# DISTRIBUTED BEAMFORMING IN RELAY NETWORKS FOR ENERGY HARVESTING MULTI-GROUP MULTICAST SYSTEMS

ICASSP 2016
Shanghai, China

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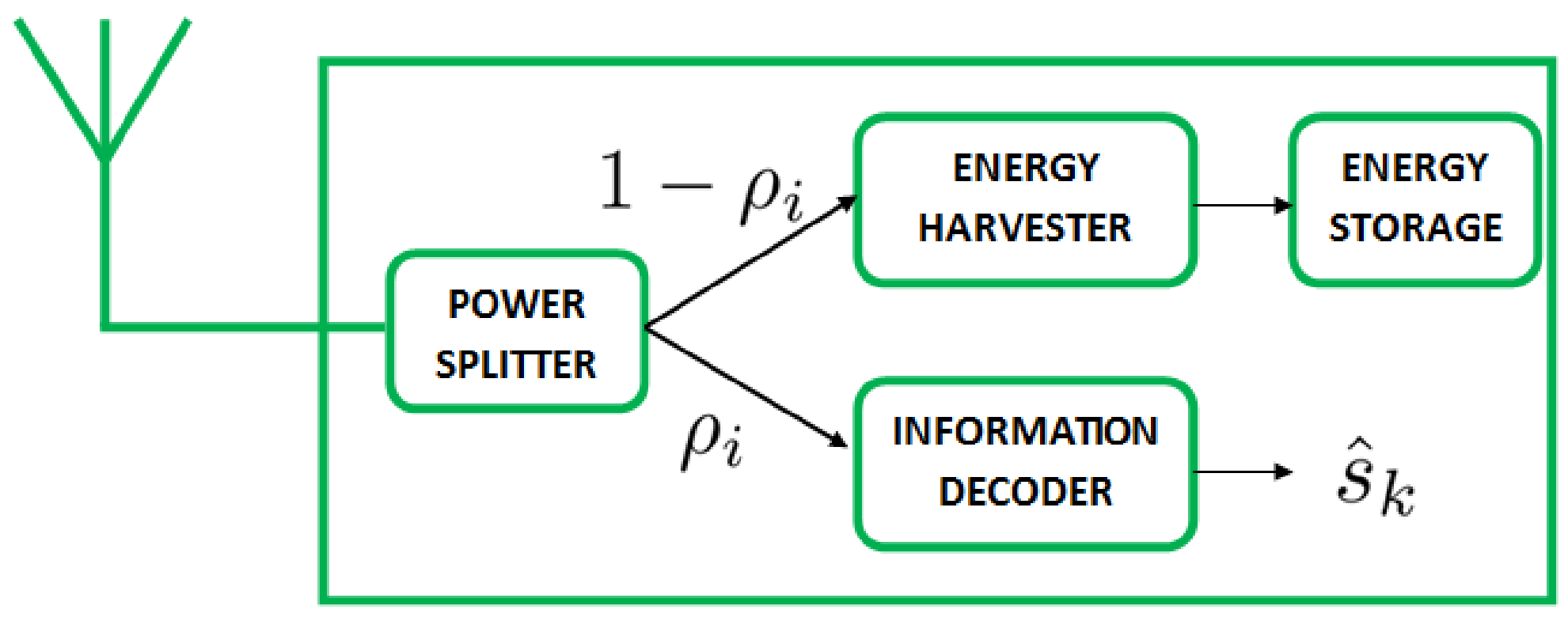
## 1 Problem Statement and Motivation

