Energy Efficiency Maximization in Multi-user MISO Mixed RF/VLC Heterogeneous Cellular Network

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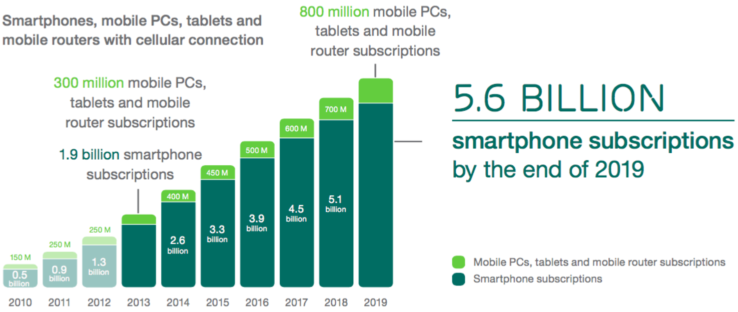
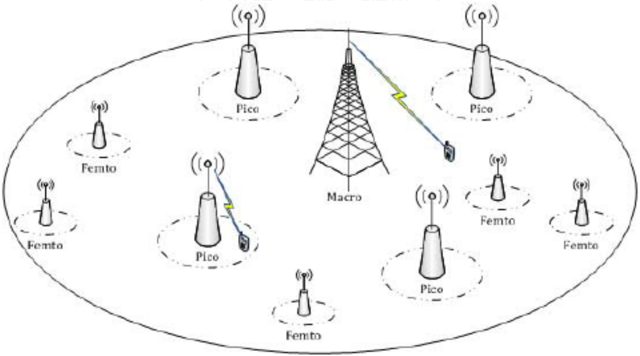
2. System Model
3. Problem Formulation
4. Simulation Results
5. Conclusions

Motivation

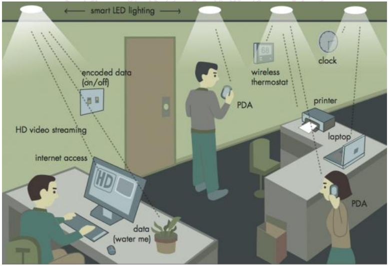


- Due to technological advancements, there is an increasing number of accesses to services using the Internet via wireless medium.

- Heterogeneous cellular network (HCN)
  - Key network architecture for the fifth generation wireless communication systems.
  - Include different types of network structures.
  - Provide higher data rate and more ubiquitous coverage.



- Recently, visible light communication (VLC) has been proposed as an energy efficient technology [1].
    - Illuminate and transmit information at the same time.
    - Insufficient bandwidth problem in radio frequency (RF) results from huge requirements nowadays can be resolved.
- In practical VLC system, light emitting diodes (LED) and photo detector (PD) can be readily used as optical transmitter and receiver.



[1] M. Kashef, M. Ismail, M. Abdallah, K. A. Qaraqe, and E. Serpedin, Energy Efficient Resource Allocation for Mixed RF/VLC Heterogeneous Wireless Networks, IEEE Journal on Selected Areas in Communications, vol. 34, no. 4, pp. 883893, Apr. 2016.

- Energy efficiency (EE) [2]
  - Defined as numbers of information bits transferred per unit energy (bits per Joule).
  - A tradeoff between data rate and power consumption.
- Related works
  - Rate maximization for the VLC system [3].
  - Resource Allocation for the mixed RF/VLC system [1].

[2] M. Sheng, L. Wang, X. Wang, Y. Zhang, C. Xu, and J. Li, Energy Efficient Beamforming in MISO Heterogeneous Cellular Networks With Wireless Information and Power Transfer, IEEE Journal on Selected Areas in Communications, vol. 34, no. 4, pp. 954968, Apr. 2016.

[3] H. Shen, Y. Deng, W. Xu, and C. Zhao, Rate-Maximized Zero-Forcing Beamforming for VLC Multiuser MISO Downlinks, IEEE Photonics Journal, vol. 8, no. 1, pp. 113, Feb. 2016.

