RF vs Lightwave Wireless Power Transfer: Research challenges and Future trends

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Wireless Communications Systems Group (WSCG)

- Aristotle University of Thessaloniki (34 departments, about 80.000 students), www.auth.gr
- Electrical & Computer Engineering Dept. (1500 undergraduate, 400 MSc and 100PhD), www.ee.auth.gr
- Wireless Communications Systems Group (WSCG)

Head: George K. Karagiannidis

6 PhD students

2 Postdocs

Research Areas

  Wireless Communications

  Optical Wireless Communications

  Wireless Power Transfer and Applications

  Communications for Biomedical Engineering

More than 500 published papers

Seven (7) patents

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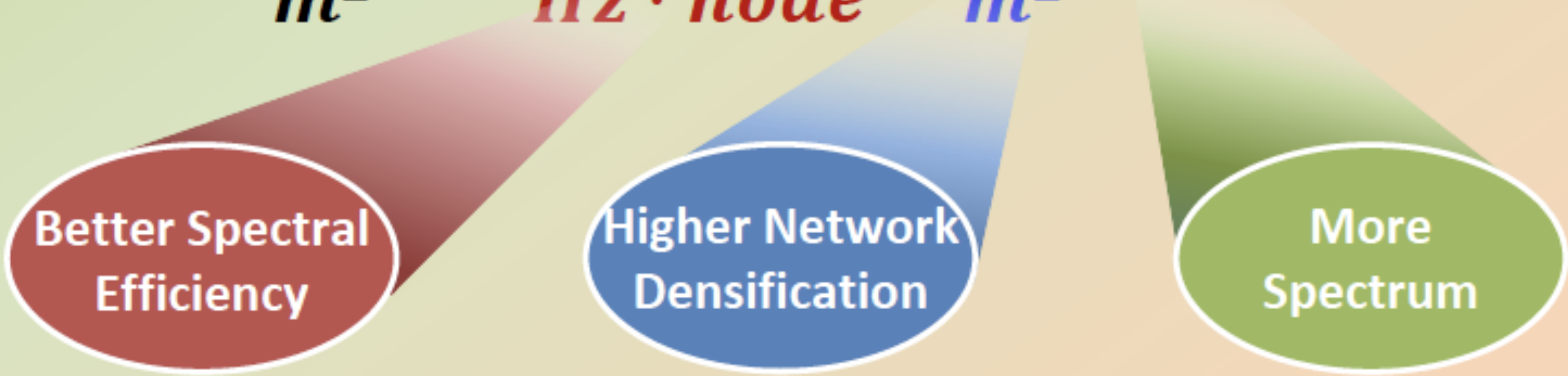
Outline

- Increasing the Area Capacity in Indoor IoT Applications
- The need for wireless power transfer
- RF vs Lightwave Wireless Power Transfer
- On going research-Four case studies
- Research challenges

Increasing the Area Capacity in 5G Systems

$$\frac{bits/s}{m^2} = \frac{bits/s}{Hz \cdot node} \cdot \frac{node}{m^2} \cdot Hz$$



- mMIMO
- NOMA
- IManagement
- Full-duplex

- Small Cells
- Cloud-RAN
- D2D
- CoMP

- Carrier Aggregation
- mmWave (60 GHz)
- OWC (VLC/IR)

OWC for Indoor IoT Applications

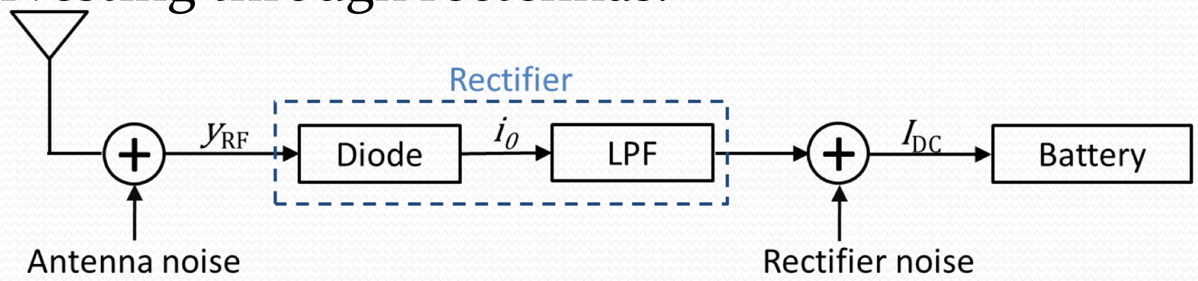
- Most of the data consumption/generation (about 80%) occurs in indoor environments [Ayyash et al., IEEE COMMAG, 2016]
- RF technology is the main enabler. LoS is not a requirement.
- Visible Light (VL) or Infrared (IR), have been recognized as promising alternative/complimentary technologies to RF [Ghassemlooy et. al, *VLC: Theory and Applications*, 2017] [Wang et. al, *VLC: Modulation and Signal Processong*, 2017]
- **Advantages** of VLC/IR: wide bandwidth, easy bandwidth reuse, no electromagnetic interference, cost-efficiency, inherent security, etc.
- **Disadvantage** of VLC/IR: Direct or diffuse LoS is required

The need for wireless power transfer

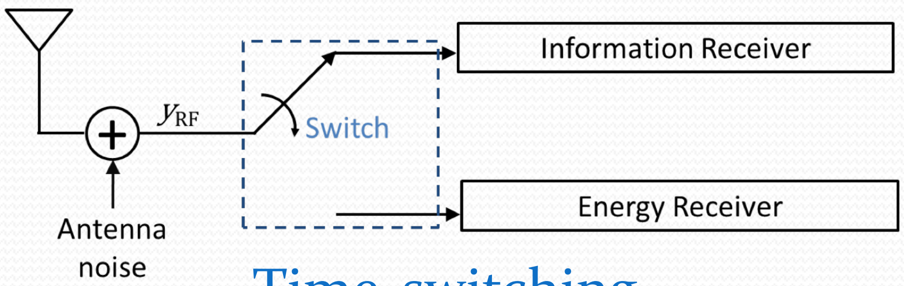
- Energy harvesting (EH) is a critical part of the operation and maintain of the IoT devices.
- Traditional EH methods rely on natural resources, such as solar and wind, which are uncontrollable. EH from artificial energy sources is needed.
- **Near-field WPT**: Non-radiative techniques are used, e.g., inductive coupling. Widely used technology, limited mainly by the distance.
- **Far-field WPT:** Harvesting energy from sources that intentionally generate EM waves (e.g. radio frequency or wireless optical).
- **Challenge: Unifying the information and energy transmission**

RF Simultaneous wireless information and power transfer (SWIPT)

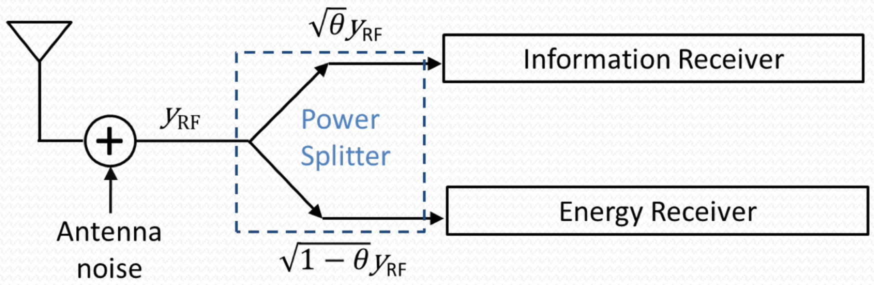
- RF SWIPT is a well-explored technology [Ding et al., IEEE COMMAG 2014]
- Energy harvesting through rectennas.



