SIMPLE COOPERATIVE TRANSMISSION SCHEMES FOR UNDERLAY SPECTRUM SHARING USING SYMBOL-LEVEL PRECODING AND LOAD-CONTROLLED ARRAYS

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K. Ntougias, D. Ntaikos, C. B. Papadias, G. K. Papageorgiou, “Simple Cooperative Transmission Schemes for Underlay Spectrum Sharing Using Symbol-Level Precoding and Load-Controlled Arrays,” *ICASSP*, Brighton, UK, May 12-17, 2019.

Introduction

- **Sub-6 GHz spectrum will be an important part of the 5G landscape.**
- **The scarcity of spectral resources and the stringent capacity requirements of 5G services, though, necessitate the use of spectral efficiency (SE) enhancement technologies.**
- **Examples include coordinated multi-point (CoMP) and spectrum sharing.**
- **The combination of CoMP and underlay spectrum sharing promises substantial SE gains.**
- **However, this concept has been largely overlooked in the literature.**
- **The use of load-controlled antenna arrays (LC-AA) and symbol-level (SL) precoding can further enhance the performance of CoMP cellular networks.**
- **Nevertheless, the corresponding research works do not consider a spectrum sharing setup.**
- **In this paper, we fill this gap in the literature.**
- **We focus on the use of standard precoding schemes and simple yet novel power allocation methods that can be applied in commercial setups.**

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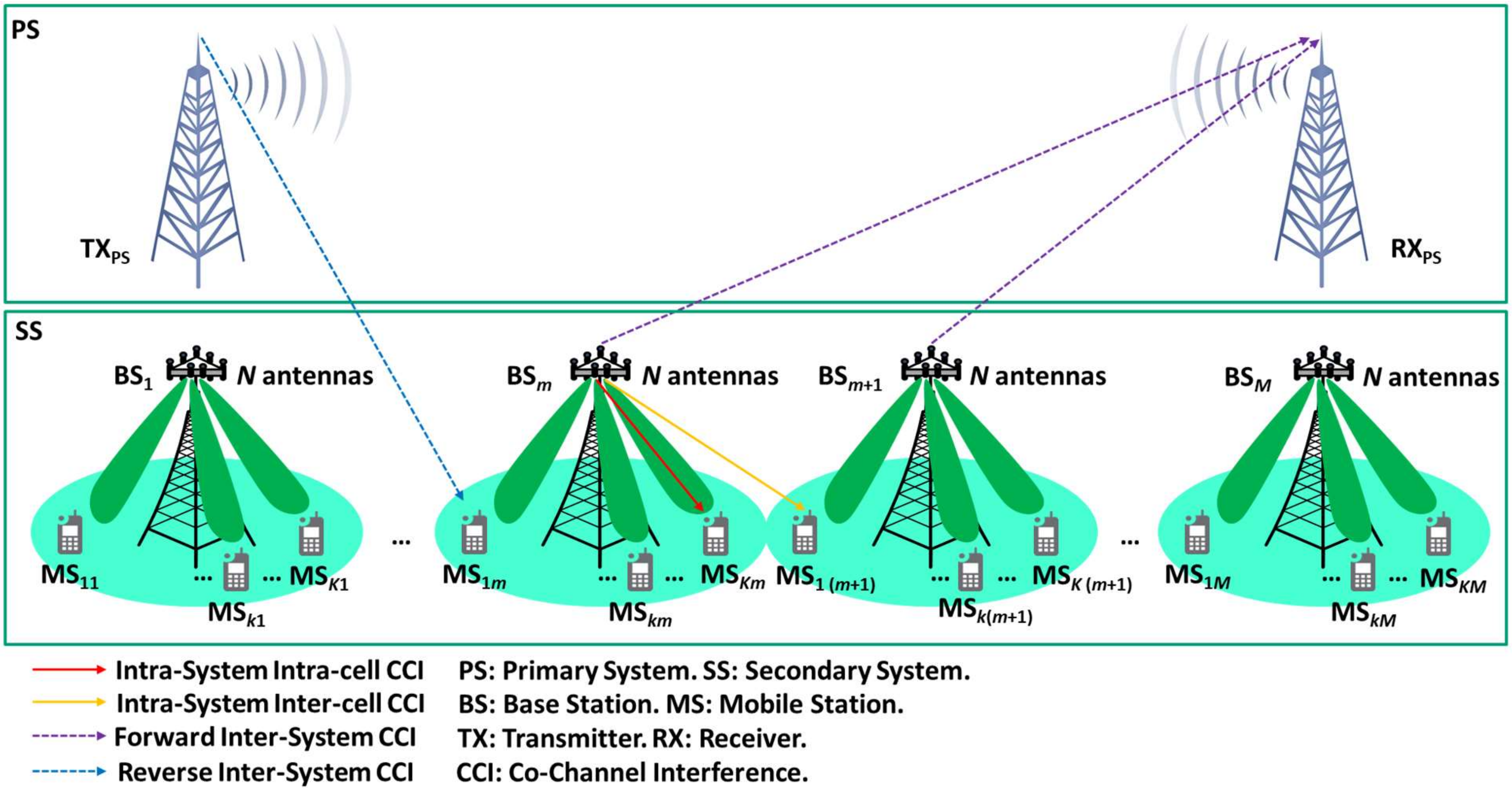
System Setup