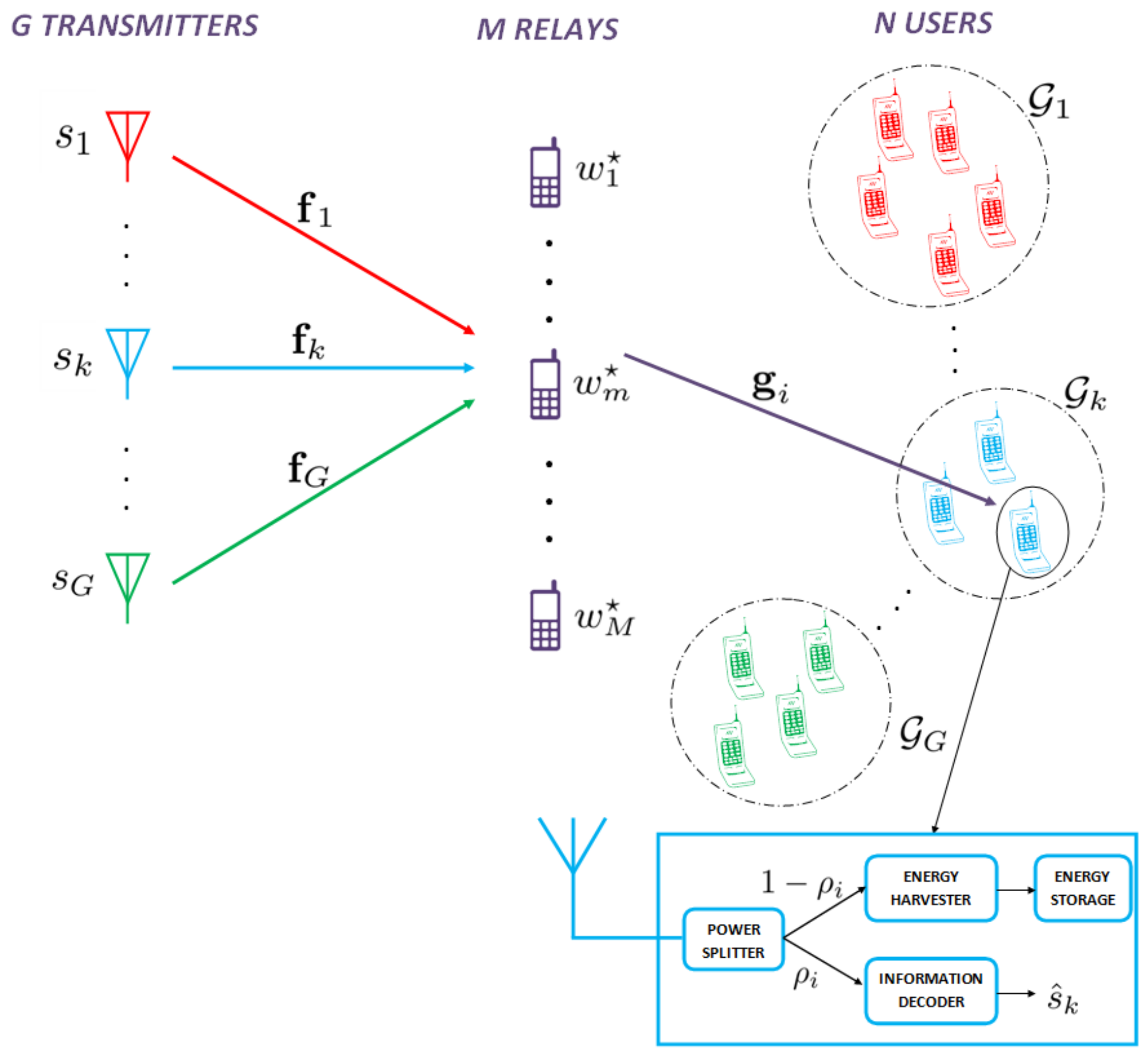
*Simultaneous Wireless Information and Power Transfer (SWIPT)*

- energy harvesting for mobile users to improve the energy efficiency and battery duration [1]
- power splitting (PS) device for both information decoding and energy harvesting



*Distributed Beamforming for Multi-Group Multicasting*

- single antenna relays as a virtual antenna array [2].
- two-hop data transmission



## 2 Contributions

- This paper is the first work which considers distributed beamforming in multi-group multicasting relay networks for SWIPT.
- The nonconvex optimization problem for the relay weights and power splitting ratios of the users is converted to a more manageable form with quadratic and second order cone constraints.
- The resulting QCQP problem is solved using feasible point pursuit-successive convex approximation (FPP-SCA) algorithm which is an efficient QCQP method proposed recently [3].
- We introduce phase-only distributed beamforming in order to prevent the uneven battery utilization [4].
- An effective algorithm is proposed using exact penalty function and an extended version of FPP-SCA.

## 3 System Model

Complex channel gains between the $k^{th}$ transmitter and the relays

Received signal at the relays (Mx1)

$$\mathbf{r} = \textstyle\sum_{k=1}^{G} \mathbf{f}_k s_k + \mathbf{n}_r$$

Information symbol for the $k^{th}$ multicast group

Transmitted signal from the relays (Mx1)

$$\mathbf{t} = \mathbf{W}^H \mathbf{r}$$

Complex conjugates of the relay weights

$$\mathbf{W} = diag\{w_1, w_2, \ ..., w_M\}$$

Received signal at the $i^{th}$ user

$$y_i = \mathbf{g}_i^T \mathbf{t} + n_{A,i} = \mathbf{g}_i^T (\mathbf{W}^H \textstyle\sum_{k=1}^{G} \mathbf{f}_k s_k + \mathbf{W}^H \mathbf{n}_r) + n_{A,i}$$