- Practical circuits for harvesting energy from radio signals are not able to decode the carried information directly. So: *Power-splitting* and *Time-switching* [Zhou et al., IEEE TCOM, 2013]



Time-switching



Power-Splitting

Practical limitations of RF SWIPT

- RF SWIPT raises safety concerns (possible impact of RF signals on health) : FCC and ETSI Restrictions
- Higher interference will enlarge the spectrum congestion problem and negatively affect the precision of electronic equipments
- **The utilization of lightwave technology is a promising alternative: Green, more efficient**

Simultaneous Lightwave Information and Power Transfer (SLIPT)

Concept: The use of VL or IR LEDs to simultaneously transmit information and transfer energy

- ✓ Many research challenges, regarding the implementation and optimization of the involved parameters

SLIPT is fundamentally different to SWIPT, due to divergent channels characteristics, transmission/reception equipment, and EH model.

The theoretical framework for SLIPT was presented for first time in

[Diamantoulakis and Karagiannidis, Globecom,2017] &
[Diamantoulakis, Karagiannidis, and Ding. IEEE TGCN, 2018]

SLIPT: A new research topic in the literature

- [Fakidis et al., PIMRC 2014]: investigates the application of optical links at the same time for high-capacity backhaul and wireless power supply
- [Wang et al., JSAC 2015], [Wang et al., ICC, 2014]: OWC receiver using a solar panel as a photodetector, which efficiently separates the DC and AC components of the modulated light
- [Rakia et al., IEEE COMML, 2016] and [Rakia et al., GLOBECOM,2016]: a dual-hop hybrid VLC/RF communication system is considered.
- [Q. Liu et al., IEEE VTMAG, 2016]: Explored the potential of laser charging for mobile wireless power transfer.
- [Xingbin et al., Hindawi, 2017]: implemented a solar panel receiver prototype that is able to gather energy and receive data simultaneously. The FOV of the PD was considered in the analysis
- **[Diamantoulakis and Karagiannidis, Globecom,2017] & [Diamantoulakis, Karagiannidis, and Ding. IEEE TGCN, 2018]**

PD or Solar Panel for SLIPT?

There are two modes of photoelectric converters (PECs):

- **Photoconductive mode**
  - An external reverse bias is needed to generate the photocurrent (the basis of **photodiodes-PDs**).
  - **Cons**: It needs external power and increases the hardware complexity.
  - **Pros**: High speed information detection
- **Photoelectric mode**
  - PECs are zero biased to exploit the photovoltaic effect (the basis of **solar cells**)
  - **Pros**: Simple and energy efficient realization, **no external power or other components are needed. It can also be used for information detection**
  - It suffers less from noise at the expense of lower speed in the information detection

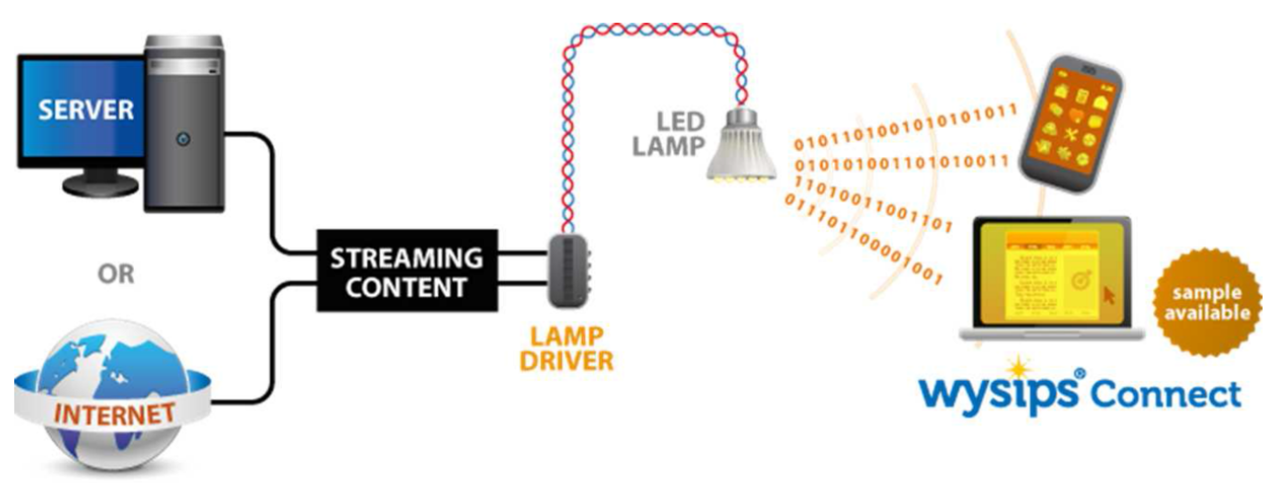
- **Conclusion: Disadvantage of use PIN and avalanche PDs for SLIPT applications since they need external power. Photovoltaic cells (solar panels) are preferred.**

RF SWIPT vs SLIPT

	RF SWIPT	SLIPT
Need for LoS	Not necessarily	Yes
Components	Antennas and rectifiers (rectennas)	Laser/LEDS, photocells (e.g., solar panels), and lenses
Receiving gain	Based on high Antenna gain	Fied-of-view (FoV) of optical receiver
EH model	Rectennas: The received RF band signal is first converted to a DC signal by a rectifier	Solar panel model: The DC part of the signal can be directly used for EH
Power sources	Artificial	Both natural and artificial
Optimization	Adaptation of the receiver's parameters (e.g., power splitting and time-switching)	The parameters of the transmitted signal and the FoV need to be adjusted.
EH efficiency	Low	Higher due to natural resources and directivity
Current industrial interest	Low at the moment	Higher