- In this work, we aim to maximize EE in a mixed RF/VLC HCN.
- Assume that the channel state information (CSI) is perfectly known at the transmitter ends.
- In order to investigate energy-efficient beamforming design to achieve high-quality EE, we develop a successive convex approximation (SCA) algorithm.

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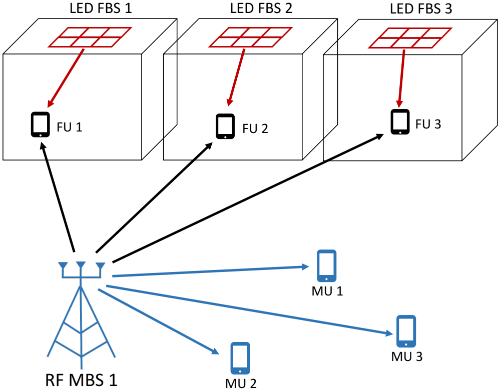
System Model



- Let x_k and s_k denote the signal intended for the k-th FU from the VLC FBS and the RF MBS.
- $\mathbf{w}_k \in \mathbb{R}^{N\times 1}$ and $\mathbf{v}_k \in \mathbb{C}^{N_t\times 1}$ denote the corresponding beamforming vectors for the k-th FU performed by the k-th VLC FBS and the RF MBS.

- The received signals at the k-th FU can be written as

$$y_k^{VLC} = |\mathbf{h}_k^T \mathbf{w}_k|^2 x_k + z_k, \quad (1)$$
$$y_k^{RF} = \mathbf{g}_k^H \mathbf{v}_k s_k + \sum_{j \neq k} \mathbf{g}_k^H \mathbf{v}_j s_j + I_k + n_k. \quad (2)$$

- For VLC channel model, we adopt a commonly used model in the presence of a LOS path [4].
- Therefore, the channel between the m-th LED luminary and the k-th FU can be expressed as

$$h_{m,k} = \begin{cases} \frac{\rho_k A_k}{D_{m,k}^2} R_0(\phi_{m,k}) \cos(\psi_{m,k}), & 0 \leq \psi_{m,k} \leq \varphi_k \\ 0, & \psi_{m,k} \geq \varphi_k \end{cases}, \qquad (3)$$

[4] Z. Yu, R. J. Baxley, and G. T. Zhou, Multi-User MISO Broadcasting for Indoor Visible Light Communication, in Acoustics, Speech and Signal Processing (ICASSP), 2013 IEEE International Conference on. IEEE, 2013, pp. 48494853.

- From [5], we can express the achievable rate for the k-th user from the VLC FBS as

$$R_k^{\mathsf{VLC}}(\{\mathbf{w}_k\}) = \frac{1}{2}\log_2\left(1 + \frac{2|\mathbf{h}_k^T\mathbf{w}_k|^2}{\pi e \sigma_{z_k}^2}\right), \tag{4}$$

where e represents natural logarithm.

- On the other hand, the achievable rate for the k-th user from the RF MBS can be written as

$$R_k^{\mathsf{RF}}(\{\mathbf{v}_k\}) = \log_2\left(1 + \frac{|\mathbf{g}_k^H\mathbf{v}_k|^2}{\sum_{j\neq k}|\mathbf{g}_k^H\mathbf{v}_j|^2 + P_k + \sigma_{n_k}^2}\right). \tag{5}$$

[5] A. Lapidoth, S. M. Moser, and M. A. Wigger, On the Capacity of Free-Space Optical Intensity Channels, IEEE Transactions on Information Theory, vol. 55, no. 10, pp. 44494461, Oct. 2009.

Problem Formulation

- In this work, we aim to maximize EE of the entire system.
- By definition, we can calculate EE as follows

$$EE(\{\mathbf{w}_k\},\ \{\mathbf{v}_k\}) \triangleq \frac{\sum_{k=1}^{K} R_k^{\mathsf{VLC}}(\{\mathbf{w}_k\}) + \sum_{k=1}^{K} R_k^{\mathsf{RF}}(\{\mathbf{v}_k\})}{P_{\mathsf{total}}(\{\mathbf{w}_k\},\ \{\mathbf{v}_k\})}, \qquad (6)$$

where

$$P_{\mathsf{total}}(\{\mathbf{w}_k\},\ \{\mathbf{v}_k\}) = P_{\mathsf{VLC}} + P_{\mathsf{RF}} + \xi_1 \sum_{k=1}^{K} \|\mathbf{w}_k\|^2 + \xi_2 \sum_{k=1}^{K} \|\mathbf{v}_k\|^2. \qquad (7)$$

  - P_{VLC} denotes the fixed power of VLC FBS.
  - P_{RF} denotes the circuit power of RF MBS.
  - ξ_1 and ξ_2 denote the amplifier coefficients.

