combining vector $\boldsymbol{u}_k, \forall k$ has a unit norm, i.e., $||\boldsymbol{u}_k||^2 = 1$.

II. PROPOSED MMSE TX-RX BEAMFORMING DESIGN

Despite the fact that the joint TX-RX linear precoding/combining techniques with the aim of maximizing data rate while suppressing the residual SI power level have been proposed in the past, maximizing data rate is, however, not typically required by actual users, which instead tend to perceive the quality of a communication system by comparing it to a given level of expectation dictated by the intended application. We therefore consider instead the TX-RX beamformer optimization problem aiming at minimizing the individual TX powers while satisfying individual target SINR requirements:

$$\begin{aligned}\min_{\boldsymbol{v}_k,\boldsymbol{v}_\ell,\boldsymbol{u}_k,\boldsymbol{u}_\ell} \quad & \sum_{k=1}^{2} ||\boldsymbol{v}_k||^2 \qquad (4a)\\ \text{s.t.} \quad & \gamma_k \geqslant \Gamma_k \ \forall k, \qquad (4b)\end{aligned}$$

where Γ_k is the target SINR for the k-th node.

TX Power Minimization with SINR Constraints via Rayleigh Quotient

Let us define the normalized precoding vector $\bar{\boldsymbol{v}}_k \triangleq \frac{\boldsymbol{v}_k}{||\boldsymbol{v}_k||}$ and the TX power $P_k = ||\boldsymbol{v}_k||^2$ such that the optimization problem in (4) can be rewritten as

$$\begin{aligned}\min_{P_1,P_2} \quad & \sum_{k=1}^{2} P_k \qquad (5a)\\ \text{s.t.} \quad & \gamma_k \geqslant \Gamma_k \ \forall k. \qquad (5b)\end{aligned}$$

which yields

$$\boldsymbol{p} = \sigma^2\left(\mathbf{I} - \boldsymbol{\Gamma}\boldsymbol{M}\right)^{-1}\boldsymbol{\Gamma}\boldsymbol{m}. \qquad (6)$$

where $\boldsymbol{p} \triangleq [P_1, P_2]^{\mathrm{T}}$, $\boldsymbol{\Gamma} = \begin{bmatrix} 0 & \Gamma_2 \\ \Gamma_1 & 0 \end{bmatrix}$, $\boldsymbol{M} = \begin{bmatrix} \frac{|\boldsymbol{u}_1\tilde{\boldsymbol{H}}_{11}\bar{\boldsymbol{v}}_1|^2}{|\boldsymbol{u}_1\boldsymbol{H}_{21}\bar{\boldsymbol{v}}_2|^2} & 0 \\ 0 & \frac{|\boldsymbol{u}_2\tilde{\boldsymbol{H}}_{22}\bar{\boldsymbol{v}}_2|^2}{|\boldsymbol{u}_2\boldsymbol{H}_{12}\bar{\boldsymbol{v}}_1|^2} \end{bmatrix}$ and $\boldsymbol{m} = \begin{bmatrix} |\boldsymbol{u}_1\boldsymbol{H}_{21}\bar{\boldsymbol{v}}_2|^{-2} \\ |\boldsymbol{u}_2\boldsymbol{H}_{12}\bar{\boldsymbol{v}}_1|^{-2} \end{bmatrix}$.

Design of RX beamforming $\boldsymbol{u}_k$

$$\max_{\substack{\boldsymbol{u}_k \\ ||\boldsymbol{u}_k||^2=1}} \frac{\boldsymbol{u}_k\overbrace{\boldsymbol{H}_{\ell k}\boldsymbol{v}_\ell\boldsymbol{v}_\ell^{\mathrm{H}}\boldsymbol{H}_{\ell k}^{\mathrm{H}}}^{\triangleq \boldsymbol{Q}_{\boldsymbol{u}_k}}\boldsymbol{u}_k^{\mathrm{H}}}{\boldsymbol{u}_k\underbrace{\left(\tilde{\boldsymbol{H}}_{kk}\boldsymbol{v}_k\boldsymbol{v}_k^{\mathrm{H}}\tilde{\boldsymbol{H}}_{kk}^{\mathrm{H}} + \sigma^2\mathbf{I}\right)}_{\triangleq \boldsymbol{W}_{\boldsymbol{u}_k}}\boldsymbol{u}_k^{\mathrm{H}}}, \qquad (7)$$

which holds a generalized Rayleigh Quotient (RQ) structure, such that the optimal solution to $\boldsymbol{u}_k$ is obtained by [3]

$$\boldsymbol{u}_k^* = \text{eigv}_{\max}\left(\boldsymbol{W}_{\boldsymbol{u}_k}^{-1}\boldsymbol{Q}_{\boldsymbol{u}_k}\right)^{\mathrm{H}}. \qquad (8)$$