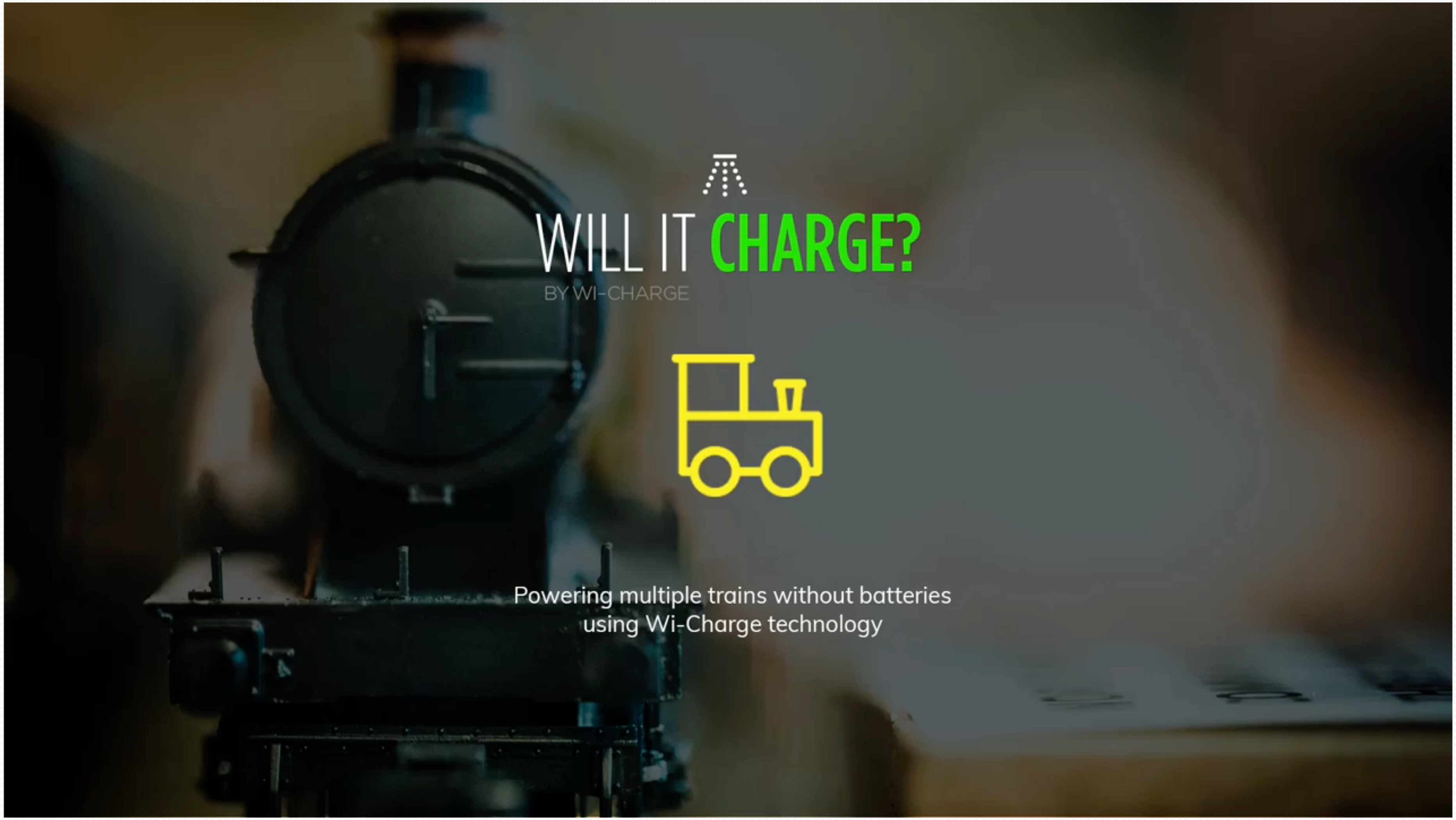
SLIPT: Industrial Interest

- **Wysips Connect:** screens and mobile phones harvest energy and also receive data through VLC [Bialic, White Paper, 2015]
- **Wi-Charge:** lightwave (infrared) power transfer is used to safely charge mobile and IoT devices (delivers ~ 1 W of energy to >5 m distance)