- Therefore, we can formulate the optimization problem as the following fractional programming problem

$$\max_{\mathbf{w}_k,\ \mathbf{v}_k} \quad \frac{\sum_{k=1}^{K} R_k^{\mathsf{VLC}}(\{\mathbf{w}_k\}) + \sum_{k=1}^{K} R_k^{\mathsf{RF}}(\{\mathbf{v}_k\})}{P_{\mathsf{total}}(\{\mathbf{w}_k\},\ \{\mathbf{v}_k\})}, \tag{8a}$$

$$\text{s.t.}\ \frac{1}{2}\log_2\left(1+\frac{2|\mathbf{h}_k^T\mathbf{w}_k|^2}{\pi e \sigma_{z_k}^2}\right) + \log_2\left(1+\frac{|\mathbf{g}_k^H\mathbf{v}_k|^2}{\sum_{j\neq k}|\mathbf{g}_k^H\mathbf{v}_j|^2 + P_k + \sigma_{n_k}^2}\right) \geq r_k,\ \forall k, \tag{8b}$$

$$\sum_{k=1}^{K} \|\mathbf{w}_k\|^2 \leq \mathsf{P}_{FBS}, \tag{8c}$$

$$\sum_{k=1}^{K} \|\mathbf{v}_k\|^2 \leq \mathsf{P}_{MBS}. \tag{8d}$$

- How to solve?
  - Exhausting search.
  - Some other efficient methods, e.x. convex optimization.
- Why use convex optimization?
  - There are some existing efficient solvers to use.

$$\max_{\mathbf{w}_k,\ \mathbf{v}_k} \quad \frac{\sum_{k=1}^{K} R_k^{\mathsf{VLC}}(\{\mathbf{w}_k\}) + \sum_{k=1}^{K} R_k^{\mathsf{RF}}(\{\mathbf{v}_k\})}{P_{\mathsf{total}}(\{\mathbf{w}_k\},\ \{\mathbf{v}_k\})}, \tag{8a}$$

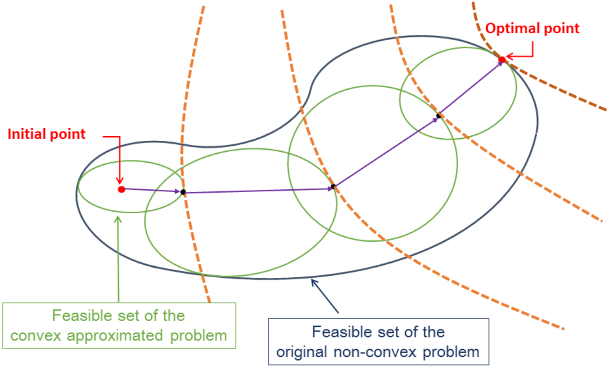
$$\text{s.t.} \quad \frac{1}{2}\log_2\left(1 + \frac{2|\mathbf{h}_k^T\mathbf{w}_k|^2}{\pi e \sigma_{z_k}^2}\right) + \log_2\left(1 + \frac{|\mathbf{g}_k^H\mathbf{v}_k|^2}{\sum_{j\neq k}|\mathbf{g}_k^H\mathbf{v}_j|^2 + P_k + \sigma_{n_k}^2}\right) \geq r_k,\ \forall k, \tag{8b}$$

$$\sum_{k=1}^{K}\|\mathbf{w}_k\|^2 \leq \mathsf{P}_{FBS}, \tag{8c}$$

$$\sum_{k=1}^{K}\|\mathbf{v}_k\|^2 \leq \mathsf{P}_{MBS}. \tag{8d}$$

What is the strategy?