Design of TX beamforming $\boldsymbol{v}_k$

Assuming that the strong SI caused by the leakage of own TX signals due to the close proximity of TX and RX antennas can be sufficiently suppressed by the RX combining vector $\boldsymbol{u}_k$, the role of the TX precoder $\boldsymbol{v}_k$ is only to direct the TX beams so as to maximize the downlink rate. For this purpose, it suffices to apply a simple Maximum Ratio Transmission (MRT) TX precoder, namely

$$\bar{\boldsymbol{v}}_k = \frac{\boldsymbol{H}_{kl}^{\mathrm{H}}\boldsymbol{u}_\ell^{\mathrm{H}}}{||\boldsymbol{H}_{kl}\boldsymbol{u}_\ell||}. \qquad (9)$$

Algorithm 1 Alt. TX Power Min. with SINR Guarantees

```
Input:
  • $P_k, \boldsymbol{H}_{kk}, \boldsymbol{H}_{\ell k}, \ \boldsymbol{C}_k \forall k$ given by [1]
Output:
  • Optimal beamformers $\bar{\mathbf{v}}_k, \mathbf{u}_k \forall k$ and transmit power $\mathbf{p} \forall k$
Steps:
1. Set $P_k = P_{\max} \forall k \in \{1,2\}$ and make arbitrary unit-norm vectors as initial RX BF vectors $\mathbf{u}_k \forall k$.
repeat
  - Compute $\bar{\boldsymbol{v}}_k \forall k$ from equation (9).
  - Compute $\boldsymbol{u}_k^* \forall k$ from equation (8).
  - Compute $\boldsymbol{p}^*$ from equation (6).
convergence or reach maximum iterations.
