光无线与射频通信混合网络

吴希平（Assist. Prof.）
都柏林大学
电气与电子工程学院

川渝前沿论坛，2022年10月12日

An introduction to University College Dublin

University College Dublin (UCD)

- Located in Dublin, the capital of Ireland
- Founded in 1854
- Ireland’s largest university (with 30,000+ students)
- 5 Nobel Laureates
- 2022 QS ranking #173

An introduction to myself

Profile

- 2015, PhD degree from University of Edinburgh
- 2015 – 2019, Research Associate at LiFi R&D Centre, University of Edinburgh
- 2019 – 2020, Senior Research Associate at University of Oxford
- 2022 – , Assistant Professor at School of EEE, UCD

Research

- Optical wireless communications (OWC)
- Hybrid OWC and RF networking
- OWC transceiver design and signal processing
- Energy harvesting
- The Internet of Things (IoT)

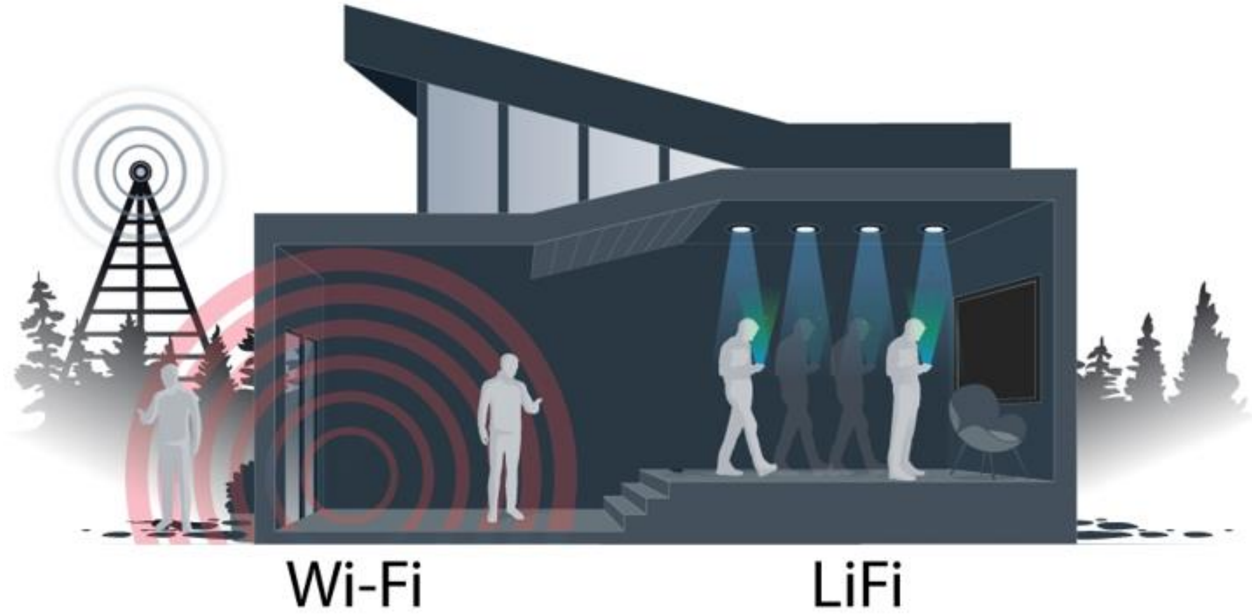
Publications

- 50+ SCI and conference papers
- 1700+ citations
- H-index is 22 (google scholar)
- “Hybrid LiFi and WiFi Networks: A Survey”

Lab

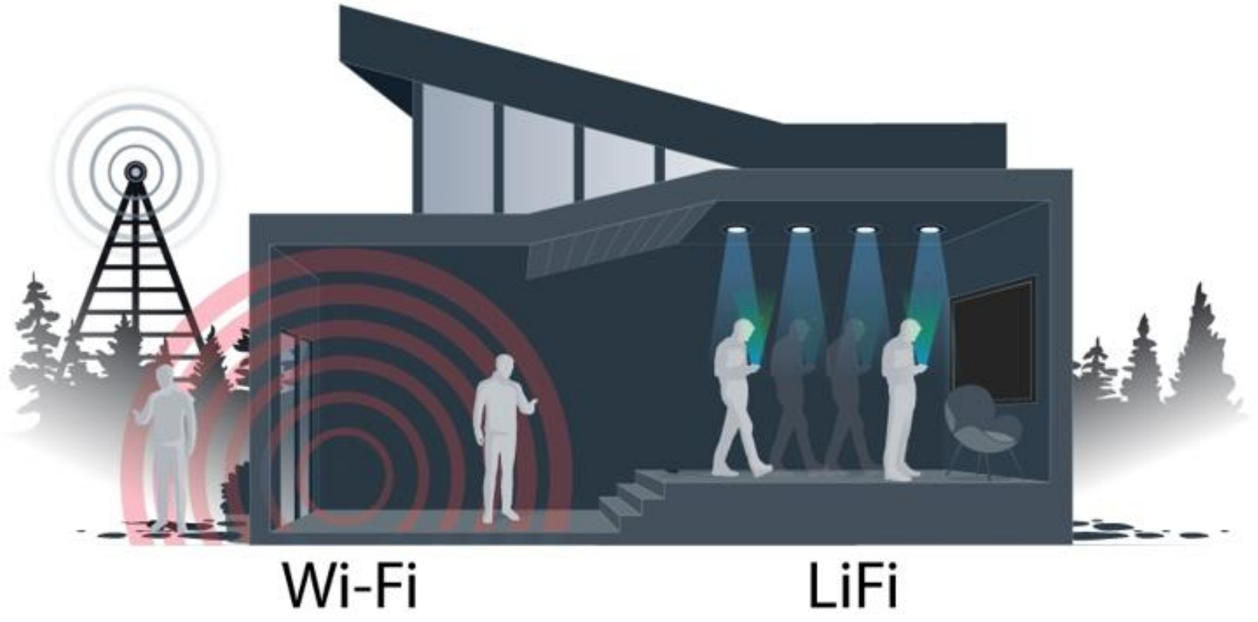
Outline

- ➢ Introduction to HyFi (Hybrid LiFi and WiFi networks)
- ➢ Hybrid network management
  - Access point selection
  - Handover
  - Mobility-aware load balancing
- ➢ Artificial Intelligence
- ➢ Parallel transmission LiFi
- ➢ Applications and Summary