- Successive convex approximation (SCA) algorithm.
    - Semi-definite relaxation (SDR)
    - Change-of-variable technique
    - First-order approximation



- Through SDR, we can approximate problem (8) as following

$$\max_{\mathbf{W}_k,\ \mathbf{V}_k} \frac{\sum_{k=1}^{K} R_k^{\mathsf{VLC}}(\{\mathbf{W}_k\}) + \sum_{k=1}^{K} R_k^{\mathsf{RF}}(\{\mathbf{V}_k\})}{P_{\mathsf{total}}(\{\mathbf{W}_k\},\ \{\mathbf{V}_k\})}, \tag{9a}$$

$$\text{s.t. } \frac{1}{2}\log_2\left(1 + \frac{2\mathrm{Tr}(\mathbf{W}_k\mathbf{H}_k)}{\pi e \sigma_{z_k}^2}\right) + \log_2\left(1 + \frac{\mathrm{Tr}(\mathbf{V}_k\mathbf{G}_k)}{\sum_{j\neq k}\mathrm{Tr}(\mathbf{V}_j\mathbf{G}_k) + P_k + \sigma_{n_k}^2}\right) \geq r_k,\ \forall k, \tag{9b}$$

$$\sum_{k=1}^{K}\mathrm{Tr}(\mathbf{W}_k) \leq \mathrm{P}_{FBS}, \tag{9c}$$

$$\sum_{k=1}^{K}\mathrm{Tr}(\mathbf{V}_k) \leq \mathrm{P}_{MBS}. \tag{9d}$$

- Then, consider the following change variables

$$\eta \triangleq \frac{\sum_{k=1}^{K} \frac{1}{2}\log_2\left(1+\frac{2\mathrm{Tr}(\mathbf{W}_k\mathbf{H}_k)}{\pi e\sigma_{z_k}^2}\right)+\sum_{k=1}^{K}\log_2\left(1+\frac{\mathrm{Tr}(\mathbf{V}_k\mathbf{G}_k)}{\sum_{j\neq k}\mathrm{Tr}(\mathbf{V}_j\mathbf{G}_k)+P_k+\sigma_{n_k}^2}\right)}{P_{\mathrm{VLC}}+P_{\mathrm{RF}}+\xi_1\sum_{k=1}^{K}\mathrm{Tr}(\mathbf{W}_k)+\xi_2\sum_{k=1}^{K}\mathrm{Tr}(\mathbf{V}_k)}, \quad (10)$$

$$e^{\lambda} \triangleq \eta, \quad (11)$$

$$e^{\mu_k} \triangleq \mathrm{Tr}(\mathbf{W}_k), \quad (12)$$

$$e^{\nu_k} \triangleq \mathrm{Tr}(\mathbf{V}_k), \quad (13)$$

$$r_k^{\mathrm{VLC}} \triangleq \frac{1}{2}\log_2\left(1+\frac{2\mathrm{Tr}(\mathbf{W}_k\mathbf{H}_k)}{\pi e\sigma_{z_k}^2}\right), \quad (14)$$

$$r_k^{\mathrm{RF}} \triangleq \log_2\left(1+\frac{\mathrm{Tr}(\mathbf{V}_k\mathbf{G}_k)}{\sum_{j\neq k}\mathrm{Tr}(\mathbf{V}_j\mathbf{G}_k)+P_k+\sigma_{n_k}^2}\right), \quad (15)$$

$$e^{\alpha_k} \triangleq 2^{r_k^{\mathrm{RF}}}-1, \quad (16)$$

$$e^{\beta_k} \triangleq \mathrm{Tr}(\mathbf{V}_k\mathbf{G}_k), \quad (17)$$

$$e^{\gamma_k} \triangleq \sum_{j\neq k}\mathrm{Tr}(\mathbf{V}_j\mathbf{G}_k)+P_k+\sigma_{n_k}^2. \quad (18)$$