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Signal and Channel Models

- **The received signal at MS$_{km}$ is given by:**

$$y_{km} = (\mathbf{h}_{km}^{m})^{\dagger}\mathbf{w}_{mk}^{m}\sqrt{P_{mk}^{m}}s_{mk}^{m}$$

Data

$$+\sum_{\substack{i=1\\ i\neq k}}^{K}(\mathbf{h}_{km}^{m})^{\dagger}\mathbf{w}_{mi}^{m}\sqrt{P_{mi}^{m}}s_{mi}^{m}$$

Intra-Cell CCI

$$+\sum_{\substack{j=1\\ j\neq m}}^{M}\sum_{l=1}^{K}\left(\mathbf{h}_{km}^{j}\right)^{\dagger}\mathbf{w}_{jl}^{j}\sqrt{P_{jl}^{j}}s_{jl}^{j}$$

Inter-Cell CCI

$$+h_{km}\sqrt{P}d + n_{km}$$

Reverse Inter-System CCI + Noise

- **In matrix form:**

$$\mathbf{y} = \mathbf{HWP}^{1/2}\mathbf{s} + \sqrt{P}\mathbf{h}d + \mathbf{n}$$

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Signal and Channel Models

- **The received signal at RX_{PS} is given by:**

$$y = g\sqrt{P}d + \sum_{m=1}^{M}\sum_{k=1}^{K} \mathbf{g}_m^{\dagger}\mathbf{w}_{mk}^{m}\sqrt{P_{mk}^{m}}\,s_{mk}^{m} + z$$

Data

Forward Inter-System CCI

Noise

- **Let us apply Zero-Forcing (ZF) precoding in a spectrum-sharing agnostic manner:**

$$\mathbf{W}^{(\mathrm{ZF})} = \mathbf{H}^{\#} = \mathbf{H}^{\dagger}\left(\mathbf{H}\mathbf{H}^{\dagger}\right)^{-1}$$

- **Then both the intra-cell and inter-cell CCI are eliminated and the SINR at MS_{km} is given by:**

$$\gamma_{km} = \frac{\left|(\mathbf{h}_{km}^{m})^{\dagger}(\mathbf{w}_{mk}^{m})^{(\mathrm{ZF})}\right|^{2} P_{mk}^{m}}{|h_{km}|^{2}P + 1}$$

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Problem Formulation

$$\max_{P_{mk}^{m}} \quad R = \sum_{m=1}^{M} \sum_{k=1}^{K} \log_2(1+\gamma_{km})$$

Sum-SE

s.t.

$$P_{mk}^{m} \geq 0$$

Nonnegative Power Constraints

$$\sum_{k=1}^{K} P_{mk}^{m} \leq P_T$$

Sum-Power Constraints

$$\sum_{m=1}^{M} \sum_{k=1}^{K} \left| \mathbf{g}_m^{\dagger} (\mathbf{w}_{mk}^{m})^{(\mathrm{ZF})} \right|^2 P_{mk}^{m} \leq P_I$$

Interference Power Constraint

Convex problem (thus having a unique solution), since ZF precoding eliminates the inter-user coupling through the interference components.

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Solution

- **Interference-Constrained Power Allocation (ICPA):**

$$\boxed{P_{mk}^{m} = \left(\frac{1}{\ln 2(\nu_m + \mu\alpha_{mk}^{m})} - \frac{1}{\lambda_{mk}^{m}}\right)^{+}} \qquad (1)$$

$$\lambda_{mk}^{m} = \frac{\left|(\mathbf{h}_{km}^{m})^{\dagger}(\mathbf{w}_{mk}^{m})^{(\mathrm{ZF})}\right|^{2}}{|h_{km}|^{2}P + 1}$$

$$\alpha_{mk}^{m} = \left|\mathbf{g}_{m}^{\dagger}(\mathbf{w}_{mk}^{m})^{(\mathrm{ZF})}\right|^{2}$$

- **This power-allocation method can be applied heuristically for other linear precoding or even symbol-level precoding schemes as well.**