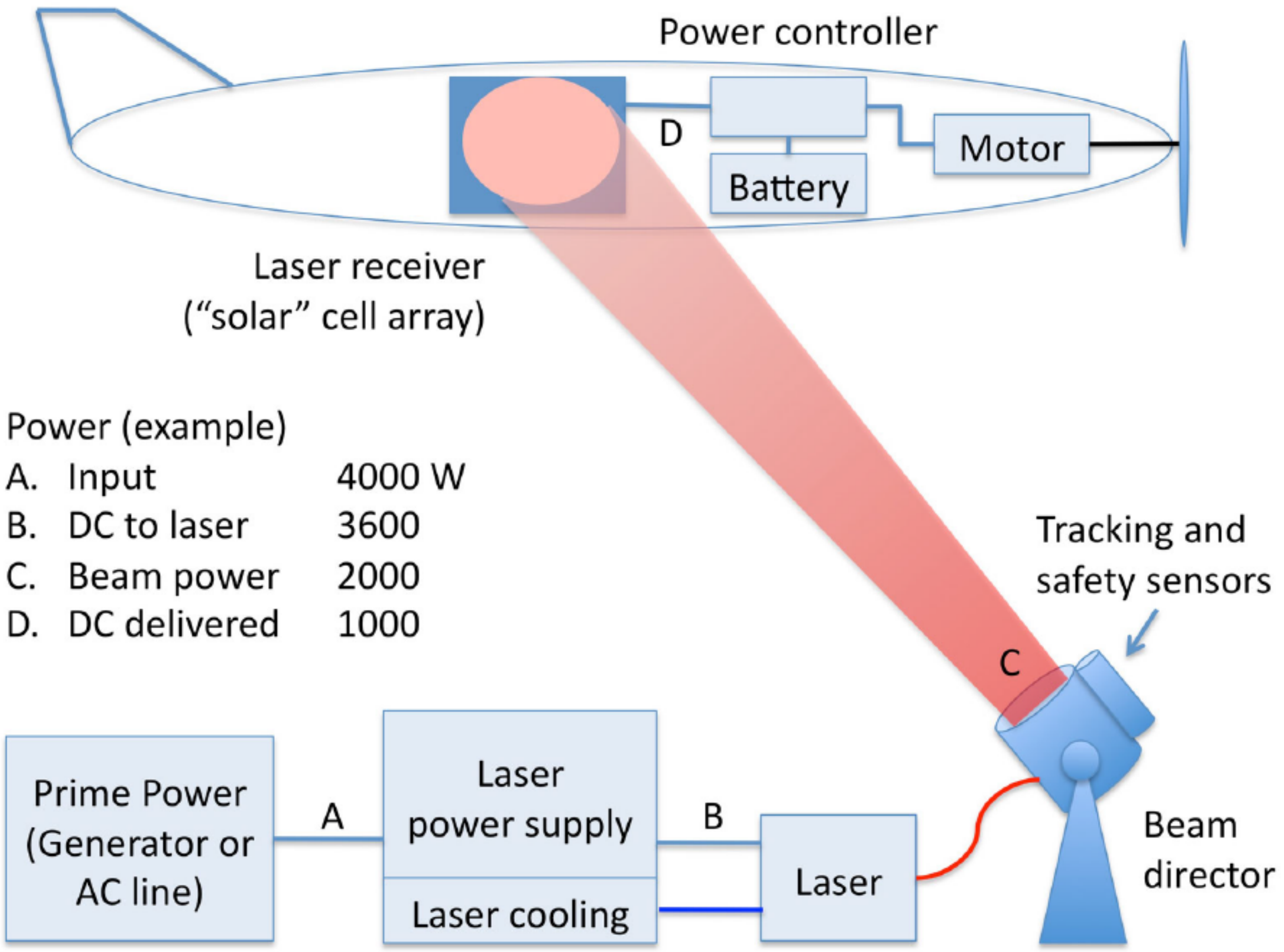
Wi-Charge Video

Wi-Charge Video

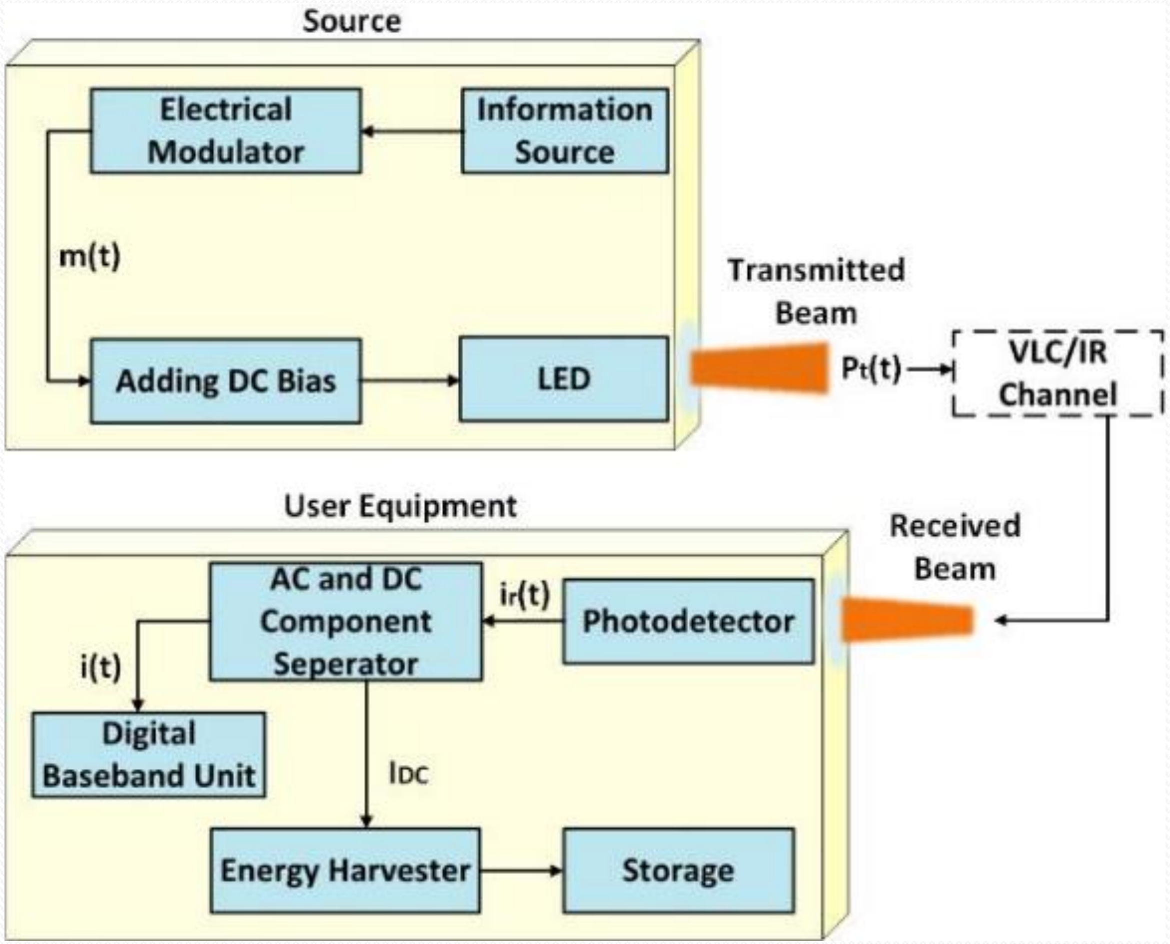


SLIPT: Industrial Interest

- WPT through laser beaming [LaserMotive]
- Lasers can transmit power to drones in flight



SLIPT Transceiver Design



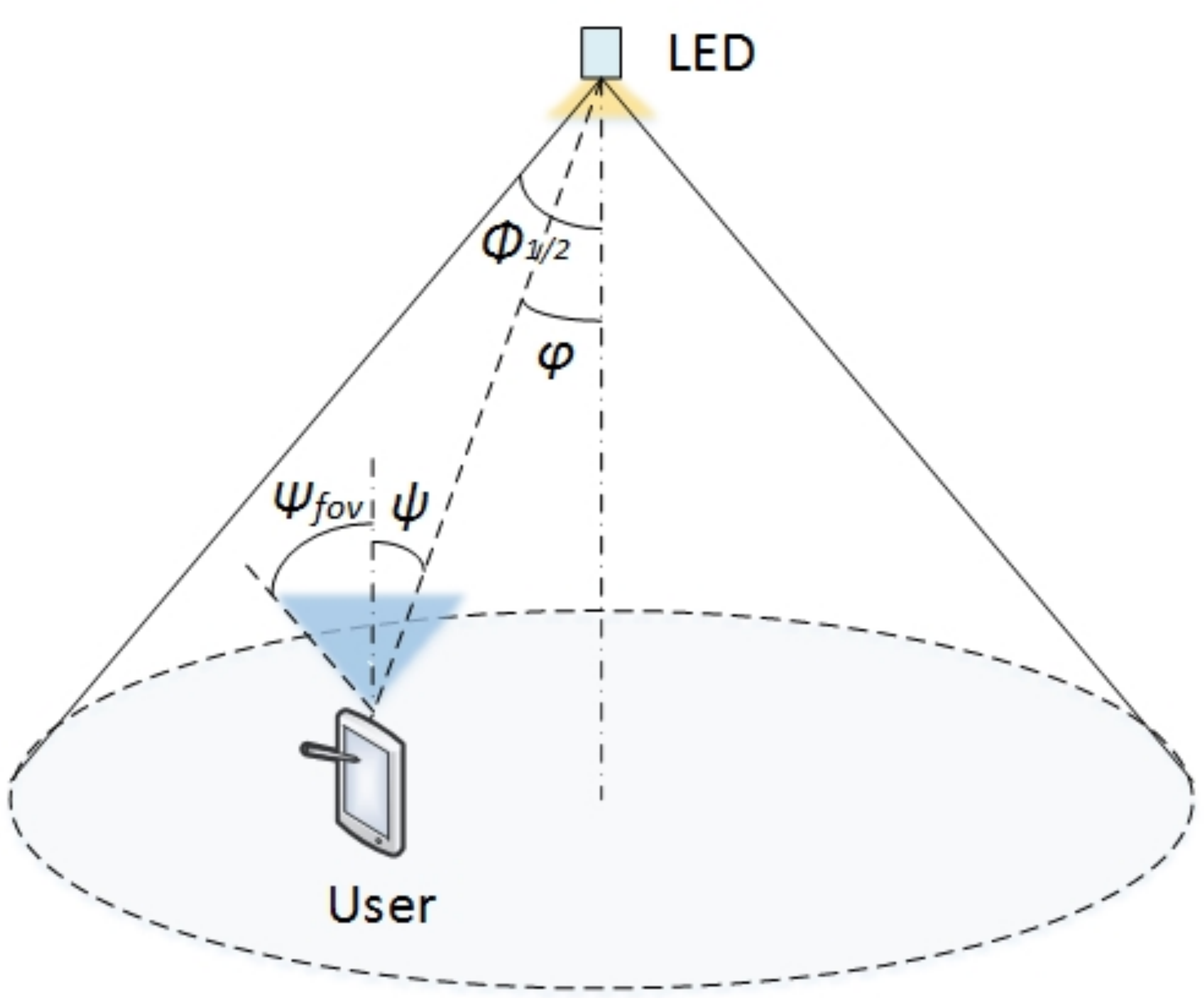
- SLIPT induces an interesting trade-off between the harvested energy and data rate or SINR
- Only the DC component can be used for energy harvesting
- The AC component carries the information.
- The following parameters need to be carefully selected:
  - **DC Bias**
  - **FOV**

SLIPT Strategies

- Feedback is required from the mobile device
- Performed either at the transmitter or at the receiver, or at both sides

- **Adjusting transmission**
  - ✓ **Policy 1:** Time-splitting
  - ✓ **Policy 2:** Time-splitting with DC bias optimization
- **Adjusting reception**
  - ✓ **Policy:** Adjustment of the FOV
- **Coordinated adjustment of transmission and reception**
  - ✓ **Policy 1:** Time-splitting with tunable FOV
  - ✓ **Policy 2:** Time-splitting with DC bias optimization and tunable FOV

Case Study 1: SLIPT in a VLC/IR downlink system



SLIPT Optimization: Time-Splitting with Tunable FOV

Lower bound $$R = T \log_2\left(1 + \frac{e}{2\pi}\gamma\right)$$ [Wang et al., JLT, 2013]