- The problem can be reformulated as

$$\max_{\substack{\mathbf{W}_k,\ \mathbf{V}_k,\ \eta,\ r_k^{VLC},\ r_k^{RF} \\ \alpha_k,\ \beta_k,\ \gamma_k,\ \lambda,\ \mu_k,\ \nu_k}} \quad \eta \tag{19a}$$

$$\text{s.t.} \quad e^{\lambda}\left(P_{VLC}+P_{RF}+\xi_1\sum_{k=1}^{K}e^{\mu_k}+\xi_2\sum_{k=1}^{K}e^{\nu_k}\right)\le\sum_{k=1}^{K}r_k^{VLC}+\sum_{k=1}^{K}r_k^{RF}, \tag{19b}$$

$$e^{\lambda}\ge\eta, \tag{19c}$$

$$e^{\mu_k}\ge\mathrm{Tr}(\mathbf{W}_k),\ \forall k, \tag{19d}$$

$$e^{\nu_k}\ge\mathrm{Tr}(\mathbf{V}_k),\ \forall k, \tag{19e}$$

$$r_k^{VLC}+r_k^{RF}\ge r_k,\ \forall k, \tag{19f}$$

$$r_k^{VLC}\le\frac{1}{2}\log_2\left(1+\frac{2\mathrm{Tr}(\mathbf{W}_k\mathbf{H}_k)}{\pi e\sigma_{z_k}^2}\right),\ \forall k, \tag{19g}$$

$$r_k^{RF}\le\log_2\left(1+e^{\alpha_k}\right),\ \forall k, \tag{19h}$$

$$e^{\alpha_k-\beta_k+\gamma_k}\le 1,\ \forall k, \tag{19i}$$

$$e^{\beta_k}\le\mathrm{Tr}(\mathbf{V}_k\mathbf{G}_k),\ \forall k, \tag{19j}$$

$$e^{\gamma_k}\ge\sum_{j\neq k}\mathrm{Tr}(\mathbf{V}_j\mathbf{G}_k)+P_k+\sigma_{n_k}^2,\ \forall k, \tag{19k}$$

(9c), (9d).

- We can apply first-order approximation to these non-convex constraints.
- For instance:
  - constraint (19c): $e^{\lambda} \geq \eta$
  $$\Downarrow$$
  $$e^{\bar{\lambda}}(\lambda - \bar{\lambda} + 1) \geq \eta.$$
  - constraint (19h): $r_k^{RF} \leq \log_2(1 + e^{\alpha_k})$
  $$\Downarrow$$
  $$r_k^{RF} \leq \log_2(1 + e^{\bar{\alpha}_k}) + \frac{e^{\bar{\alpha}_k}(\alpha_k - \bar{\alpha}_k)}{\ln 2(1 + e^{\bar{\alpha}_k})}.$$
  - constraints (19d), (19e) and (19k) can use similar technique.

$$\max_{\substack{\mathbf{W}_k,\ \mathbf{V}_k,\ \eta,\ r_k^{VLC},\ r_k^{RF}\\ \alpha_k,\ \beta_k,\ \gamma_k,\ \lambda,\ \mu_k,\ \nu_k}} \quad \eta \tag{20a}$$

$$\text{s.t.} \quad e^{\bar{\lambda}}(\lambda - \bar{\lambda} + 1) \geq \eta, \tag{20b}$$

$$e^{\bar{\mu}_k}(\mu_k - \bar{\mu}_k + 1) \geq \mathsf{Tr}(\mathbf{W}_k),\ \forall k, \tag{20c}$$

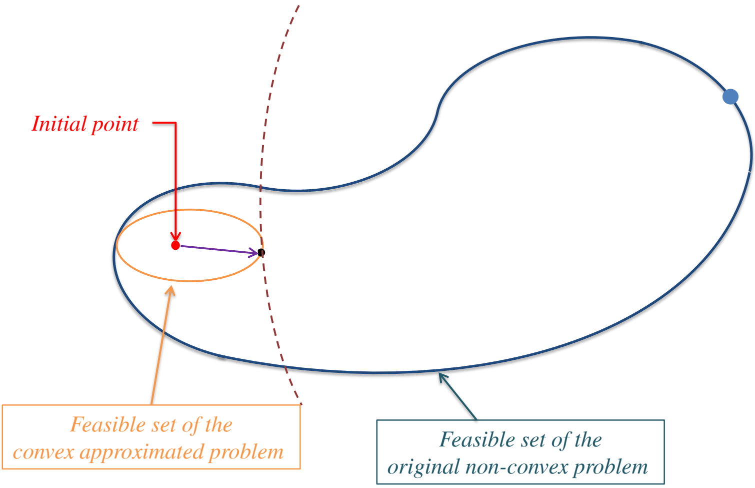
$$e^{\bar{\nu}_k}(\nu_k - \bar{\nu}_k + 1) \geq \mathsf{Tr}(\mathbf{V}_k),\ \forall k, \tag{20d}$$