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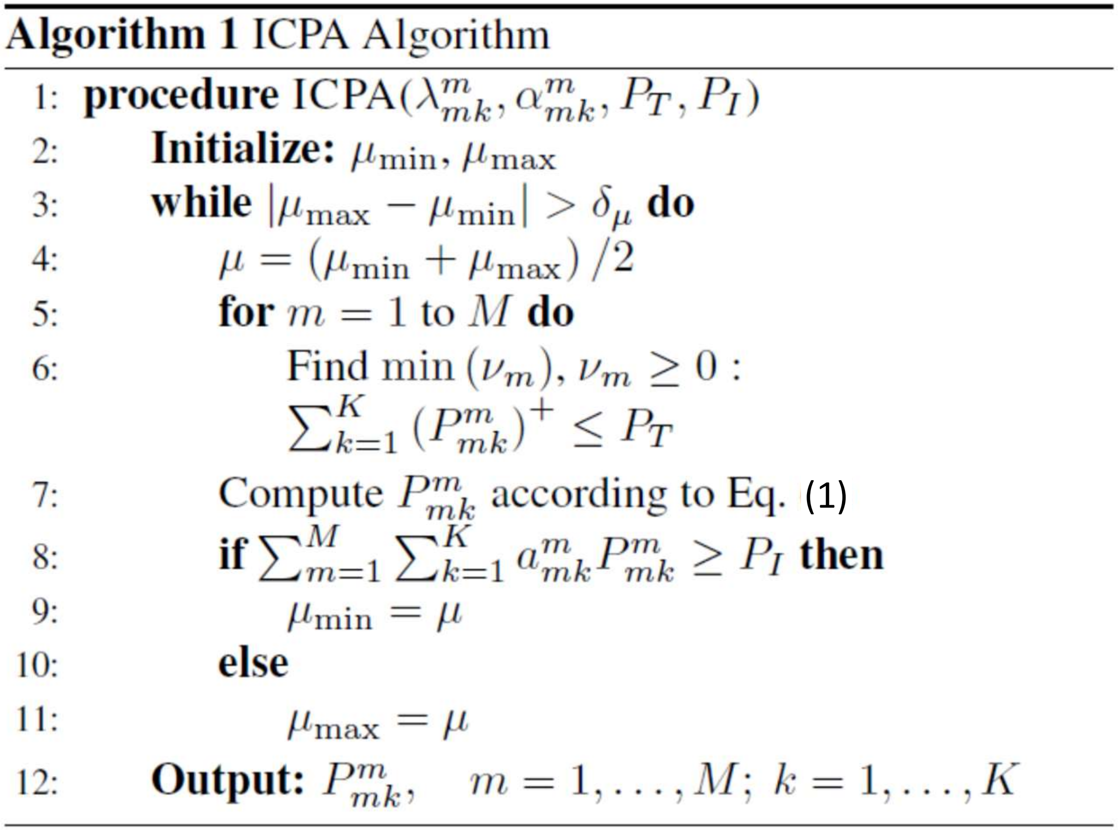
Algorithm