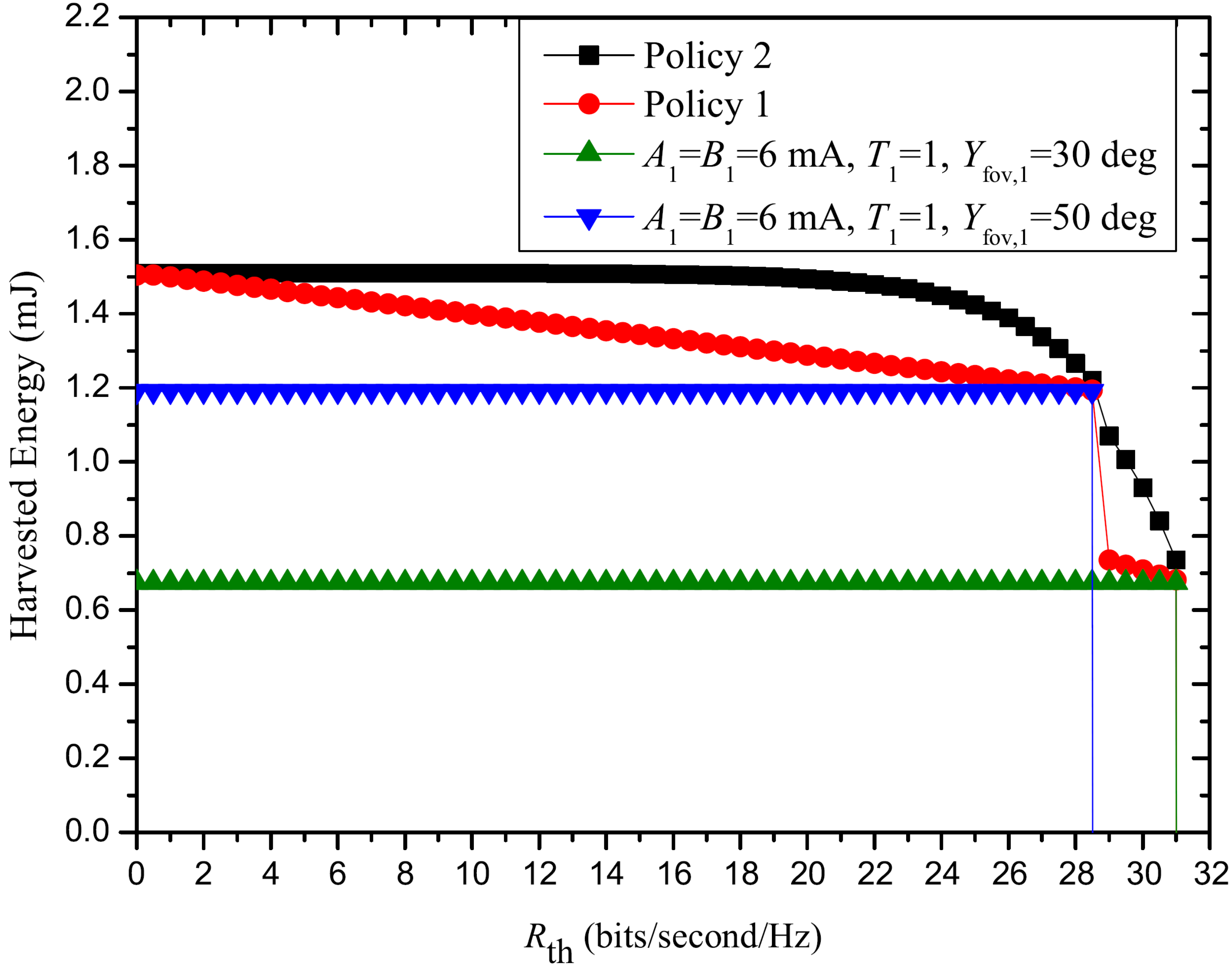
$$\begin{aligned}
\max_{T,\Psi_{\text{fov},1}} \quad & E_{\text{TS}} \\
\textbf{s.t.} \quad & \text{C}_1 : R \geq R_{\text{th}}, \\
& \text{C}_2 : \gamma_1 \geq \gamma_{\text{th}}, \\
& \text{C}_3 : 0 \leq T \leq 1, \\
& \text{C}_4 : \Psi_{\text{fov},1} \in \{\Psi_{\text{fov}}^{[1]}, .., \Psi_{\text{fov}}^{[M]}\}
\end{aligned}$$

$$T^* = \frac{R_{\text{th}}}{\log_2\left(1 + \frac{e(\eta h P_{\text{LED}}(I_H - I_L))^2}{8\pi(P_I(\Psi_{\text{fov},1}^*) + \sigma^2)}\right)}$$

$$\begin{aligned}
\max_{B_1,A_1,T,\Psi_{\text{fov},1}} \quad & E_{\text{TSBO}} \\
\textbf{s.t.} \quad & \text{C}_1 : R \geq R_{\text{th}}, \\
& \text{C}_2 : \gamma_1 \geq \gamma_{\text{th}}, \\
& \text{C}_3 : A_1 \leq \min(B_1 - I_{\text{L}}, I_{\text{H}} - B_1), \\
& \text{C}_4 : 0 \leq T \leq 1, \\
& \text{C}_5 : A_1 \geq 0, \\
& \text{C}_6 : I_{\text{L}} \leq B_1 \leq I_{\text{H}}, \\
& \text{C}_7 : \Psi_{\text{fov},1} \in \{\Psi_{\text{fov}}^{[1]}, .., \Psi_{\text{fov}}^{[M]}\}.
\end{aligned}$$

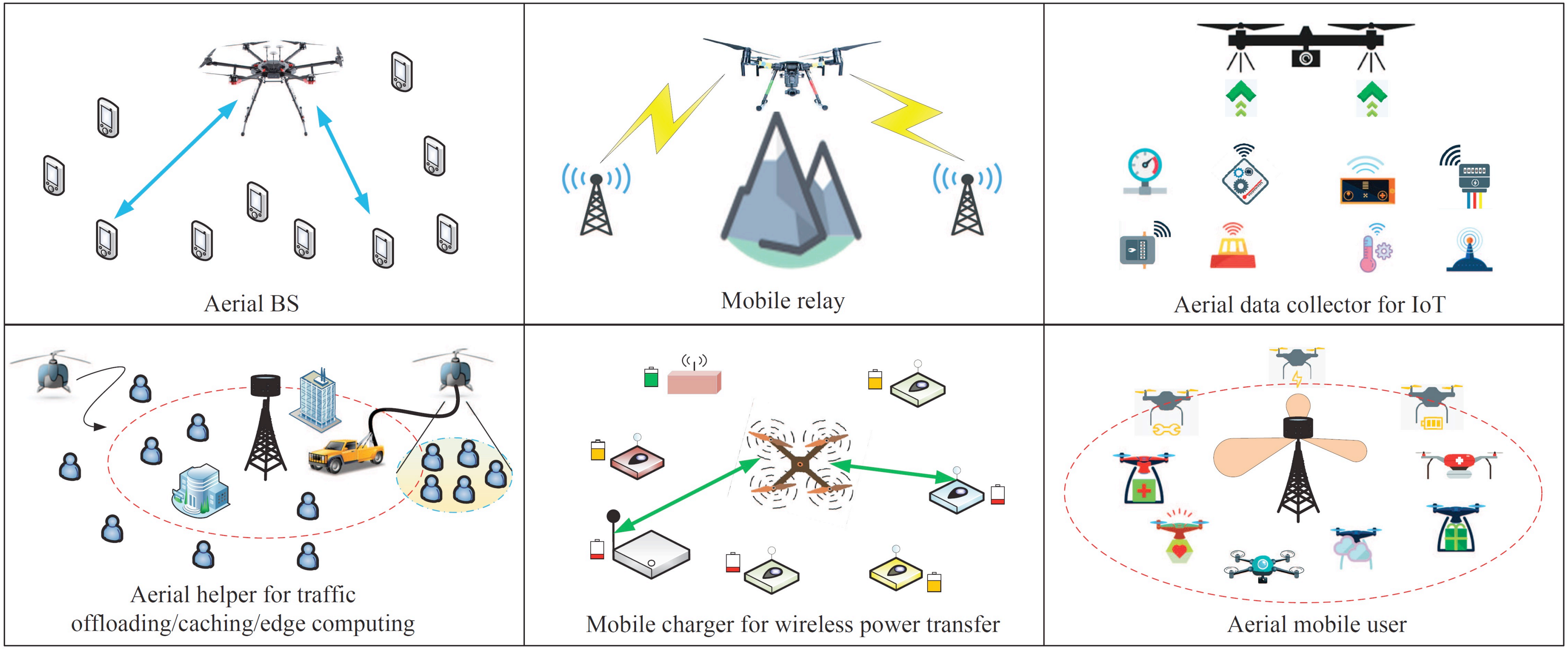
$$A_1 = \frac{1}{nhP_{\text{LED}}}\sqrt{\frac{2\pi(P_{\text{I}}(\Psi_{\text{fov},1}) + \sigma^2)(2^{\frac{R_{\text{th}}}{T}} - 1)}{e}}$$