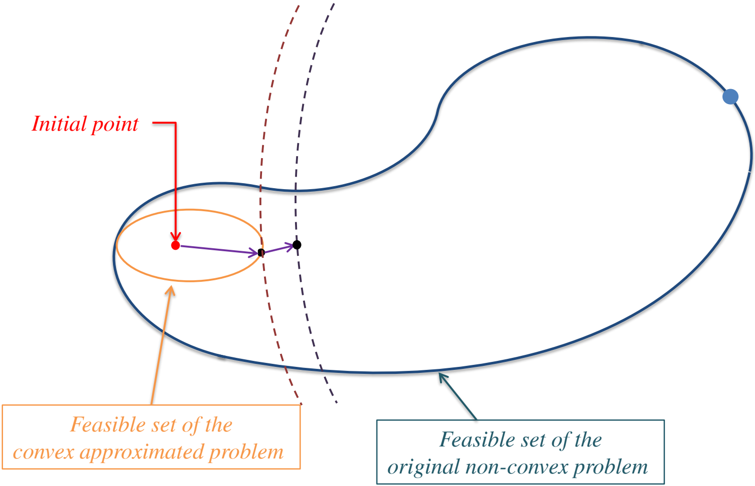
$$r_k^{RF} \leq \log_2\left(1 + e^{\bar{\alpha}_k}\right) + \frac{e^{\bar{\alpha}_k}(\alpha_k - \bar{\alpha}_k)}{\ln 2(1 + e^{\bar{\alpha}_k})},\ \forall k, \tag{20e}$$

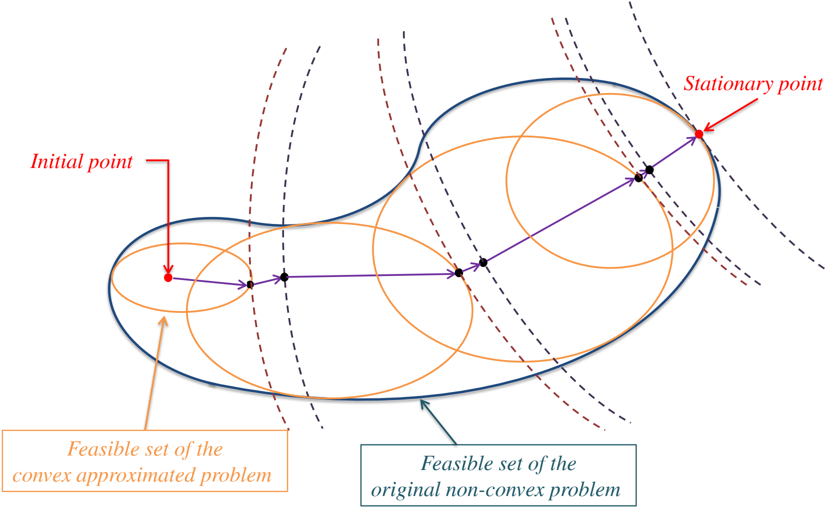
$$e^{\bar{\gamma}_k}(\gamma_k - \bar{\gamma}_k + 1) \geq \sum_{j \neq k} \mathsf{Tr}(\mathbf{V}_j \mathbf{G}_k) + P_k + \sigma_{n_k}^2,\ \forall k, \tag{20f}$$