Complex channel gains between the relays and the $i^{th}$ user

$$\mathbf{G}_i = diag\{g_{i,1}, g_{i,2}, ..., g_{i,M}\}$$

$$\mathbf{w} = [\ w_1\ w_2\ ...\ w_M\ ]^T$$

Received signal at the information decoder (ID) of the $i^{th}$ user

$$y_{I,i} = \sqrt{\rho_i}(\mathbf{w}^H \mathbf{G}_i \sum_{k=1}^{G} \mathbf{f}_k s_k + \mathbf{w}^H \mathbf{G}_i \mathbf{n}_r + n_{A,i}) + n_{I,i}$$

Signal fed into the energy harvester (EH) of the $i^{th}$ user

$$y_{E,i} = \sqrt{1-\rho_i}(\mathbf{w}^H \mathbf{G}_i \sum_{k=1}^{G} \mathbf{f}_k s_k + \mathbf{w}^H \mathbf{G}_i \mathbf{n}_r + n_{A,i})$$

## 4 QoS-Aware Distributed Beamforming for SWIPT

- In quality of service (QoS) aware beamforming, it is desired to minimize the total power transmitted from the relays by ensuring that the SINR and the harvested power at each user is above a certain threshold.

Total transmitted power from the relays

$$P_T = \sum_{m=1}^{M} \mathbb{E}\{|t_m|^2\} = \sum_{m=1}^{M} |w_m|^2 \mathbb{E}\{|r_m|^2\} = \mathbf{w}^H \mathbf{D} \mathbf{w}$$

$$\mathbf{D} = diag\{\mathbb{E}\{|r_1|^2\}, ..., \mathbb{E}\{|r_M|^2\}\}$$

$$\mathbf{h}_{k,i} = \mathbf{G}_i \mathbf{f}_k \qquad \mathbf{Q}_{k,i} = \textstyle\sum_{l \neq k} P_l \mathbf{h}_{l,i} \mathbf{h}_{l,i}{}^H$$

$$\min_{\mathbf{w} \in \mathbb{C}^M, \{\rho_i\}_{i=1}^N} \quad \mathbf{w}^H \mathbf{D} \mathbf{w} \qquad (5.a)$$

$$s.t. \ \frac{\rho_i P_k \mathbf{w}^H \mathbf{h}_{k,i} \mathbf{h}_{k,i}{}^H \mathbf{w}}{\rho_i \mathbf{w}^H (\mathbf{Q}_{k,i} + \sigma_r^2 \mathbf{G}_i \mathbf{G}_i{}^H) \mathbf{w} + \rho_i \sigma_{A,i}^2 + \sigma_{I,i}^2} \geq \gamma_i, \qquad (5.b) \xrightarrow{} \text{SINR constraints}$$

$$\xi_i(1-\rho_i)(\mathbf{w}^H (P_k \mathbf{h}_{k,i} \mathbf{h}_{k,i}{}^H + \mathbf{Q}_{k,i} + \sigma_r^2 \mathbf{G}_i \mathbf{G}_i{}^H) \mathbf{w} + \sigma_{A,i}^2) \geq \mu_i \qquad (5.c) \xrightarrow{} \text{Harvested power constraints}$$

$$0 < \rho_i < 1, \quad \forall i \in \mathcal{G}_k, \forall k \in \{1, ..., G\} \qquad (5.d)$$

$$|w_m|^2 D_{m,m} \leq p_m, \quad m = 1, 2, ..., M \qquad (5.e) \xrightarrow{} \text{Individual relay power constraints}$$

- Let us express (5) in a simpler way by decoupling $\mathbf{w}$ and $\rho_i$'s.

$$\mathbf{T}_{k,i} = P_k \mathbf{h}_{k,i} \mathbf{h}_{k,i}{}^H - \gamma_i (\mathbf{Q}_{k,i} + \sigma_r^2 \mathbf{G}_i \mathbf{G}_i{}^H)$$

$$\mathbf{S}_{k,i} = P_k \mathbf{h}_{k,i} \mathbf{h}_{k,i}{}^H + \mathbf{Q}_{k,i} + \sigma_r^2 \mathbf{G}_i \mathbf{G}_i{}^H$$

$$\min_{\mathbf{w} \in \mathbb{C}^M, \{\rho_i\}_{i=1}^N} \quad \mathbf{w}^H \mathbf{D} \mathbf{w} \qquad (6.a)$$

$$s.t. \ \mathbf{w}^H \mathbf{T}_{k,i} \mathbf{w} \geq \frac{\gamma_i \sigma_{I,i}^2}{\rho_i} + \gamma_i \sigma_{A,i}^2 \qquad (6.b)$$

$$\mathbf{w}^H \mathbf{S}_{k,i} \mathbf{w} \geq \frac{\mu_i}{\xi_i(1-\rho_i)} - \sigma_{A,i}^2, \qquad (6.c)$$

$$0 < \rho_i < 1, \quad \forall i \in \mathcal{G}_k, \forall k \in \{1, ..., G\} \qquad (6.d)$$

$$|w_m|^2 D_{m,m} \leq p_m, \quad m = 1, 2, ..., M \qquad (6.e)$$

- The problem in (6) is not convex since the matrices $\mathbf{T}_{k,i}$ and $\mathbf{S}_{k,i}$ are not negative semidefinite.
- The following lemma enables us to write (6.b) and (6.c) as quadratic constraints which are easier to tackle.