Some Results



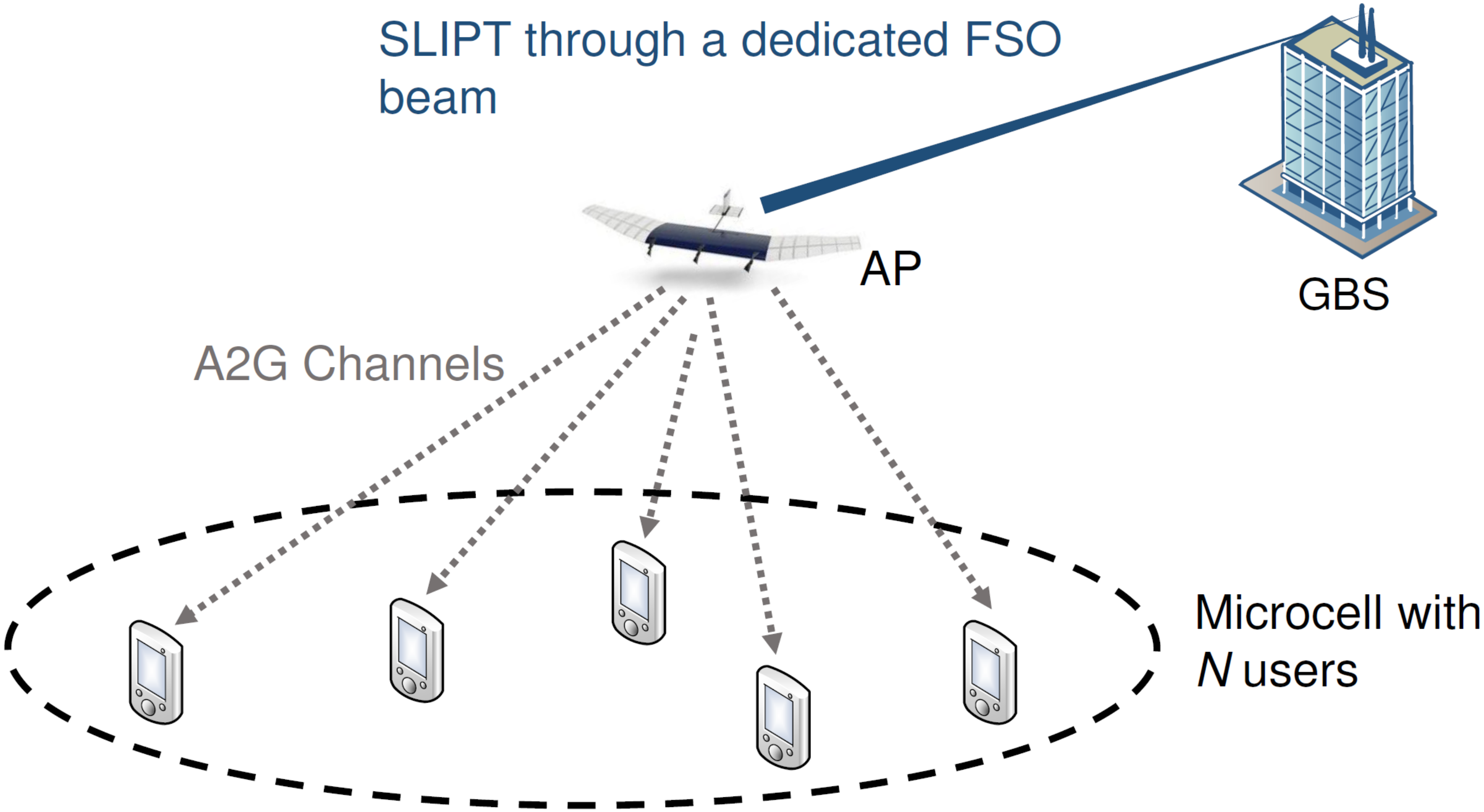
- **Policy 1:** Time-splitting
- **Policy 2:** Time-splitting with DC bias optimization

Aerial Platforms



Q. Wu, L. Liu, Member and R. Zhang, "Fundamental Tradeoffs in Communication and Trajectory Design for UAV-Enabled Wireless Network", Arxiv May 2018

Case study 2: SLIPT in Aerial Platforms



P. D. Diamantoulakis, K. N. Pappi, Z. Ma, X. Lei, P. C. Sofotasios, and G. K. Karagiannidis, "Airborne Radio Access Networks with Simultaneous Lightwave Information and Power Transfer (SLIPT)," IEEE Global Communications Conference (GLOBECOM), Abu Dhabi, UAE, Dec. 2018.

Problem formulation

- We aim to maximize the minimum user capacity for fairness.

$$\max_{\theta,\boldsymbol{P},\boldsymbol{w},\boldsymbol{\tau}} \quad \min\{R_1, ..., R_N\}$$

$$\text{s.t.} \quad \text{C1}: 0 \le \theta \le 1, \text{C2}: w_n \ge 0, \tau_n \ge 0, \forall n \in \mathcal{N},$$

$$\text{C3}: \sum_{n=1}^{N} w_n \le W, \text{C4}: \sum_{n=1}^{N} \tau_n \le T, \text{C5}: P_n \ge 0,$$

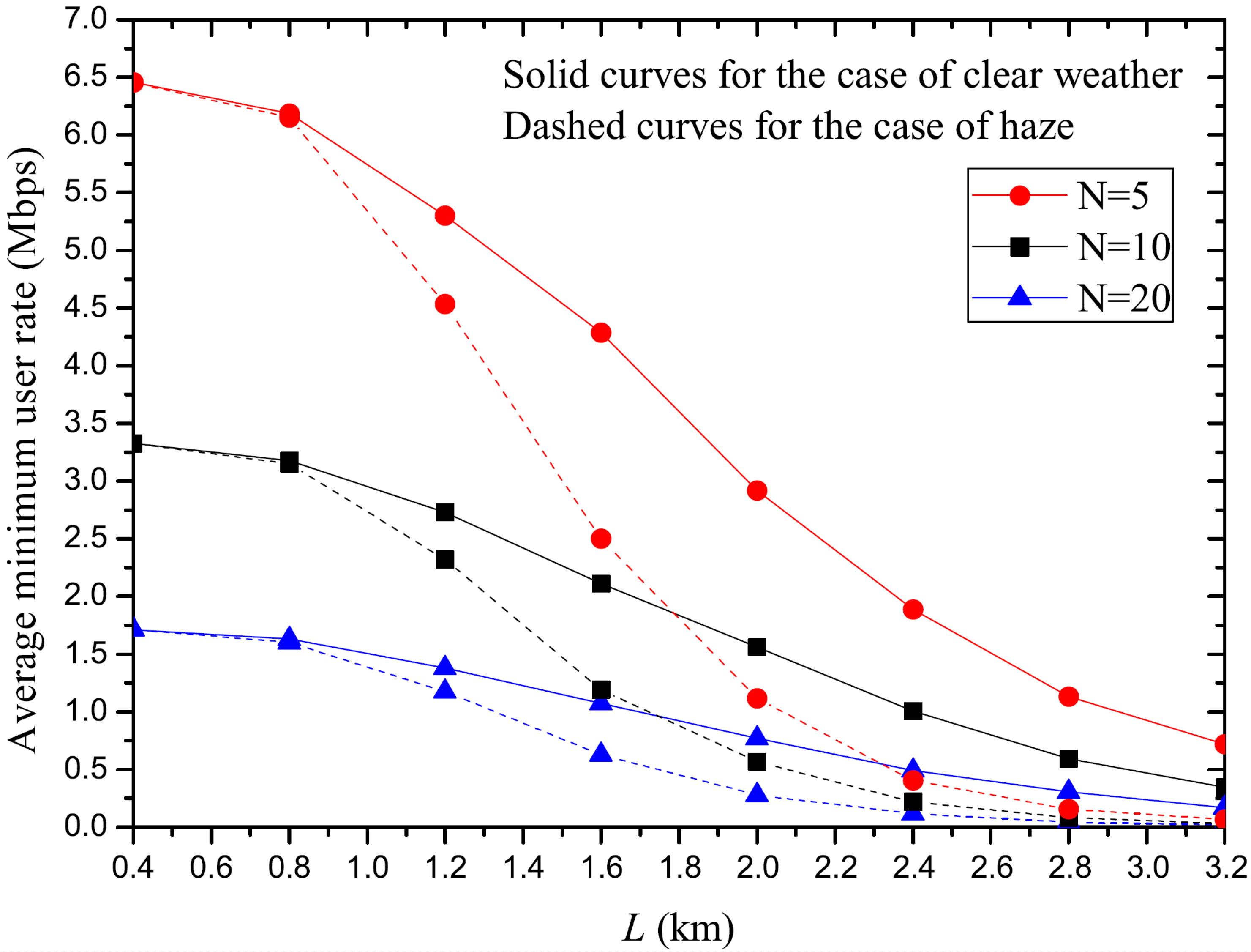
$$\text{C6}: (1-\theta)TB\log_2\left(1+\frac{\gamma}{2\pi\exp(1)}\right) \ge \sum_{n=1}^{N} w_n t_n \log_2\left(1+\frac{P_n g_n}{w_n N_0}\right),$$