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III. SIMULATION RESULTS

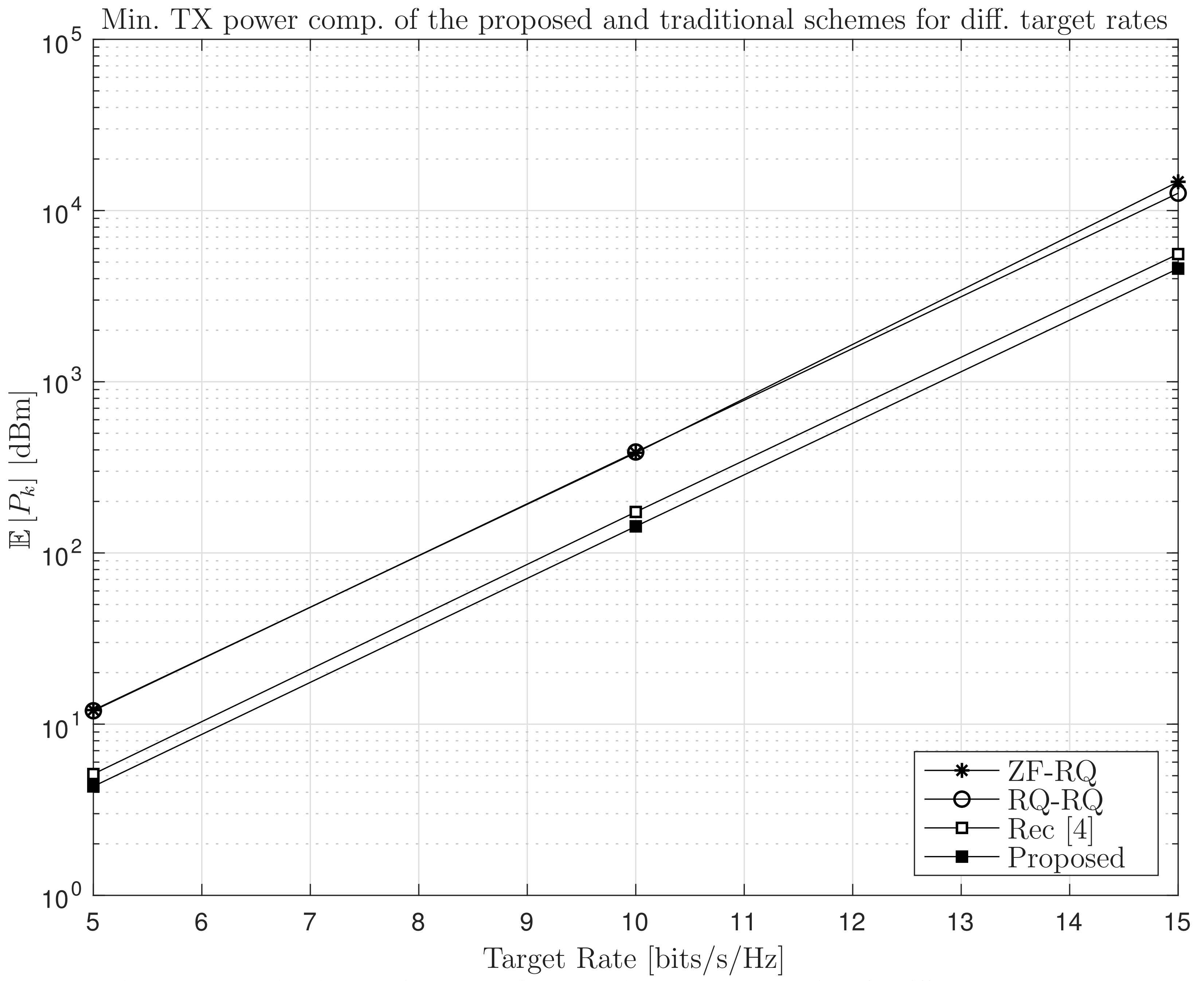

Fig. 2. Proposed and conventional preceding methods TX power comparison for different target rates.

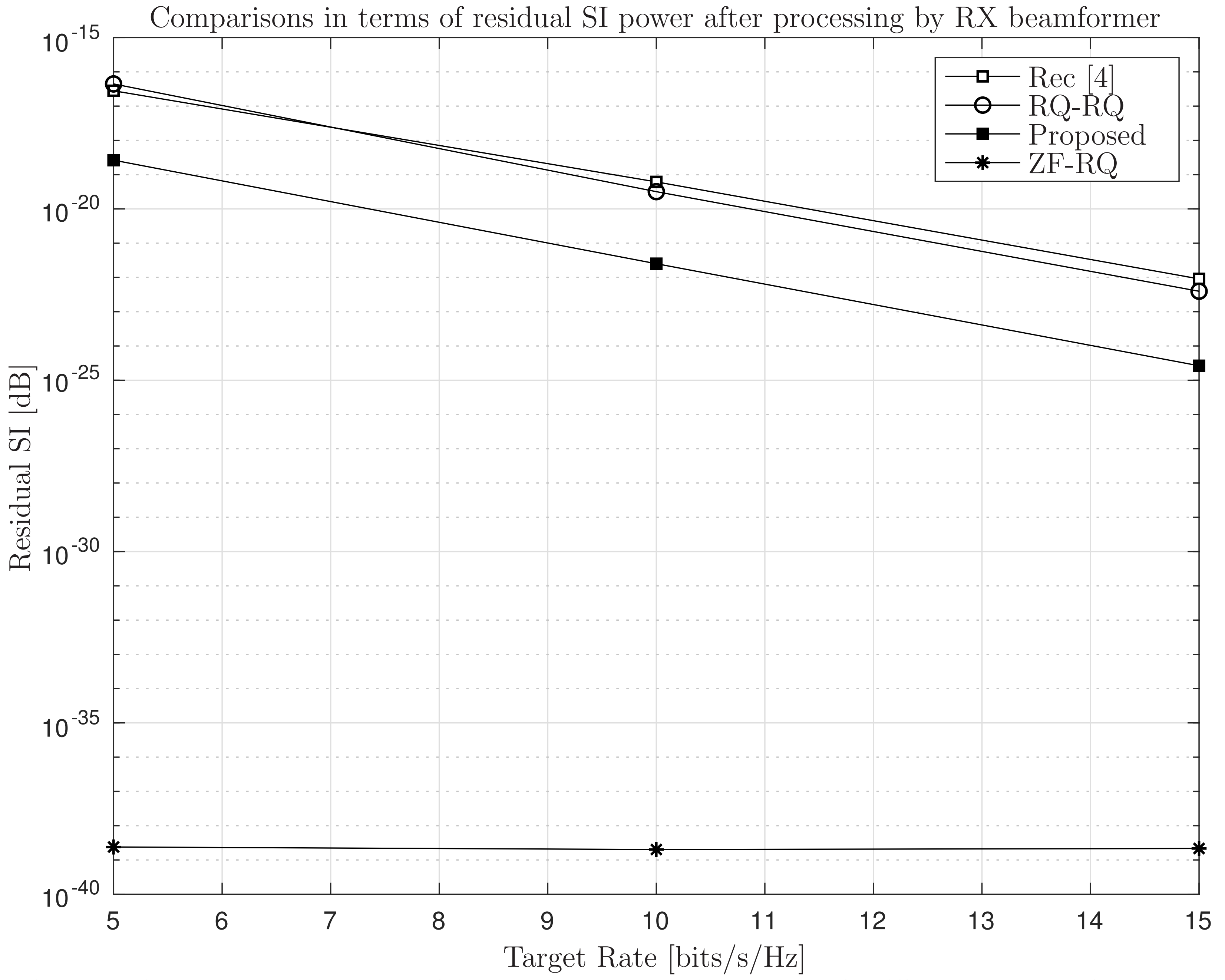

Fig. 3. Residual SI power comparisons of the proposed and conventional methods for different target rates after RX BF.

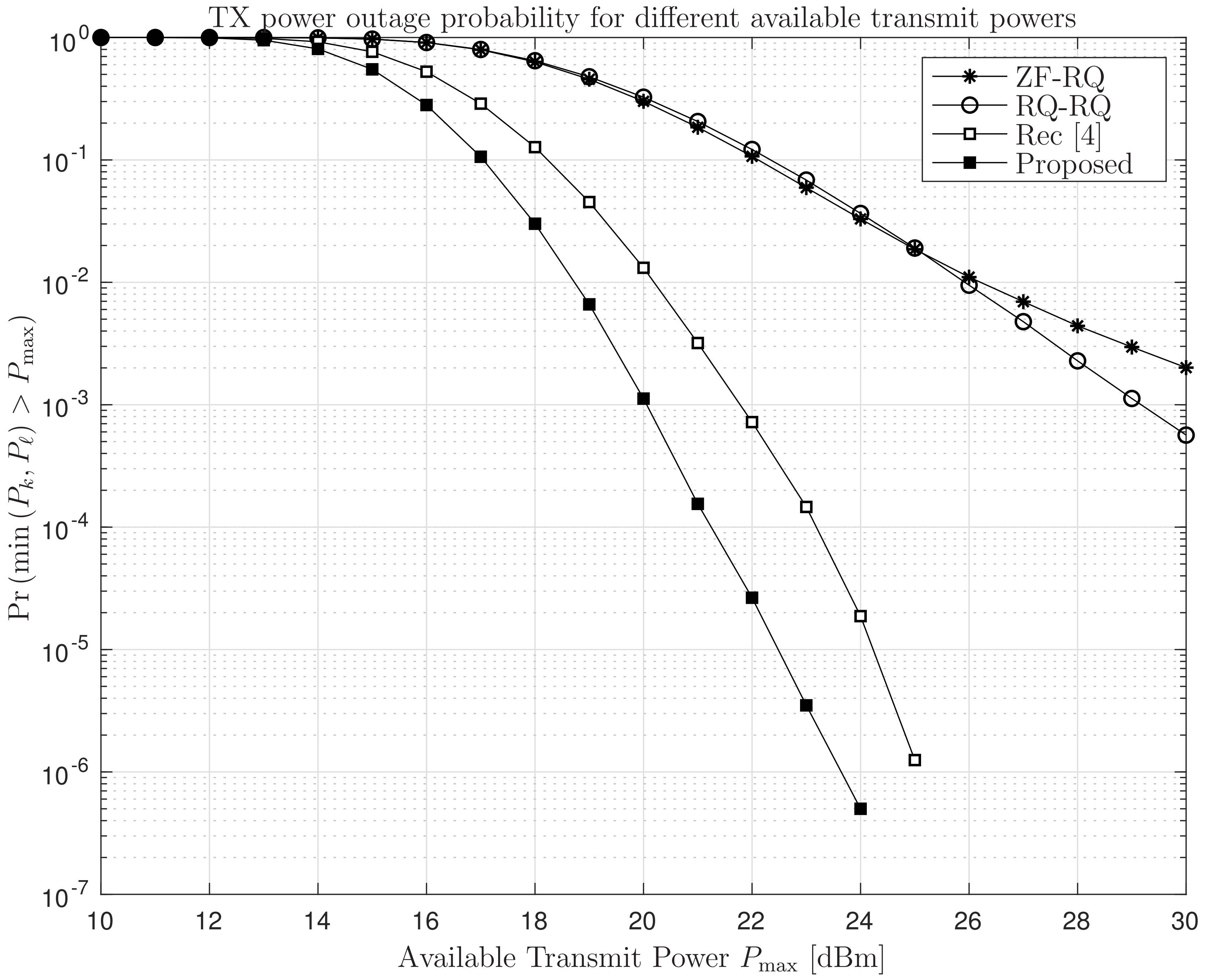

Fig. 4. TX power outage probability for different available TX powers with the fixed target rate $R_k = R_\ell = 8$ [bps/Hz].

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