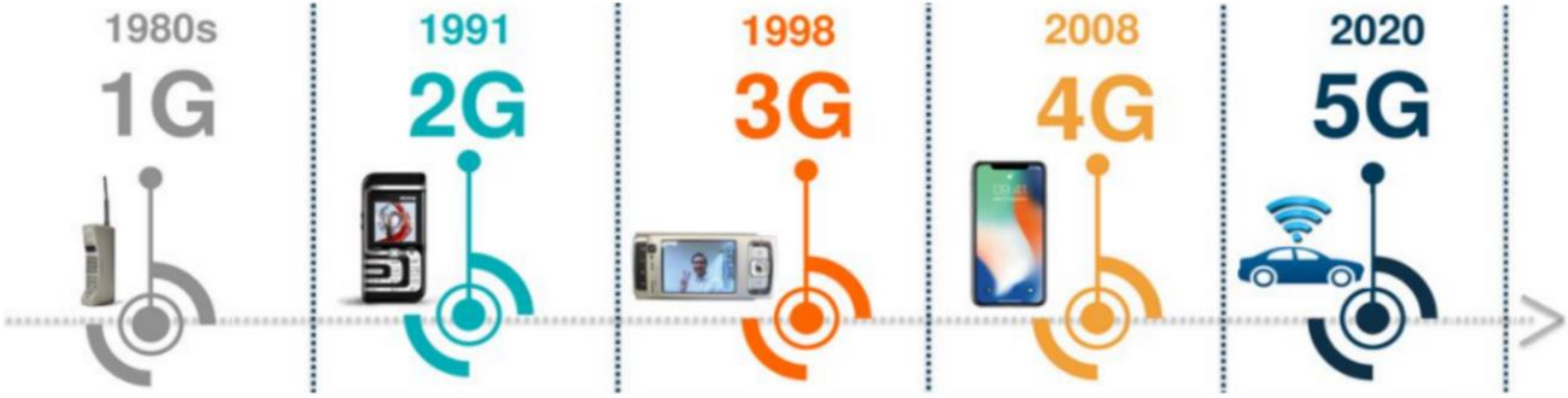


Outline

- ➢ Introduction to HyFi (Hybrid LiFi and WiFi networks)
- ➢ Hybrid network management
  - Access point selection
  - Handover
  - Mobility-aware load balancing
- ➢ Artificial Intelligence
- ➢ Parallel transmission LiFi
- ➢ Applications and Summary



Towards 6G



2030

6G

Full spectrum
Full coverage

- 2.4 kbps
- 1000 ms
- Analog phone

- 64 kbps
- 500 ms
- Feature phone

- 2 Mbps
- 100 ms
- Internet phone

- 1 Gbps[1]
- 50 ms
- Smart phone

- 10 Gbps[2]
- 20 ms[3]
- IoT

- 1000 Gbps[4]
- < 1 ms
- Holographic display

Enabled technology → **Enabling** technology

[1] The theoretical peak data rate of 4G is 1 Gbps, while the average data rate in practice is about 30 Mbps.
[2] The theoretical peak data rate of 5G is 10 Gbps, while the average data rate in practice is about 200 Mbps.
[3] The theoretical delay target of 5G is 1 ms, while the average delay in practice is 21-26 ms.
[4] 6G is expected to provide an average data above 10 Gbps, which can meet the demand of 60 fps holographic displaying (9.44 Gbps).

Towards 6G (cont.)

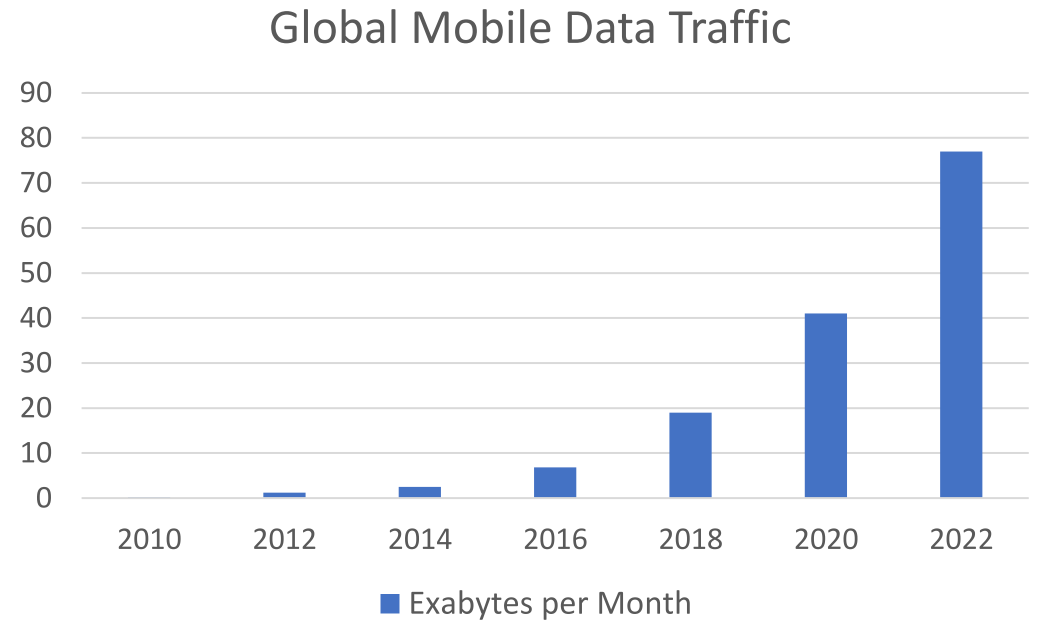
Trends:

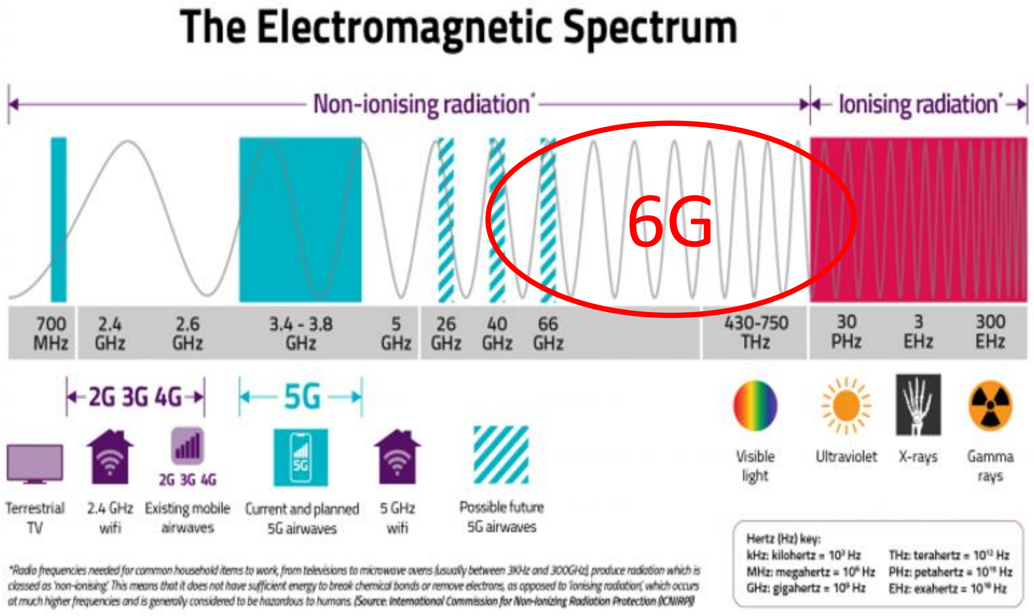
- Mobile data traffic increases exponentially
- About 80% data traffic occurs indoor
- Spectrum efficiency (SE) increases linearly

$$\text{Capacity} = \text{Bandwidth} \times \text{Spectrum Efficiency} \times \text{Reuse}$$

Development directions:

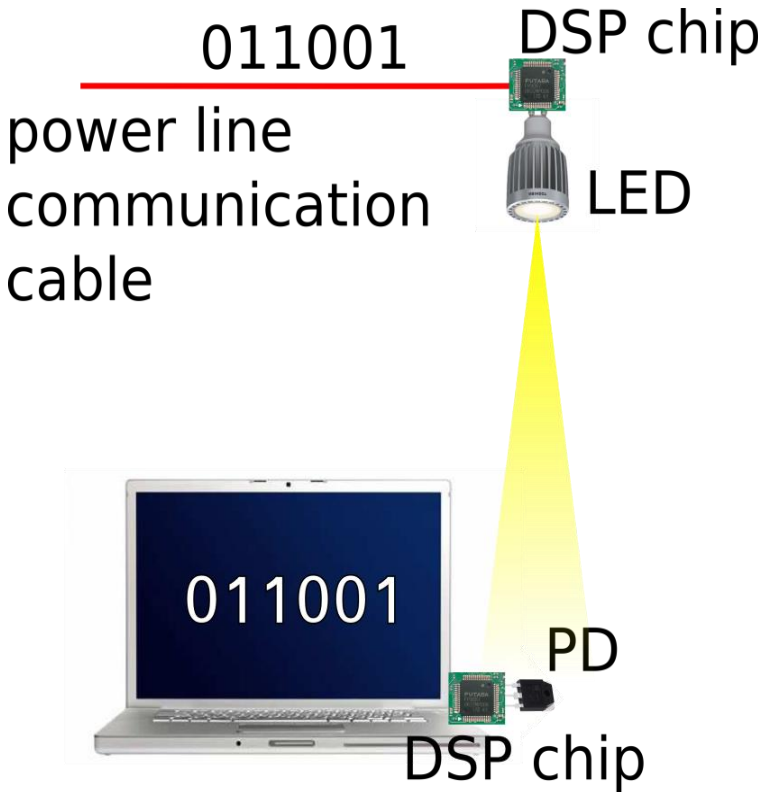
- Increase reuse $\Rightarrow$ Small Cell
- Extend bandwidth $\Rightarrow$ mmWave, THz, VLC





A brief review of LiFi

- A network variant of visible light communications (VLC)
- LEDs or laser diodes (LD) as the transmit antenna
- Intensity modulations
  - On-off keying (OOK)
  - Colour shift keying (CSK)
  - Pulse modulation
  - O-OFDM (DCO, ACO)
- Photodiodes as the receive antenna
  - PN PD
  - PIN PD
  - APD (Avalanche photodiode)
  - SPAD (Single-photo avalanche diode)



A brief review of LiFi (cont.)