$$\text{C7}: \theta T F_1 I_{\text{L},1} V_{\text{oc},1} + (1-\theta) T F_2 I_{\text{L}} V_{\text{oc},2} \ge \varepsilon \sum_{n=1}^{N} P_n \tau_n.$$

- Non-convex constraints

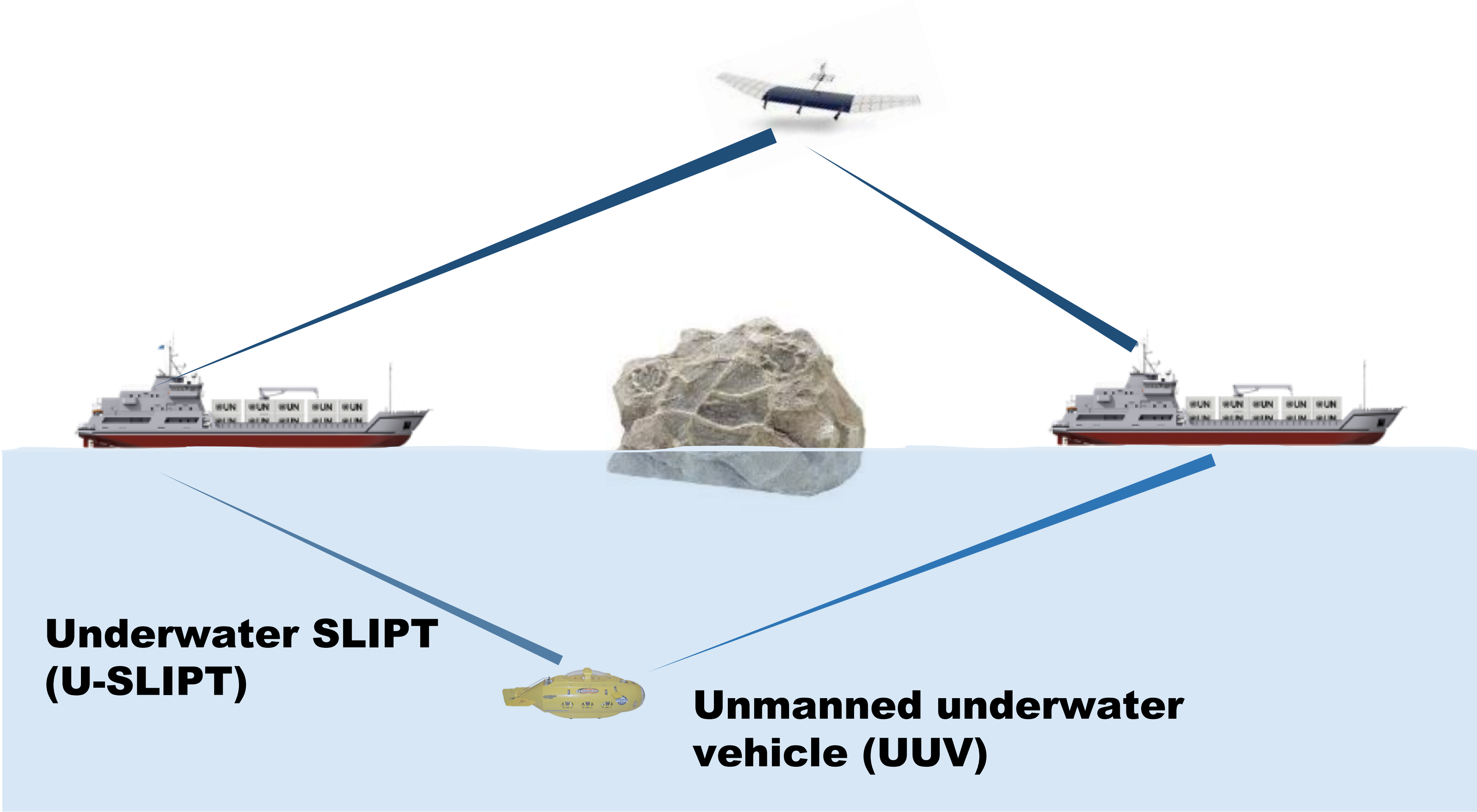
Non-convex!!!

Results

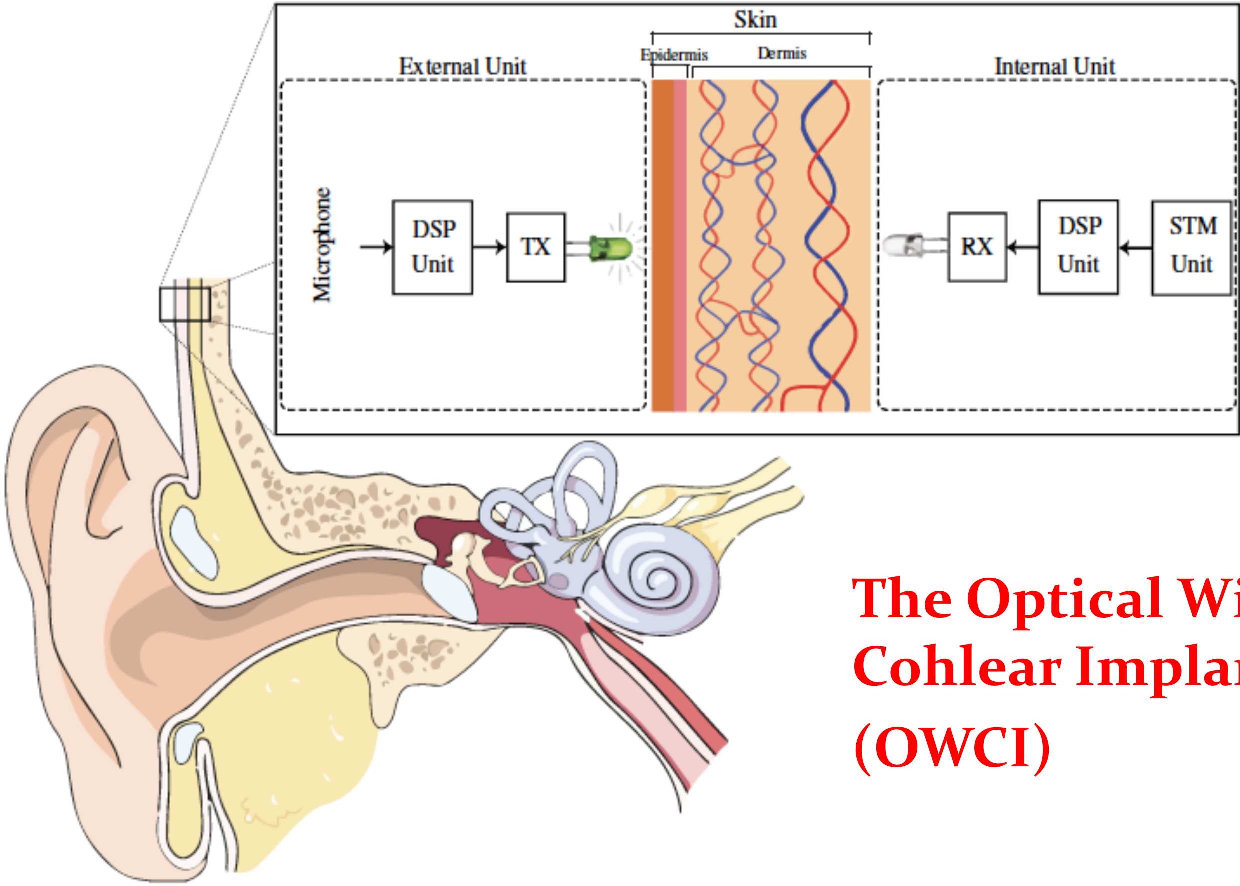


Solid curves for the case of clear weather
Dashed curves for the case of haze
N=5
N=10
N=20
Average minimum user rate (Mbps)
L (km)
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2