$$\text{(9c), (9d), (19b), (19f), (19g), (19i), (19j).}$$

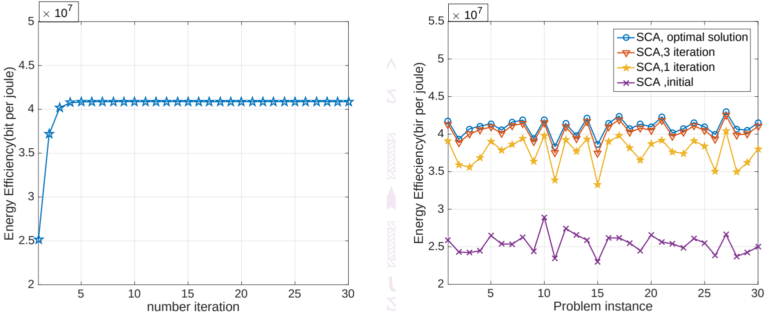
- Problem (20) is now an approximate convex problem and can be solved by standard convex solvers.


Initial point
Feasible set of the
convex approximated problem
Feasible set of the
original non-convex problem


Initial point
Feasible set of the
convex approximated problem
Feasible set of the
original non-convex problem

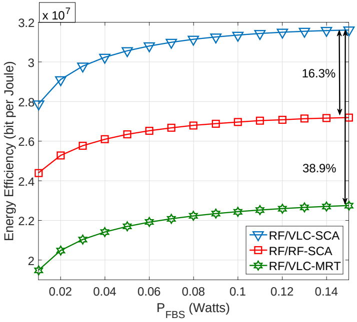

Initial point
Stationary point
Feasible set of the convex approximated problem
Feasible set of the original non-convex problem

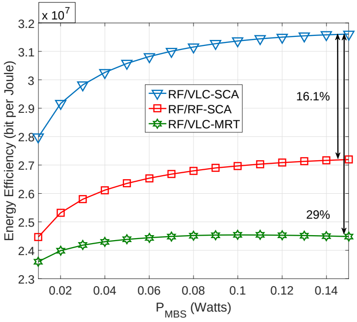
Convergence behavior for the proposed SCA algorithm



- The SCA algorithm converges when the number of iteration is around 5 on average.
- The SCA algorithm converges rapidly since the performance achieved in the fifth iteration is already very close to the optimal value.

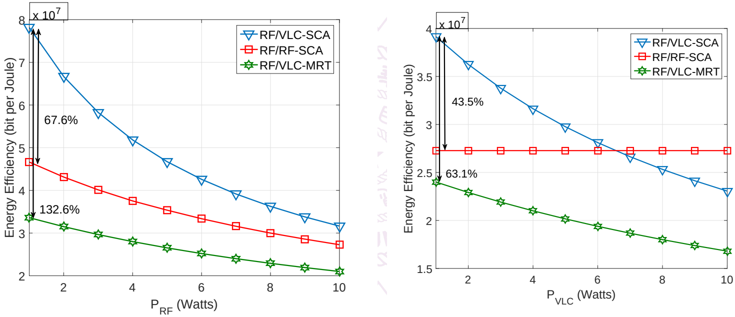
EE performance versus total power of the FBS, P_{FBS} and the MBS, P_{MBS}.





- **SCA** outperforms **MRT** scheme.
- The EE performance of **RF/VLC** network structure is better than **RF/RF** structure.
- With the increase of P_{FBS} and P_{MBS}, EE also increases.

EE performance versus circuit power consumption of the MBS, P_{RF} and the FBS, P_{VLC}.



- The EE of **RF/VLC** and **RF/RF** decrease with increasing of P_{RF}.
- The EE of **RF/VLC** decreases with increasing of P_{VLC} while the EE of **RF/RF** is unchanged with the same parameter.

Conclusions

- In this work, we consider an advanced HCN architecture that combines RF and VLC.
- We tackle the optimization problem by the SCA algorithm since the original problem is non-convex and difficult to solve.
- The EE performance of **SCA** improves by 132.6% compared to the **MRT** scheme and improves by 67.6% compared to **RF/RF** structure.
- For future work, we plan to extend to imperfect CSI case and consider the broadcasting transmission strategy.

Thank you!

Q & A