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Algorithm 1 ICPA Algorithm
procedure ICPA($\lambda_{mk}^m, \alpha_{mk}^m, P_T, P_I$)
    Initialize: $\mu_{\min}, \mu_{\max}$
    while $|\mu_{\max} - \mu_{\min}| > \delta_\mu$ do
        $\mu = (\mu_{\min} + \mu_{\max})/2$
        for $m = 1$ to $M$ do
            Find $\min(\nu_m)$, $\nu_m \geq 0$ :
            $\sum_{k=1}^K (P_{mk}^m)^+ \leq P_T$
        Compute $P_{mk}^m$ according to Eq. (1)
        if $\sum_{m=1}^M \sum_{k=1}^K a_{mk}^m P_{mk}^m \geq P_I$ then
            $\mu_{\min} = \mu$
        else
            $\mu_{\max} = \mu$
    Output: $P_{mk}^m$,    $m = 1, \ldots, M;\ k = 1, \ldots, K$
```

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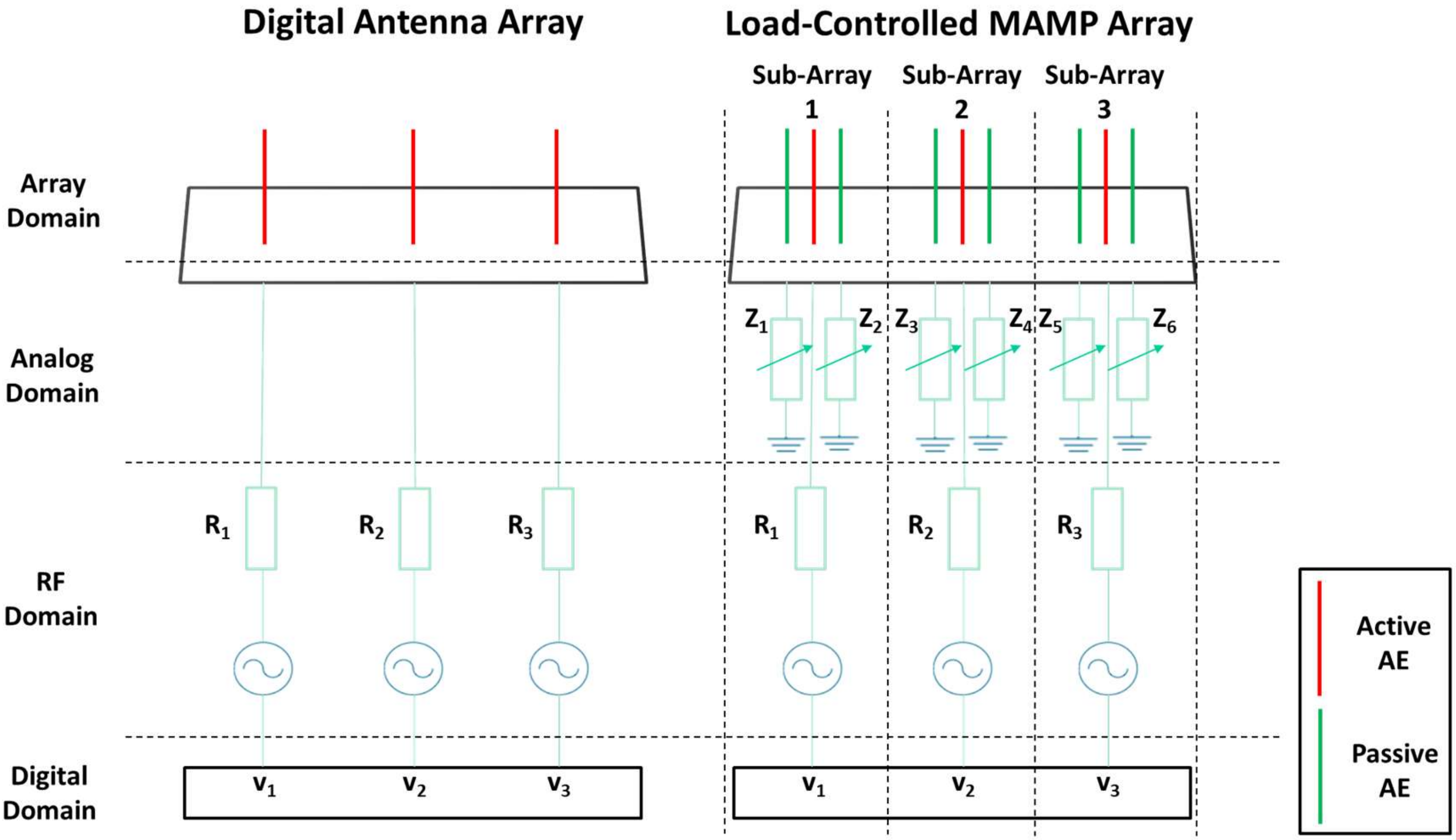
Load-Controlled Antenna Arrays (1/3)



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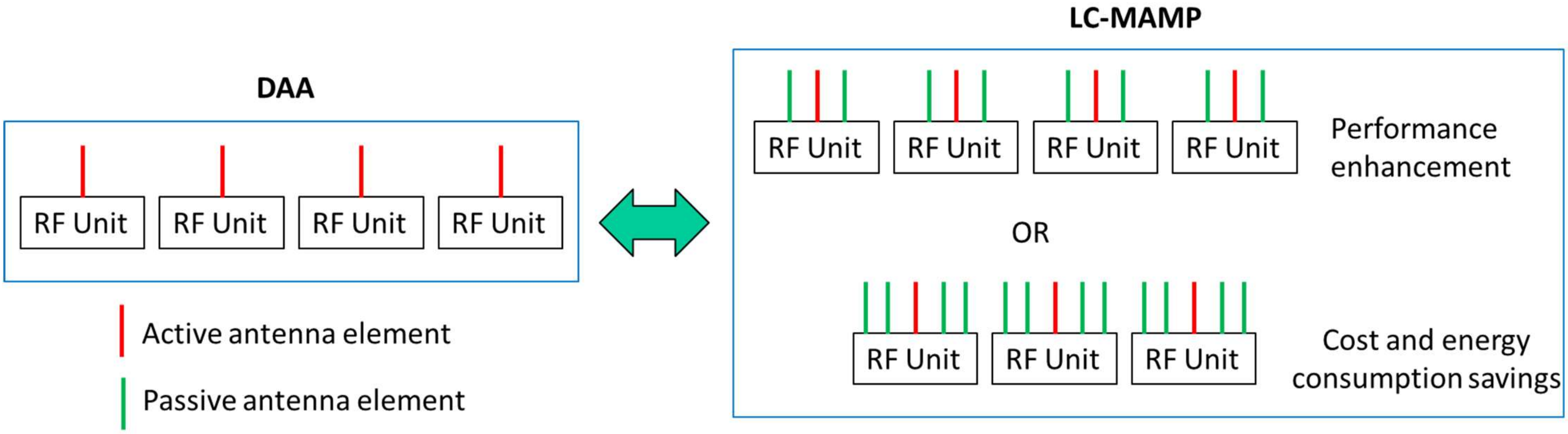
Load-Controlled Antenna Arrays (2/3)