***Lemma 1*:** There exists an optimum solution of (7), $\{\mathbf{w}_{opt}, \{\upsilon_{i_{opt}}, \kappa_{i_{opt}}\}_{i=1}^N\}$ such that $\upsilon_{i_{opt}} = \frac{1}{\rho_{i_{opt}}}$ and $\kappa_{i_{opt}} = \frac{1}{1-\rho_{i_{opt}}}$, $i = 1, ..., N$ where $\{\mathbf{w}_{opt}, \{\rho_{i_{opt}}\}_{i=1}^N\}$ is the optimum solution of (6).

$$\min_{\mathbf{w} \in \mathbb{C}^M, \{\upsilon_i, \kappa_i\}_{i=1}^N} \quad \mathbf{w}^H \mathbf{D} \mathbf{w} \qquad (7.a)$$

$$s.t. \ \mathbf{w}^H \mathbf{T}_{k,i} \mathbf{w} \geq \gamma_i \sigma_{I,i}^2 \upsilon_i + \gamma_i \sigma_{A,i}^2 \qquad (7.b)$$

$$\mathbf{w}^H \mathbf{S}_{k,i} \mathbf{w} \geq \frac{\mu_i}{\xi_i} \kappa_i - \sigma_{A,i}^2 \qquad (7.c)$$

$$\left\| \begin{matrix} \upsilon_i - \kappa_i \\ 2 \end{matrix} \right\|_2 \leq \upsilon_i + \kappa_i - 2 \qquad (7.d)$$

$$\forall\, i \in \mathcal{G}_k, \forall\, k \in \{1, ..., G\}$$

$$|w_m|^2 D_{m,m} \leq p_m, \quad m = 1, 2, ..., M \qquad (7.e)$$

- (7) is a nonconvex QCQP problem.
- FPP-SCA is an effective method for QCQP problems which has less worst-case computational complexity than the well-known semidefinite relaxation.

## 5 FPP-SCA Approach

$$\mathbf{T}_{k,i} = \mathbf{T}_{k,i}^{(+)} + \mathbf{T}_{k,i}^{(-)} \qquad \mathbf{S}_{k,i} = \mathbf{S}_{k,i}^{(+)} + \mathbf{S}_{k,i}^{(-)}$$

$$\mathbf{T}_{k,i}^{(+)}, \ \mathbf{S}_{k,i}^{(+)} \succeq 0 \xrightarrow{\qquad} \text{Positive semidefinite parts}$$

$$\mathbf{T}_{k,i}^{(-)}, \ \mathbf{S}_{k,i}^{(-)} \preceq 0 \xrightarrow{\qquad} \text{Negative semidefinite parts}$$

$$\mathbf{T}_{k,i}^{(+)} = P_k \mathbf{h}_{k,i} \mathbf{h}_{k,i}{}^H$$

$$\mathbf{T}_{k,i}^{(-)} = -\gamma_i (\mathbf{Q}_{k,i} + \sigma_r^2 \mathbf{G}_i \mathbf{G}_i{}^H)$$

$$\mathbf{S}_{k,i}^{(+)} = \mathbf{S}_{k,i} = P_k \mathbf{h}_{k,i} \mathbf{h}_{k,i}{}^H + \mathbf{Q}_{k,i} + \sigma_r^2 \mathbf{G}_i \mathbf{G}_i{}^H$$

**Algorithm 1:** FPP-SCA Algorithm for SWIPT with QoS-Aware Distributed Beamforming

**Initialization:** Set $k = 0$ and randomly generate an initial point $\mathbf{z}_0$.
**Iterations:** $k = k + 1$.
**1)** Solve the following problem in (10).

$$\min_{\mathbf{w} \in \mathbb{C}^M, \{\upsilon_i, \kappa_i\}_{i=1}^N, \{s_i, r_i\}_{i=1}^N} \quad \mathbf{w}^H \mathbf{D} \mathbf{w} + \lambda \sum_{i=1}^{N} (s_i + r_i) \qquad (10.a)$$

$$s.t. \ \mathbf{w}^H \mathbf{T}_{k,i}^{(-)} \mathbf{w} + 2\,\mathrm{Re}\{\mathbf{z}_{k-1}^H \mathbf{T}_{k,i}^{(+)} \mathbf{w}\} - \mathbf{z}_{k-1}^H \mathbf{T}_{k,i}^{(+)} \mathbf{z}_{k-1} + s_i \geq \gamma_i \sigma_{I,i}^2 \upsilon_i + \gamma_i \sigma_{A,i}^2 \qquad (10.b)$$