Advantages

- ➢Wide spectrum resource (~300 THz)
- ➢High link data rates
  - 10s Gb/s using LEDs [1]
  - Tb/s using laser diodes [2]
- ➢High security
- ➢Feasibility in RF-restricted areas, e.g., hospitals and underwaters
- ➢Potential energy savings

Limitations

- ➢Relatively short range (a few meters in diameter)
- ➢Possibly frequent handovers
- ➢Susceptible to channel blockages

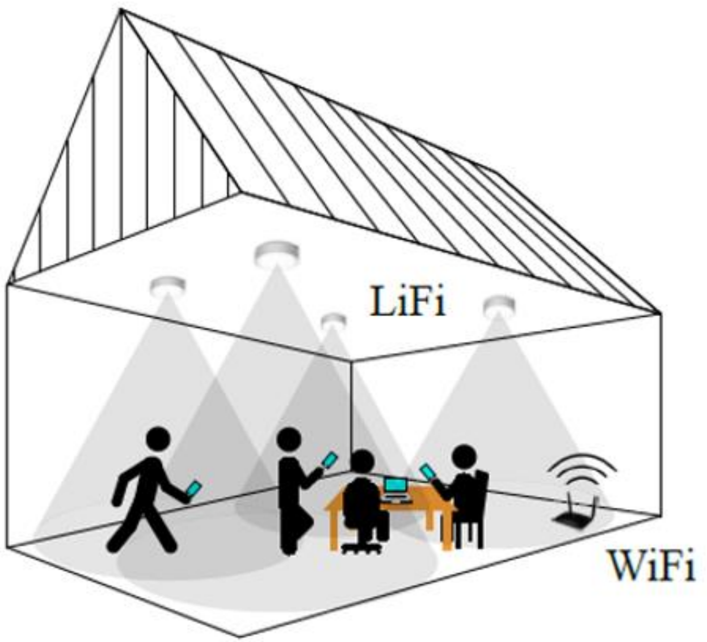
The **complementation** between LiFi and RF brings a great opportunity to work together!

[1] R. Bian, I. Tavakkolnia and H. Haas, "15.73 Gb/s Visible Light Communication With Off-the-Shelf LEDs," *Journal of Lightwave Technology*, vol. 37, no. 10, pp. 2418-2424, May 2019.

[2] E. Sarbazi, H. Kazemi, M. Dehghani Soltani, M. Safari and H. Haas, "A Tb/s Indoor Optical Wireless Access System Using VCSEL Arrays," *IEEE 31st Annual International Symposium on Personal, Indoor and Mobile Radio Communications*, 2020.

Hybrid LiFi and WiFi networks (HyFi)

- The concept can be traced back to 2011 [3].
- The first comprehensive survey in 2021 [4].
- Complementary access point (AP) properties:
  - Coverage: WiFi AP >> LiFi AP
  - Capacity: WiFi AP < LiFi AP
- Key challenges lie in:
  - How to ***deploy*** the hybrid network?
  - How to ***manage*** the hybrid network?
  - How to ***apply*** the hybrid network?

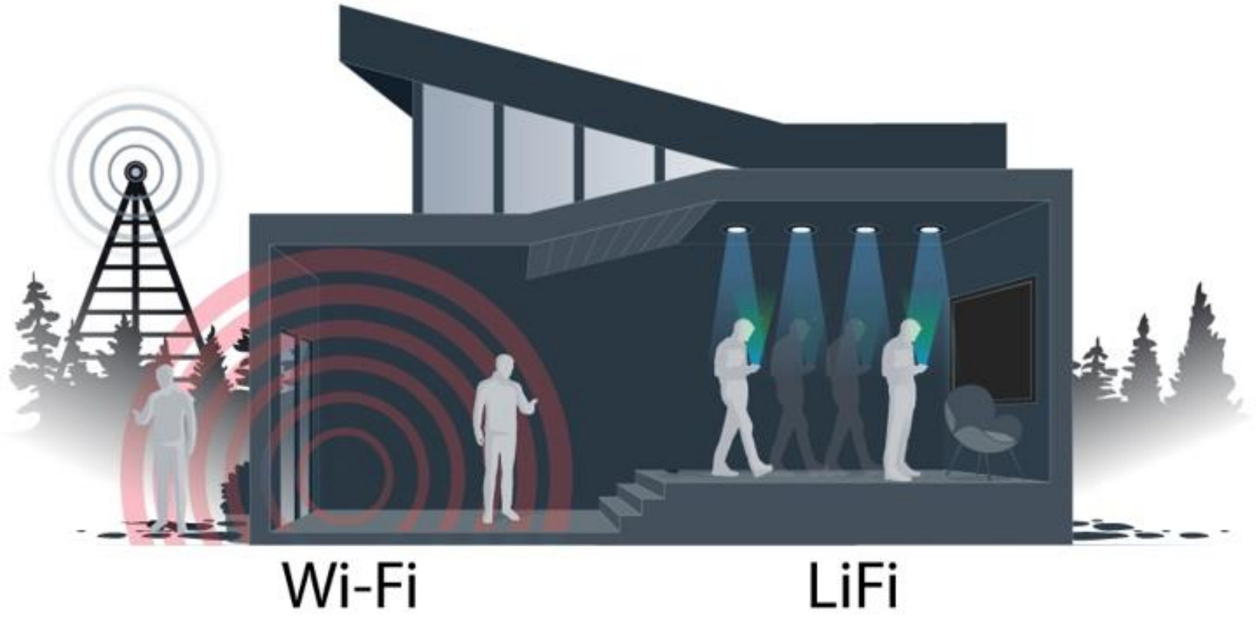


Conceptual diagram of HyFi [4]

[3] M. B. Rahaim et al. "A hybrid radio frequency and broadcast visible light communication system," *in 2011 IEEE GLOBECOM Workshops (GC Wkshps),* Houston, TX, 2011, pp. 792–796.
[4] **X. Wu** et al. "Hybrid LiFi and WiFi Networks: A Survey," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 2, pp. 1398-1420, 2nd Quart. 2021.