Case Study 3: Underwater SLIPT



Case Study 4: Transdermal SLIPT



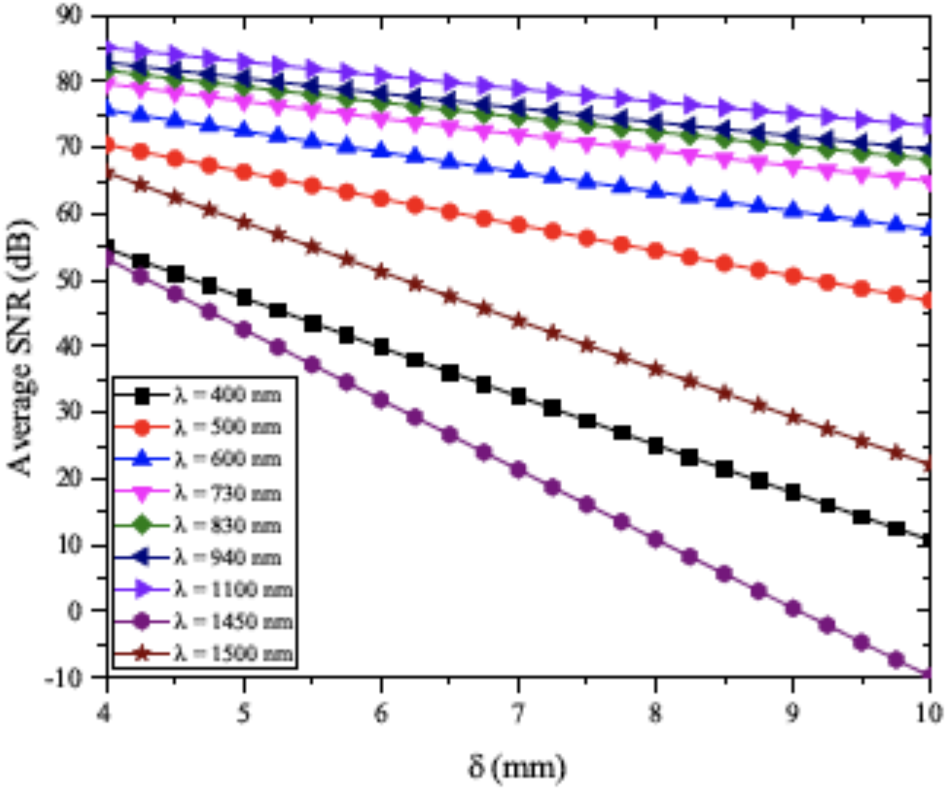
The Optical Wireless Cohlear Implants (OWCI)

[1] S. E. Trevlakis, A.-A. A. Boulogeorgos, and G. K. Karagiannidis, "On the Impact of Misalignment Fading in Transdermal Optical Wireless Communications", in 7th International Conference on Modern Circuits and Systems Technologies, Thessaloniki, Greece, May 2018.

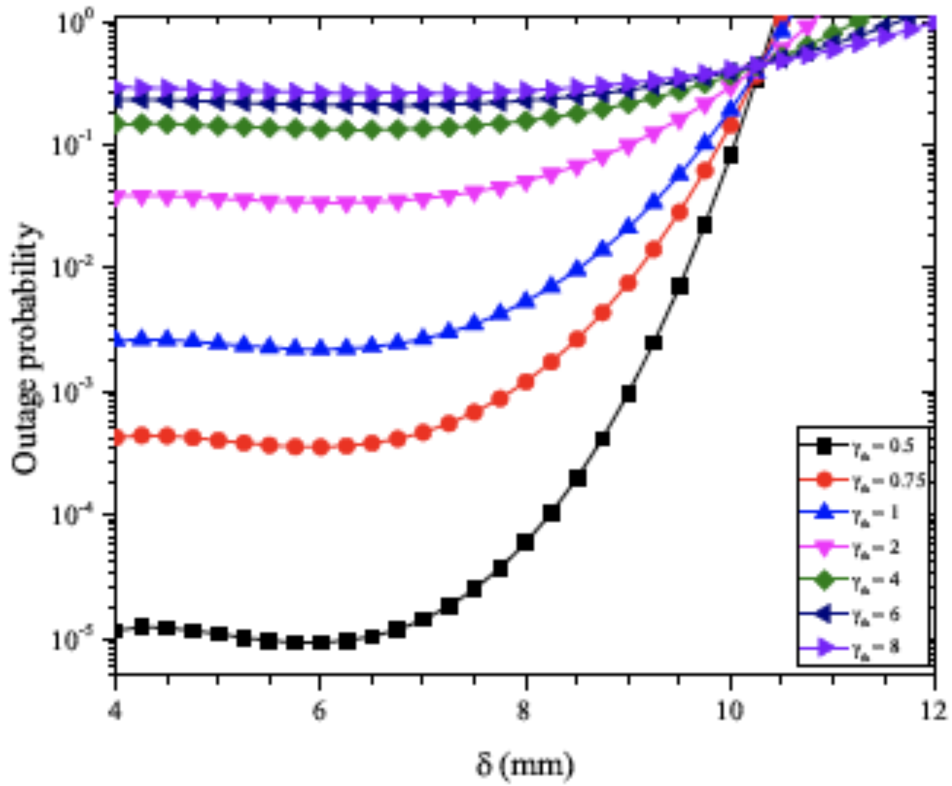
[2] S. E. Trevlakis, A.-A. A. Boulogeorgos, and G. K. Karagiannidis, "Outage Performance of Transdermal Optical Wireless Links in the Presence of Pointing Errors", in 19th IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC) 2018, Kalamata, Greece, June 2018.

[3] S. E. Trevlakis, A.-A. A. Boulogeorgos, P. Sofotasios, and G. K. Karagiannidis, "Optical Wireless Cohlear Impants", submitted to Nature Communications.

OWCI: Impact of skin thickness on the OWCI's effectiveness



(a) Average SNR vs skin thickness for different values of wavelength.



(b) Outage probability vs skin thickness for different values of SNR threshold, for $\lambda = 1500$ nm.

Challenges for future research

- Hardware design
  - ✓ Solar panels provide lower-speed linear photodetection than PINs and Avalanche PDs: Need for using separate receivers or new generation solar cells
  - ✓ Hybrid receivers (using both optical and RF energy harvesting)
  - ✓ Size of the mobile devices versus the photodetector's light-collecting area
  - ✓ Exploit the use of new bulbs (both VL and IR)
- Description of fundamental limits, e.g., considering the randomness of terminals' positions.
- Resource allocation
  - ✓ Multinode coordination
  - ✓ Power allocation and injection angle in multiLED systems
- SLIPT in emerging applications, e.g., building/human health monitoring, indoor environmental monitoring, unmanned aerial/underwater vehicles etc.

Thank you very much!

The modern bronze statue of Pythagoras in Pythagorion, Samos Island, GRECCE