$$2\,\mathrm{Re}\{\mathbf{z}_{k-1}^H \mathbf{S}_{k,i}^{(+)} \mathbf{w}\} - \mathbf{z}_{k-1}^H \mathbf{S}_{k,i}^{(+)} \mathbf{z}_{k-1} + r_i \geq \frac{\mu_i}{\xi_i} \kappa_i - \sigma_{A,i}^2 \qquad (10.c)$$

$$(7.d), (7.e)$$

where $\lambda \gg 1$ forces the slack variables $\{s_i, r_i\}_{i=1}^N$ towards zero.
**2)** Set $\mathbf{z}_k = \mathbf{w}_k$ where $\mathbf{w}_k$ is the optimum solution of (10) at the $k^{th}$ iteration.
**3)** Terminate if the maximum iteration number, $k = k_{max}$, is reached or $||\mathbf{w}_k - \mathbf{z}_{k-1}|| \leq \epsilon$ for sufficiently small $\epsilon > 0$.
**End:**
**4)** Take the candidate beamformer weight vector $\mathbf{w}^\star$ as $\mathbf{w}_k$ and power splitting ratios $\rho_i^\star$ as $\frac{1}{\upsilon_{ik}}$ after scaling $\upsilon_{ik}$ and $\kappa_{ik}$ such that $\frac{1}{\upsilon_{ik}} + \frac{1}{\kappa_{ik}} = 1$ where $\{\upsilon_{ik}, \kappa_{ik}\}_{i=1}^N$ is obtained by solving (10) at the $k^{th}$ iteration.
**5)** Scale $\mathbf{w}^\star$ if necessary such that (6.b) and (6.c) are satisfied without violating (6.e).

## 6 Distributed Phase-Only Beamforming

- Algorithm 1 designs beamformer such that the relays can adjust their powers arbitrarily.
- The major drawback of this approach is the uneven battery utilization of the relays, resulting a node running out of energy independent of the others.
- To overcome this problem, we propose phase-only beamformer.
- QoS-aware distributed phase-only beamforming problem can be written as,

$$\min_{\mathbf{w} \in \mathbb{C}^M, \{\upsilon_i, \kappa_i\}_{i=1}^N, p} \quad p \qquad (11.a)$$

$$s.t. \ |w_m|^2 D_{m,m} = p \qquad (11.b)$$

$$p \leq p_m \quad m = 1, 2, ..., M \qquad (11.c)$$

$$(7.b), (7.c), (7.d)$$

$$\min_{\mathbf{w} \in \mathbb{C}^M, \{\upsilon_i, \kappa_i\}_{i=1}^N, p} \quad p \qquad (12.a)$$