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Load-Controlled Antenna Arrays (3/3)

- **We can perform channel-aware precoding with LC-AAs by mapping the precoded signals onto the antenna currents:**

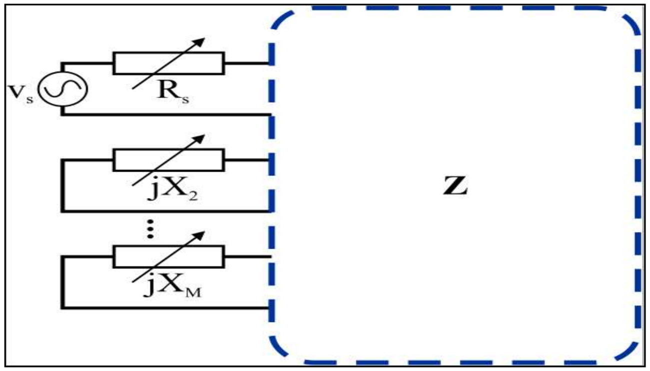
System model: $\mathbf{y} = \mathbf{H}\mathbf{i} + \mathbf{n}$

Precoding: $\mathbf{y} = \mathbf{H}\mathbf{W}\mathbf{s} + \mathbf{n}$

$$\boxed{\mathbf{i} = \mathbf{W}\mathbf{s}}$$

- **Then, we have to calculate the corresponding loading values that will generate these currents through the generalized Ohm's law:**

$$\boxed{\mathbf{i} = (\mathbf{Z} + \mathbf{Z}_L)^{-1}\mathbf{v}}$$



- **However, we should ensure that the real part of the input impedance (which depends on the loads and, therefore, on the precoded signal) is positive to achieve high radiation efficiency.**

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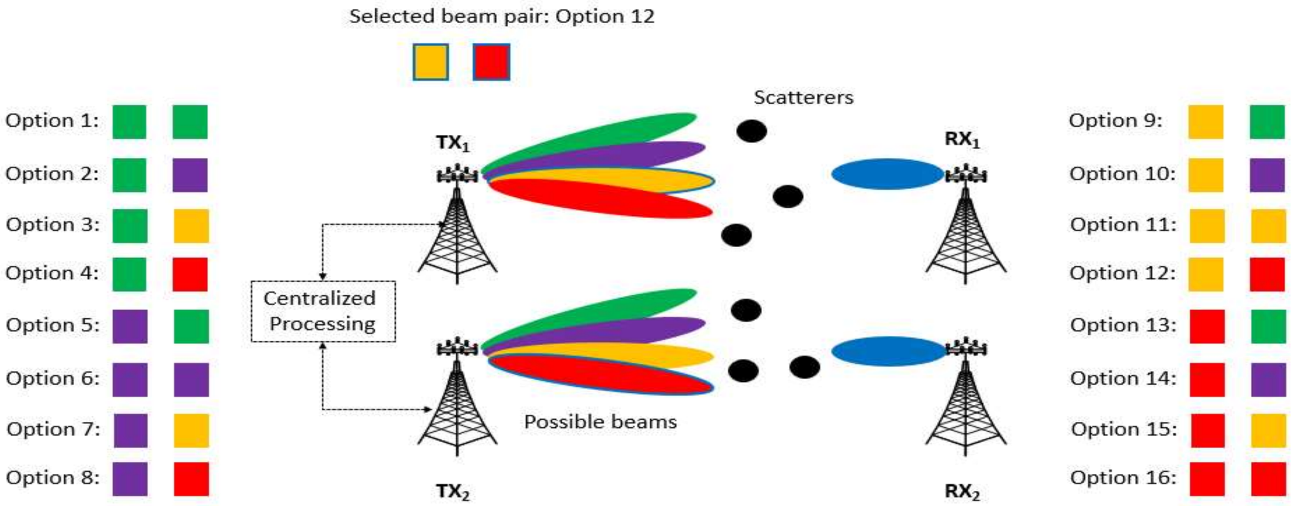
Joint Beam Selection and Precoding (JBSP)

1. **Learning:** The MSs report the channel estimates or the SINR for each beam combination.