Outline

- ➢ Introduction to HyFi (Hybrid LiFi and WiFi networks)
- ➢ Hybrid network management
  - Access point selection
  - Handover
  - Mobility-aware load balancing
- ➢ Artificial Intelligence
- ➢ Parallel transmission LiFi
- ➢ Applications and Summary



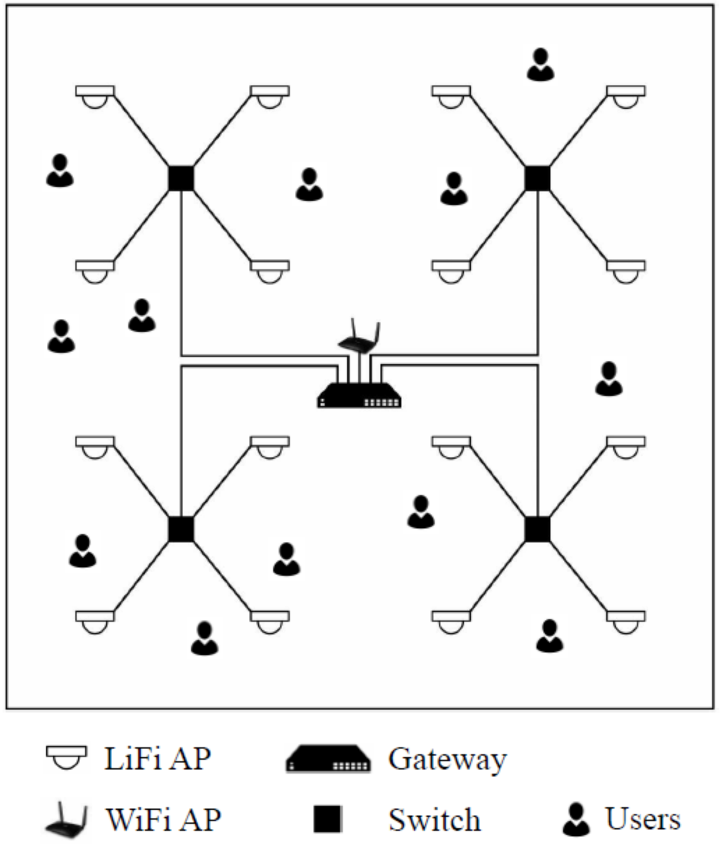
Hybrid Network Management

HyFi network topology:

- One WiFi AP and a number of LiFi APs
- All APs are managed by a central unit (hypervisor)
- LiFi APs can be grouped (through a switch)

Should a user be served by ***LiFi or WiFi***?

- Channel quality
- Data rate requirement
- Resource availability
- Mobility
- Light-path blockage



Network topology of HyFi

Access Point Selection

- Consider ***quasi-static*** users
- Some APs (especially WiFi) could be overloaded
- The user ***may should not*** be connected to the AP providing ***the highest*** SNR
- Can be solved through proportional fairness (PF) optimization [5]:

$$
\begin{aligned}
\text{maximise} \quad & \sum_u \log\left(R_u = \sum_i \chi_{i,u}\rho_{i,u}r_{i,u}\right) \\
\text{subject to} \quad & \chi_{i,u} \in \{0,1\}, \quad \forall i,u; \\
& \sum_i \chi_{i,u} = 1, \quad \forall u; \\
& 0 \le \rho_{i,u} \le 1, \quad \forall i,u; \\
& \sum_u \chi_{i,u}\rho_{i,u} \le 1, \quad \forall i.
\end{aligned}
$$

where i is the index of APs;
u is the index of users;
$\chi_{i,u}$ indicates the link connectivity;
$\rho_{i,u}$ is the portion of link resource;
$r_{i,u}$ is the link capacity, which depends on the SNR;
R_u is the achieved data rate of user u.

- However, ***centralized optimization*** requires an ***excessive*** amount of processing time!
- Does not suit real-time network implementation

[5] X. Li et al. "Cooperative Load Balancing in Hybrid Visible Light Communications and WiFi," *IEEE Trans. Commun.*, vol. 63, no. 4, pp. 1319-1329, April 2015.

Fuzzy Logic-Based Method

Challenges:

- Access point selection in HyFi
- Low computational complexity

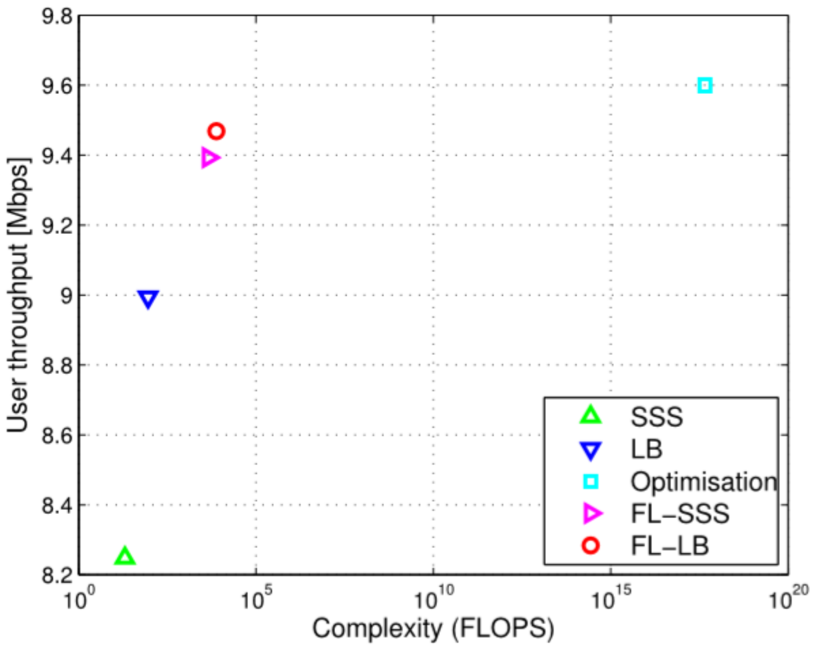
Two-stage algorithm [6]:

- Stage 1: determine WiFi users (using fuzzy logic)
- Stage 2: assign the remaining users to LiFi

Rule No.	Operator	Required rate	Wi-Fi SNR	SNR var. of adj. Li-Fi APs	Activity of adj. Li-Fi APs	Assigned to Wi-Fi
1	AND	-	High	Low	High	Positive
2	AND	Low	*not* Low	Low	High	Positive
3	AND	-	High	Low	Med	Neutral
4	AND	Med	*not* Low	Med	High	Neutral
5	OR	-	-	High	Low	Negative
6	AND	High	Low	-	-	Negative

Limitations:

- Sub-optimal
- Sensitive to change of network environment



[6] **X. Wu**, M. Safari and H. Haas, “Access Point Selection for Hybrid Li-Fi and Wi-Fi Networks,” *IEEE Transactions on Communications*, vol. 65, no. 12, pp. 5375-5385, Dec. 2017.

Game Theory-Based Method

- Both the optimization and fuzzy logic-based methods make the decisions ***once and for all***.

- In contrast, the GT-based method [7] lets each user keep looking for a better ***payoff***, which is the user's satisfaction:

$$\pi_{i,u} = \min\left\{\frac{\rho_{i,u} r_{i,u}}{\hat{R}_u}, 1\right\}$$

- When the user's payoff is below the average payoff, a mutation probability is set to allow the user to choose a new AP

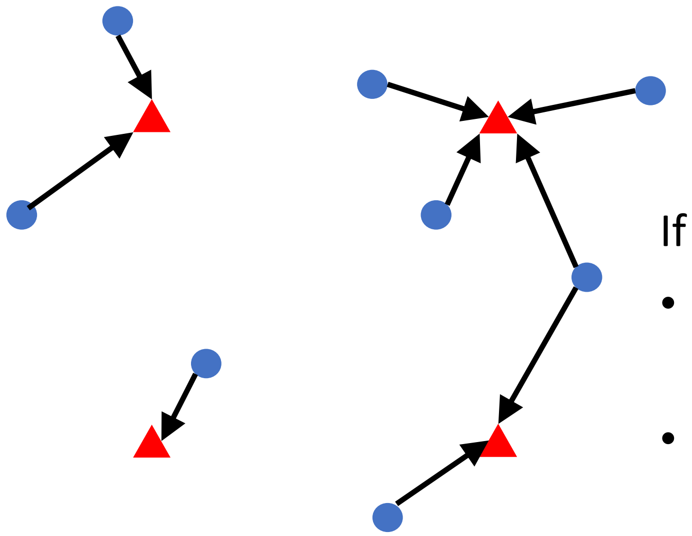
[7] Y. Wang, **X. Wu** and H. Haas, "Load Balancing Game with Shadowing Effect for Indoor Hybrid LiFi/RF Networks," *IEEE Transactions on Wireless Communications*, vol. 16, no. 4, pp. 2366-2378, Apr. 2017.

Game Theory-Based Method

- Both the optimization and fuzzy logic-based methods make the decisions ***once and for all***.

- In contrast, the GT-based method [7] lets each user keep looking for a better ***payoff***, which is the user's satisfaction:

$$\pi_{i,u} = \min\left\{\frac{\rho_{i,u} r_{i,u}}{\hat{R}_u}, 1\right\}$$



If a mutation occurs

- Find an AP providing the highest payoff
- Update the payoff for other users

- When the user's payoff is below the average payoff, a mutation probability is set to allow the user to choose a new AP

- ***Deep learning*** methods, which use a similar concept of payoff but can adapt its strategy to the network environment, are also applicable.

[7] Y. Wang, **X. Wu** and H. Haas, "Load Balancing Game with Shadowing Effect for Indoor Hybrid LiFi/RF Networks," *IEEE Transactions on Wireless Communications*, vol. 16, no. 4, pp. 2366-2378, Apr. 2017.

Handover

The handover issue is particularly challenging for HyFi due to:

- Ultra-dense networks ⇒ frequent handovers
- Heterogeneous networks ⇒ overlapped coverage
- Light-path blockages ⇒ connectivity loss

a) a stationary user experiencing light-path blockages

b) a mobile user acrossing cell borders

Handover types:

- Horizontal handover (same air interface, same route)
- Vertical handover (change air interface, same route)
- Diagonal handover (change both air interface and route)