$$s.t. \ |w_m|^2 D_{m,m} \leq p \qquad (12.b)$$

$$|w_m|^2 D_{m,m} \geq p \qquad (12.c)$$

$$p \leq p_m \quad m = 1, 2, ..., M \qquad (12.d)$$

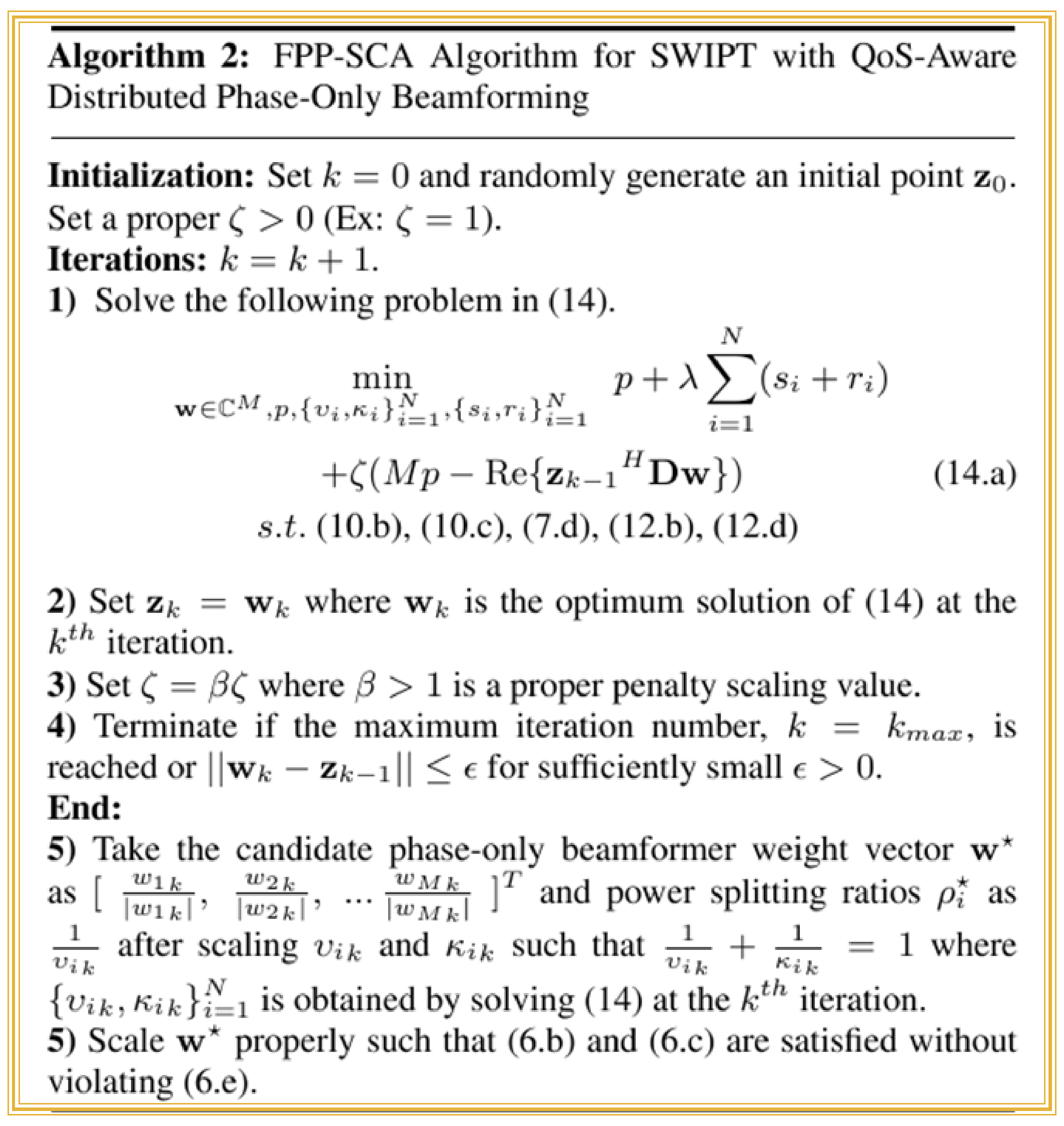
$$(7.b), (7.c), (7.d)$$

$$\min_{\mathbf{w} \in \mathbb{C}^M, \{\upsilon_i, \kappa_i\}_{i=1}^N, p} \quad p + \zeta \sum_{m=1}^{M} \max\{0, p - |w_m|^2 D_{m,m}\} \qquad (13.a)$$

$$s.t. \ (7.b), (7.c), (7.d), (12.b), (12.d)$$

$$\max\{0, p - |w_m|^2 D_{m,m}\} = p - |w_m|^2 D_{m,m} \text{ by (12.b)}$$

$$\zeta \textstyle\sum_{m=1}^{M} \max\{0, p - |w_m|^2 D_{m,m}\} = \zeta(Mp - \mathbf{w}^H \mathbf{D} \mathbf{w})$$



**Algorithm 2:** FPP-SCA Algorithm for SWIPT with QoS-Aware Distributed Phase-Only Beamforming

```
Initialization: Set $k = 0$ and randomly generate an initial point $\mathbf{z}_0$.
Set a proper $\zeta > 0$ (Ex: $\zeta = 1$).
Iterations: $k = k + 1$.
1) Solve the following problem in (14).
    $\min_{\mathbf{w}\in\mathbb{C}^M, p, \{\upsilon_i,\kappa_i\}_{i=1}^N, \{s_i,r_i\}_{i=1}^N} \quad p + \lambda\sum_{i=1}^{N}(s_i + r_i) + \zeta(Mp - \mathrm{Re}\{\mathbf{z}_{k-1}{}^H\mathbf{D}\mathbf{w}\})$    (14.a)
    $s.t.$ (10.b), (10.c), (7.d), (12.b), (12.d)
2) Set $\mathbf{z}_k = \mathbf{w}_k$ where $\mathbf{w}_k$ is the optimum solution of (14) at the $k^{th}$ iteration.
3) Set $\zeta = \beta\zeta$ where $\beta > 1$ is a proper penalty scaling value.
4) Terminate if the maximum iteration number, $k = k_{max}$, is reached or $||\mathbf{w}_k - \mathbf{z}_{k-1}|| \leq \epsilon$ for sufficiently small $\epsilon > 0$.
End:
5) Take the candidate phase-only beamformer weight vector $\mathbf{w}^\star$ as $[\ \frac{w_{1k}}{|w_{1k}|}, \frac{w_{2k}}{|w_{2k}|}, \dots \frac{w_{Mk}}{|w_{Mk}|}\ ]^T$ and power splitting ratios $\rho_i^\star$ as $\frac{1}{\upsilon_{ik}}$ after scaling $\upsilon_{ik}$ and $\kappa_{ik}$ such that $\frac{1}{\upsilon_{ik}} + \frac{1}{\kappa_{ik}} = 1$ where $\{\upsilon_{ik}, \kappa_{ik}\}_{i=1}^N$ is obtained by solving (14) at the $k^{th}$ iteration.
5) Scale $\mathbf{w}^\star$ properly such that (6.b) and (6.c) are satisfied without violating (6.e).
```