2. **Beam Selection:** The best beam combination (in terms of sum-SE) is selected.
3. **Transmission:** Precoded signals are transmitted over the selected beams.

Beamforming: Analog domain (loads).
- Admits any input signal.
- Beam selection to improve performance.

Precoding: Digital domain (baseband).
- Full control.
- Inter-BS cooperation to improve performance.



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Symbol-Level ZF Precoding

- **This precoding scheme "zero-forces" only the destructive interference (at symbol level) and leaves unaffected the constructive interference.**
- **It improves the performance in the low-SNR regime.**
- **Calculation of the precoding matrix symbol-by-symbol (Binary Phase Shift Keying (BSPK) input assumed, i.e., $s_i = \pm 1$):**

$$\boxed{\mathbf{W}^{(\mathrm{CIZF})} = \mathbf{W}^{(\mathrm{ZF})}\mathbf{T} = \mathbf{H}^{\dagger}\mathbf{R}^{-1}\mathbf{T}}$$

$$\mathbf{R} = \mathbf{H}\mathbf{H}^{\dagger}$$

$$\mathbf{G} = \mathrm{diag}(\mathbf{s})\mathrm{Re}(\mathbf{R})\mathrm{diag}(\mathbf{s})$$

$$\tau_{kk} = \rho_{kk}$$

$$\begin{cases} \tau_{km} = 0 & \text{if } g_{km} < 0 \\ \tau_{km} = \rho_{km} & \text{otherwise} \end{cases}$$

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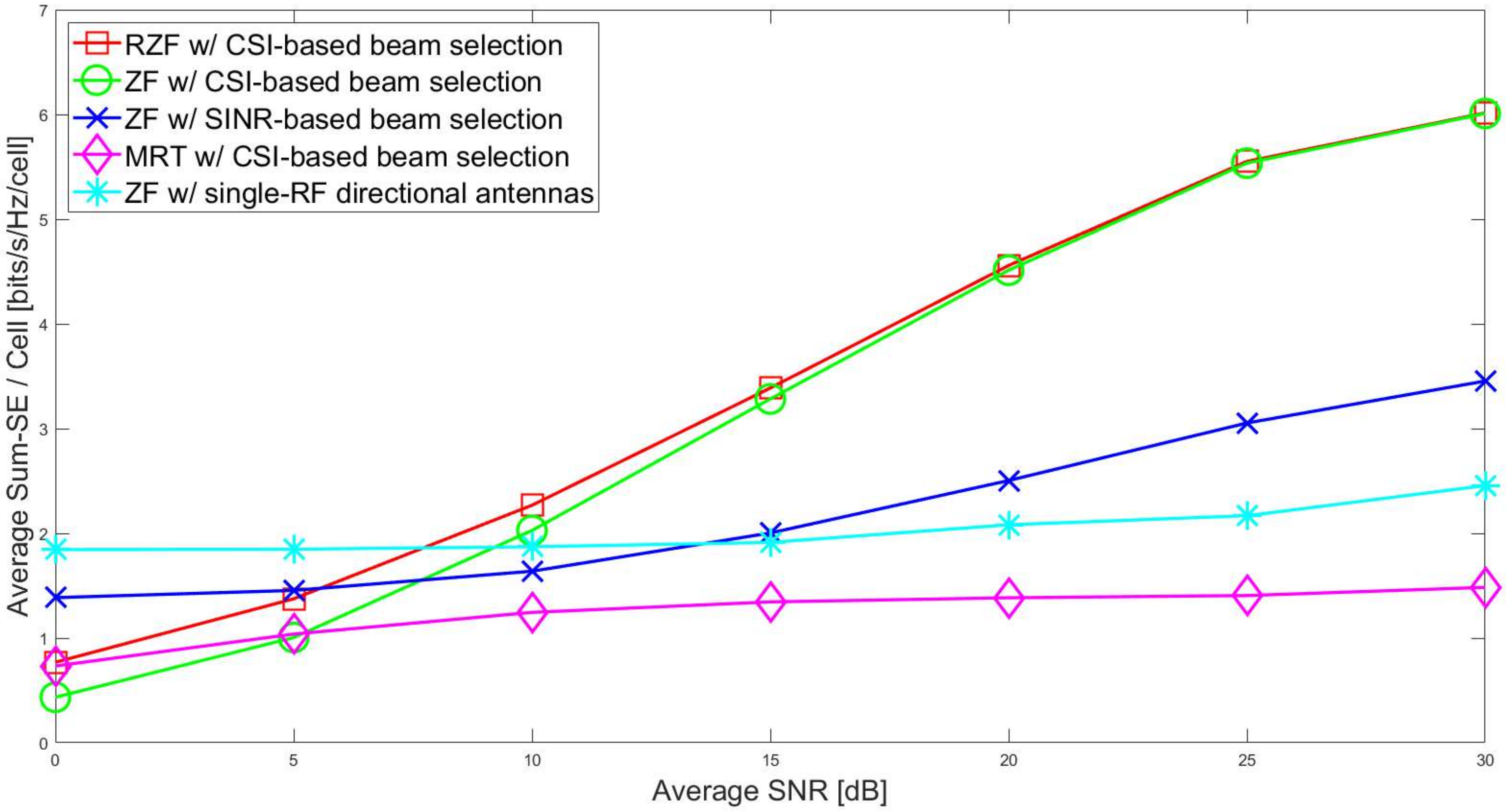
Performance Evaluation via Numerical Simulations (1/3)



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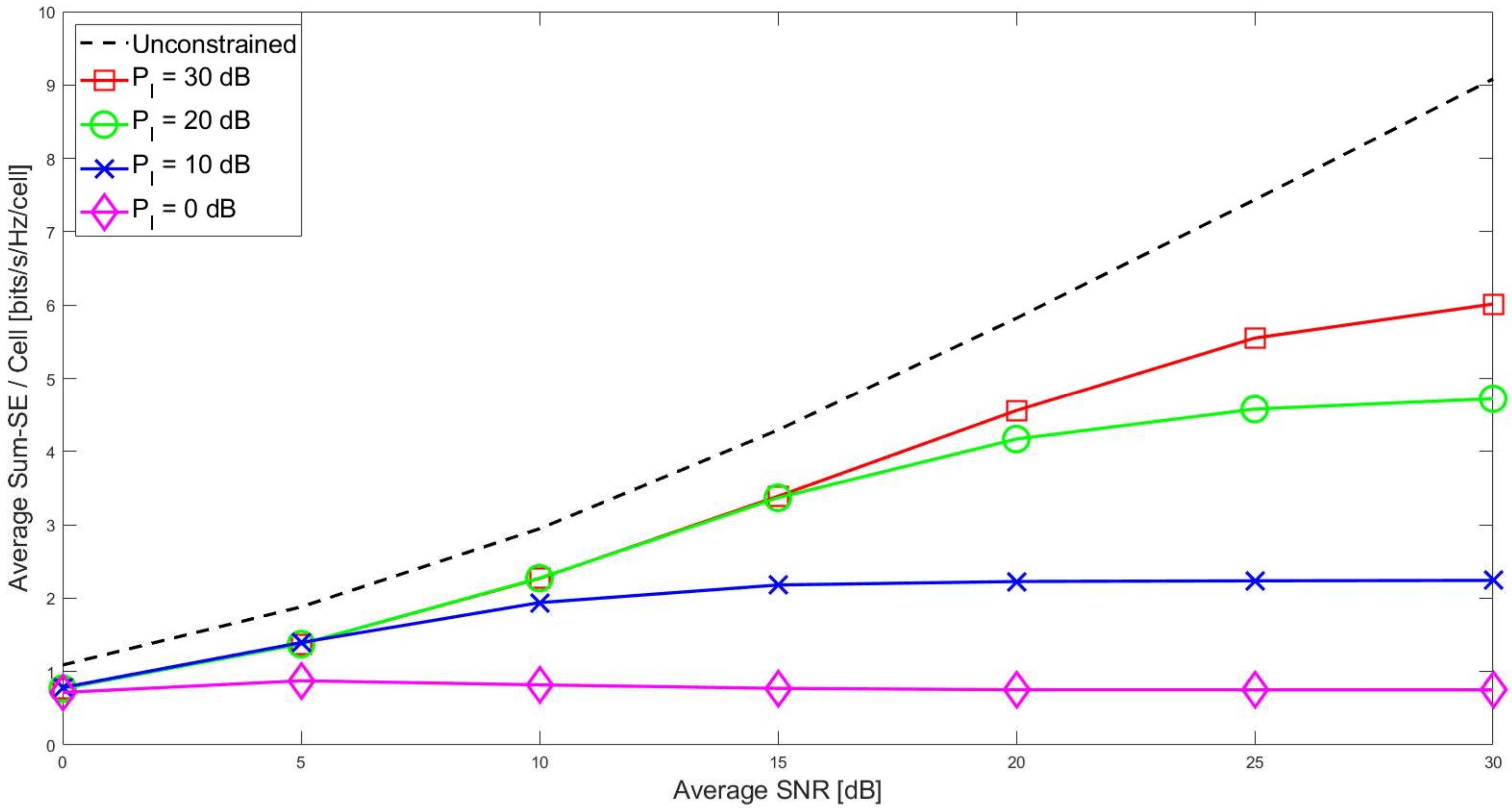
Performance Evaluation via Numerical Simulations (2/3)



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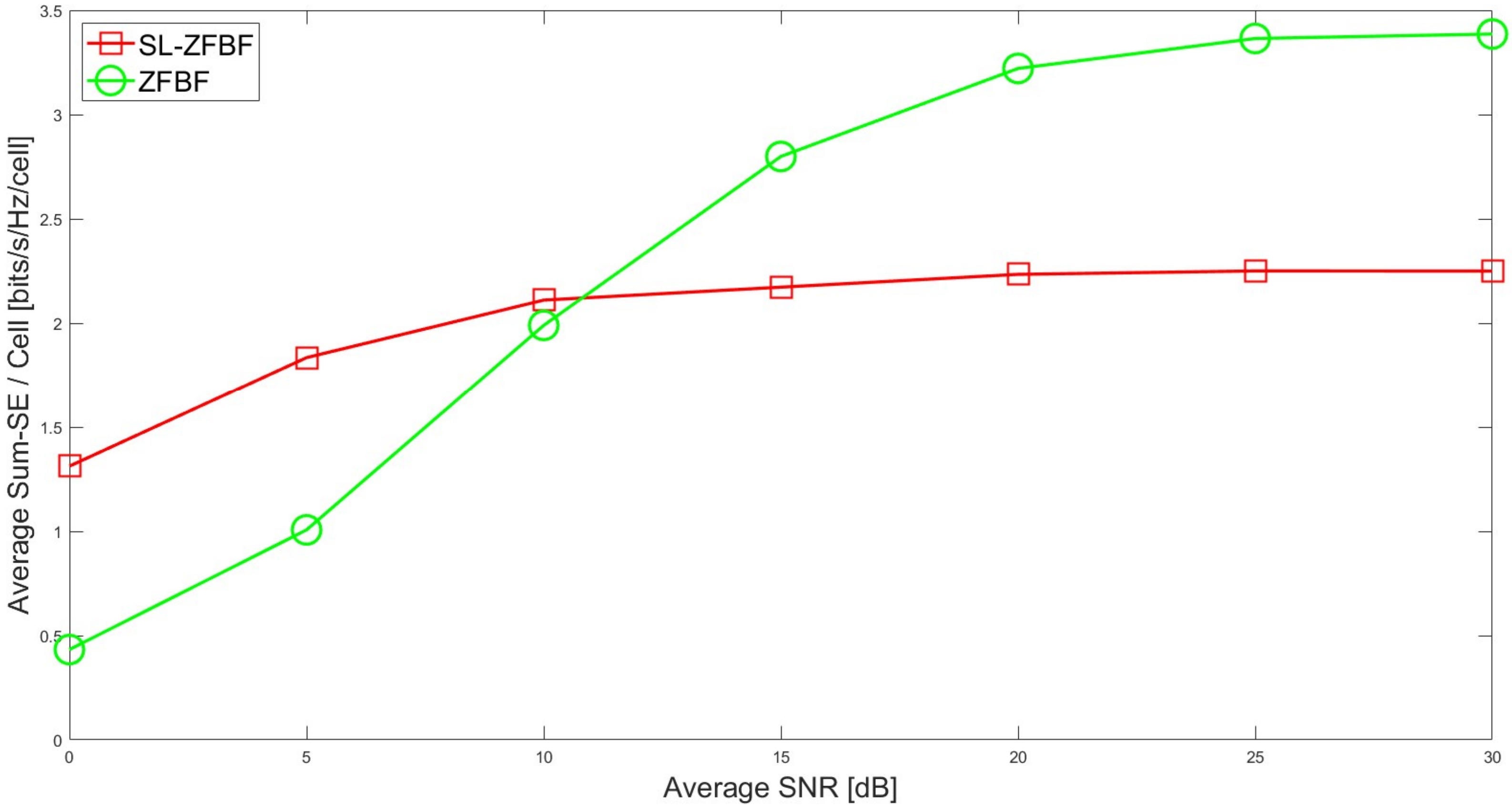
Performance Evaluation via Numerical Simulations (3/3)



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Summary and Conclusions

- A coordinated beamforming (CBF) and interference-constrained power allocation (ICPA) strategy that maximizes the sum-SE of cellular networks in underlay spectrum sharing setups has been derived in this work.
- The application of standard linear precoding schemes has been considered (MRT, ZF, RZF).
- Also, the use of SL ZF precoding which exploits the constructive symbol-level interference to improve the performance at the low SNR regime has been studied.
- Furthermore, a joint beam selection and precoding (JBSP) method that enables us to perform arbitrary channel-dependent precoding with LC-AAs is presented.
- This method performs beamforming in the analog domain followed by beam selection (switching) and digital precoding to overcome the load computation difficulties.
- Load-controlled antenna arrays improve the performance for a target cost and energy consumption (# of RF chains) thanks to their higher array gain / narrower beams.
- Numerical simulations indicate that this technique performs significantly well for small-to-moderate IPT values and highlight the performance gains of LC-AAs and SL precoding.

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