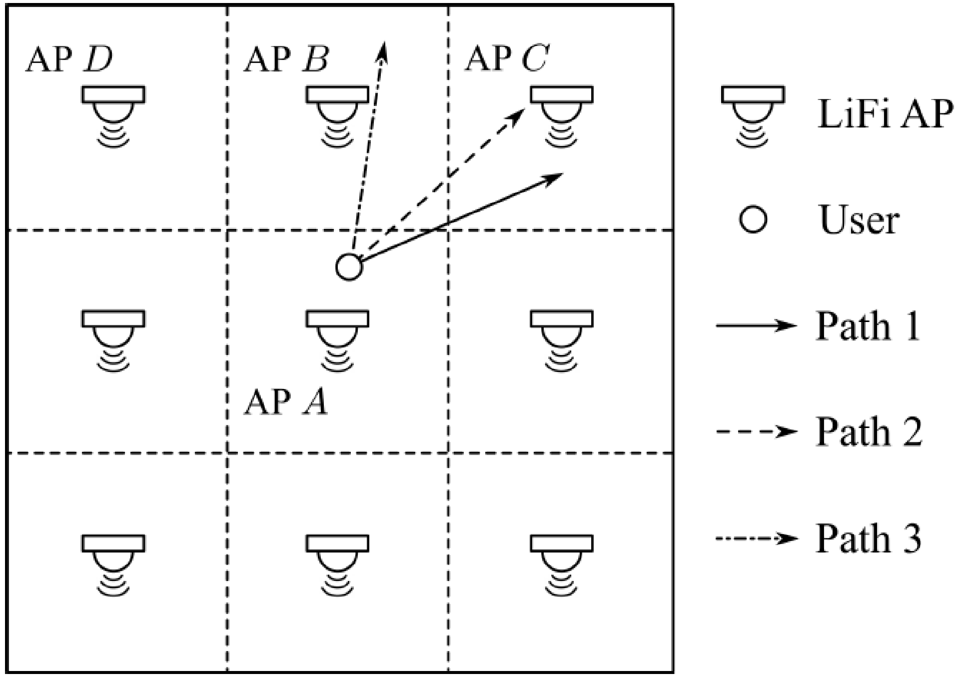
Horizontal handover for LiFi

Challenges:

- ➢ Relatively small coverage range, usually 2-3 meters in diameter
- ➢ Considerably frequent handovers, even when the user moves in a moderate speed

To reduce the HHO rate:

- ➢ Optimize the separation between APs
  - The ideal coverage area of a LiFi AP is 2 to 8 m^2, depending on the user density and handover overhead
- ➢ Soft handover
  - In the case of non-overlapping coverage
- ➢ Handover skipping
  - Trajectory based (conventional)
  - RSS based

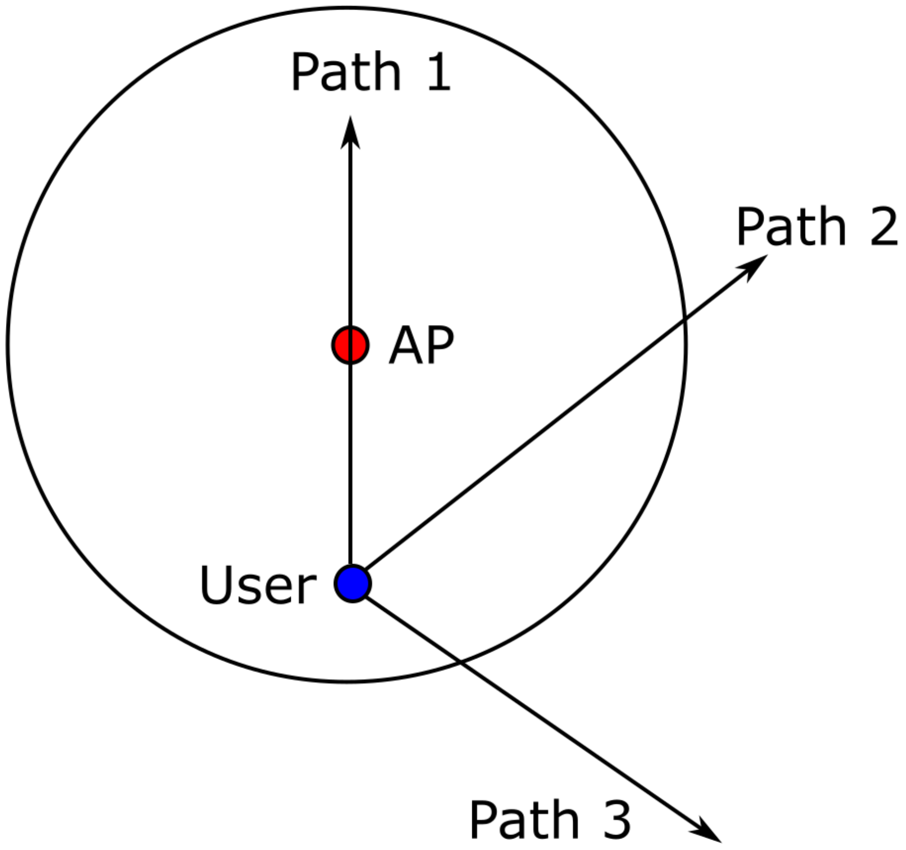


RSS-based handover skipping

- Received signal strength (RSS) is commonly used in the existing handover protocol.
- ***RSS*** indicates the ***distance*** between the user and the AP but cannot reflect the movement direction.
- ***The rate of change in RSS*** can be used to indicate the user's ***movement direction***.
- ***Combining RSS and its rate of change*** to allow the user to skip some APs [8]:

$$\Gamma_i = P_i^{(t_0)} + \lambda \Delta P_i$$

where λ can adjust the dominance between RSS and its rate of change



[8] **X. Wu** and H. Haas, "Handover skipping for LiFi," IEEE Access, vol. 7, pp. 38 369–38 378, 2019.

Vertical handover between LiFi and WiFi

The user usually requires a VHO between LiFi and WiFi when:

- RSS is below threshold
- The current host AP is congested
- LiFi connectivity is lost or restored

Reasons for LiFi connectivity loss:

- The light-path is blocked by opaque objects, such as human bodies and furniture
- The PD’s receiving orientation is significantly deviated from the LoS path.

To avoid unnecessary VHOs:

- Markov decision process
- Predict parameters (e.g. interruption duration, message sizes, delay, queue length and data rate)

These methods:

- Adjust th… sed on channel…
- Not cons… erent handover costs between …O and VHO

HHO or VHO?