## 7 Simulation Results

- Total number of relays=$M$=20.
- Source power=$P_k$ = 10 W.
- Noise variances=$\sigma_r^2 = \sigma_{A,i}^2 = \sigma_{I,i}^2$=0.1.
- Maximum allowable power for each relay=$p_i$= 2 W.
- Number of users=$N$.
- Harvested power threshold=$\mu$.

### *Transmitted Power for Different Number of Users*

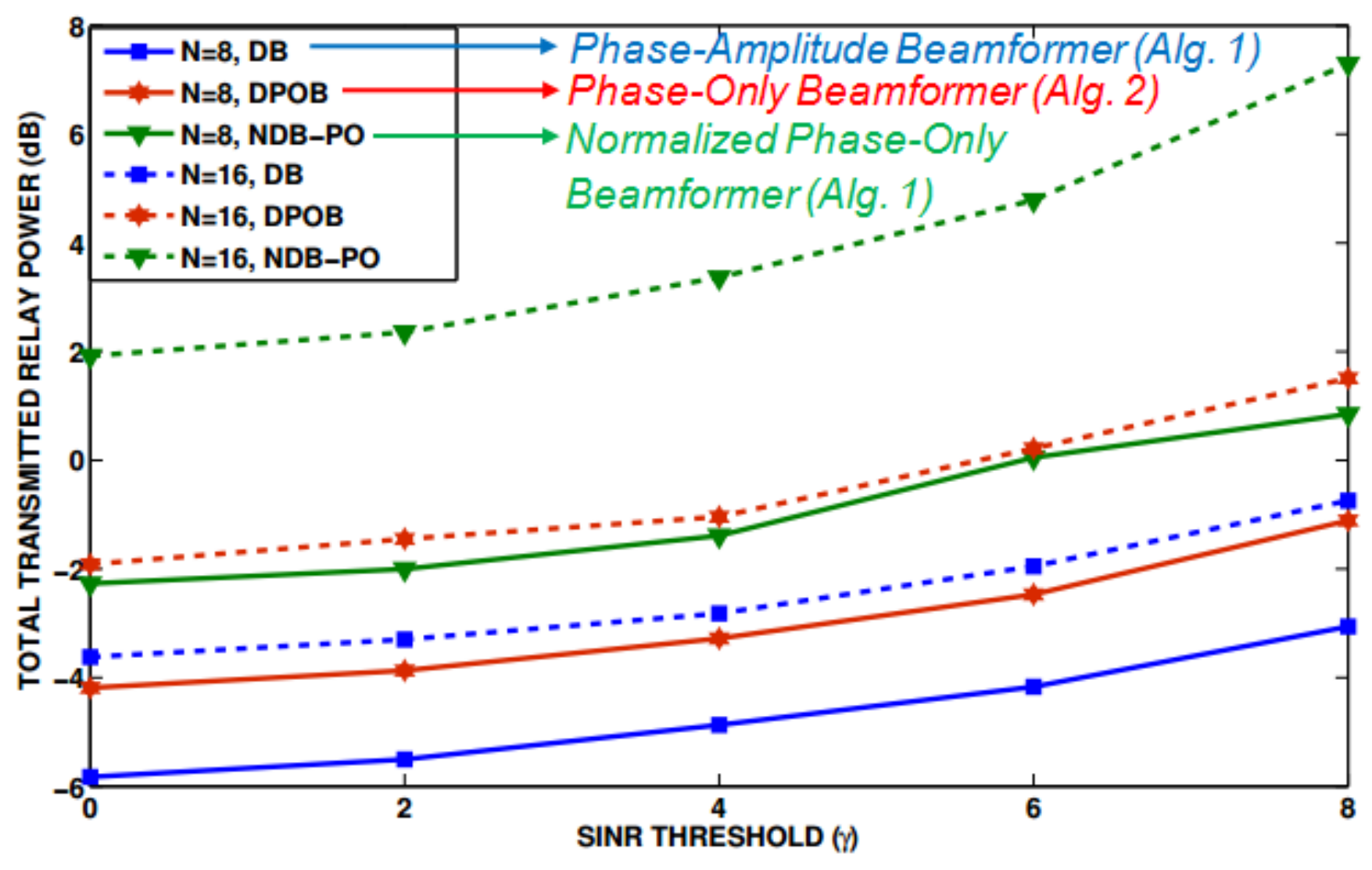


**Fig. 1**. Total transmitted relay power versus SINR threshold, $\gamma$ for single group multicasting scenario.

### *Transmitted Power for Different Harvested Power Thresholds*

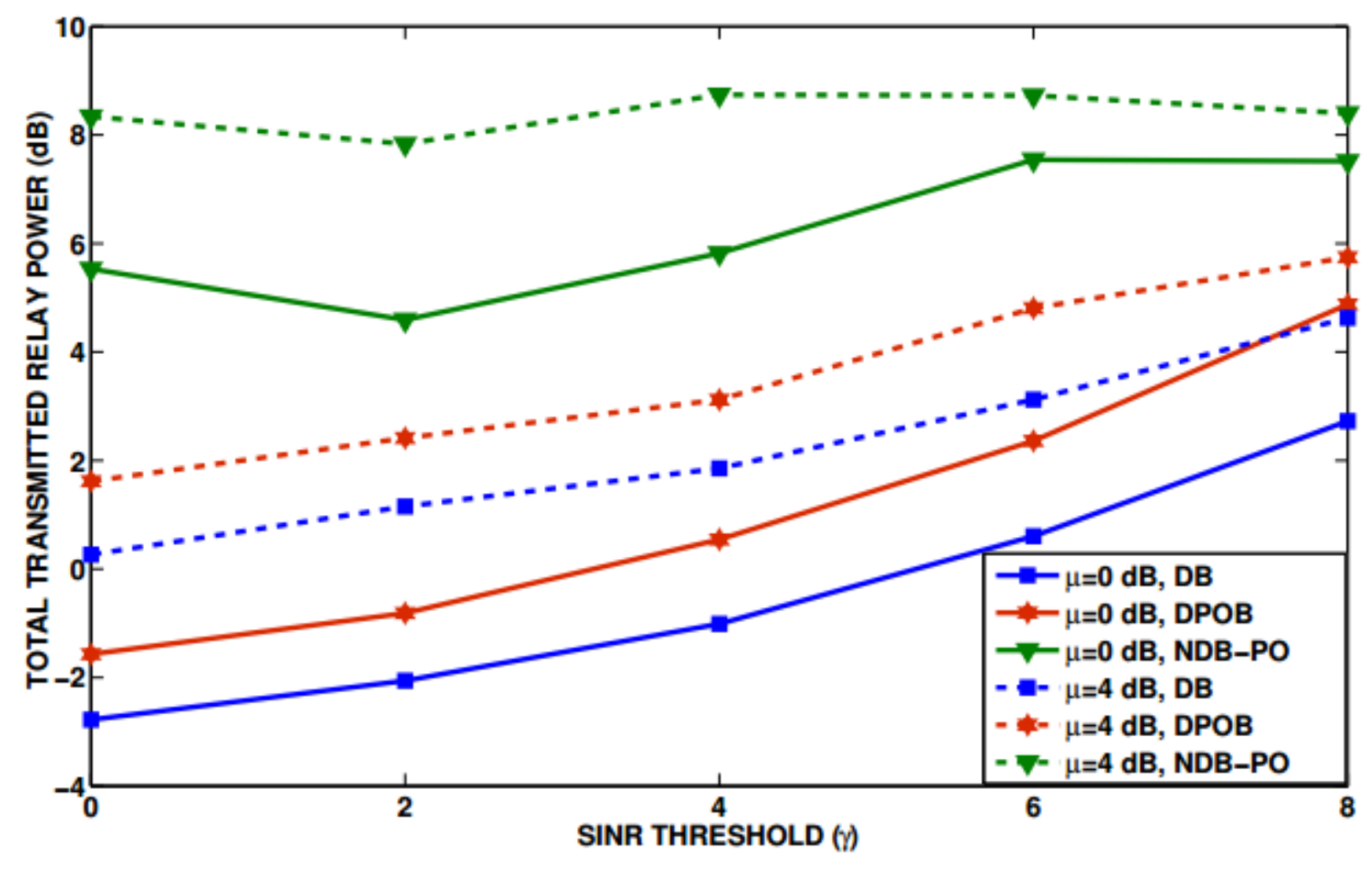


**Fig. 2**. Total transmitted relay power versus SINR threshold, $\gamma$ for two-group multicasting scenario.

## CONCLUSIONS

- In this paper, SWIPT for multi-group multicast relay systems is considered.
- Two algorithms are proposed:
  *Algorithm 1: Phase-Amplitude Distributed Beamformer*
  *Algorithm 2: Phase-Only Distributed Beamformer*
- It is shown that the performance of Algorithm 2 is approximately 2 dB worse than Algorithm 1.
- The main advantage of Algorithm 2 is the even battery utilization for relays.
- In addition, Algorithm 2 performs significantly better than normalized phase-only beamformer obtained by Algorithm 1.

## References

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