Mobility-Aware Load Balancing

Challenge:

- Conventional LB does not consider user mobility, which would significantly compromise the network performance

Solution:

- Jointly consider LB and the handover cost [9]:

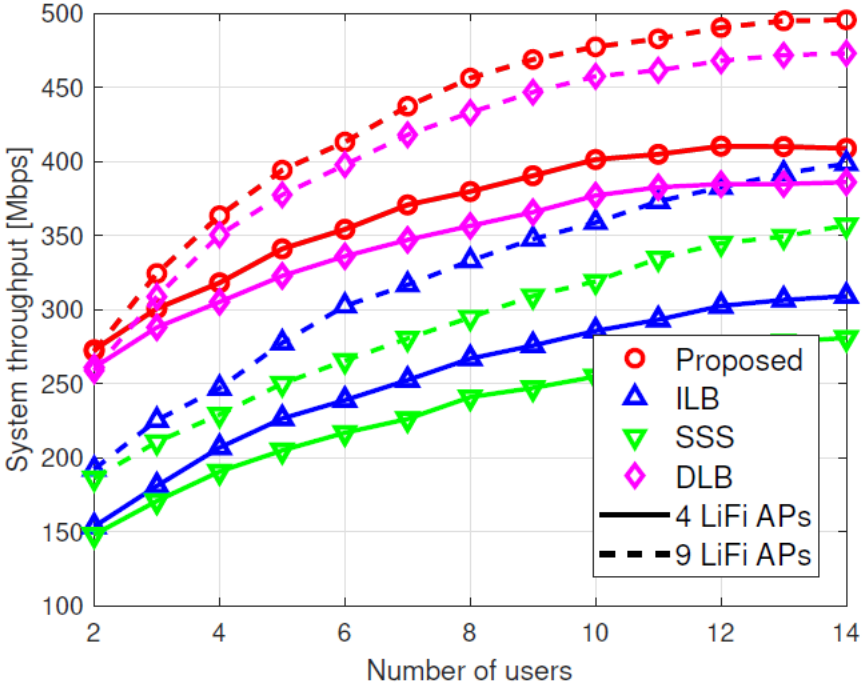
$$F_{\text{ILB}}\left(\boldsymbol{\chi}^{(t)}, \boldsymbol{\rho}^{(t)}\right) = \sum_{u}\sum_{i} \chi_{i,u}^{(t)} \log\left(\rho_{i,u}^{(t)} r_{i,u}^{(t)}\right)$$

$$F_{\text{prop.}}(\boldsymbol{\chi}, \boldsymbol{\rho}) = \sum_{u}\sum_{\kappa} \chi_{\kappa,u} \log\left(\sum_{\alpha} \tau_{\kappa,u}^{\alpha} r_{u}^{\alpha} \min\{\rho_{u}^{\alpha}, 1 - \varrho_{u}^{\alpha}\}\right)$$

Network access type (LiFi only, WiFi only, LiFi/WiFi)

Measure the HO cost due to light-path blockage

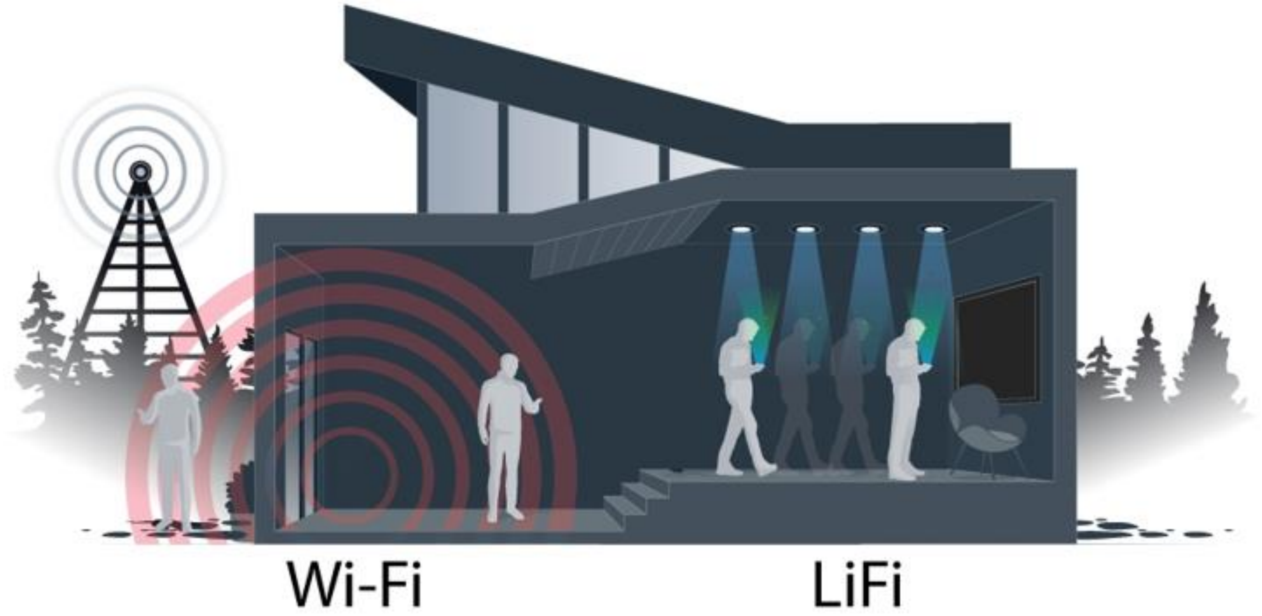
Measure the HO cost due to mobility



[9] **X. Wu** and H. Haas, "Load Balancing for Hybrid LiFi and WiFi Networks: To Tackle User Mobility and Light-Path Blockage," *IEEE Transactions on Communications*, vol. 68, no. 3, pp. 1675-1683, Mar. 2020.

Outline

- ➢ Introduction to HyFi (Hybrid LiFi and WiFi networks)
- ➢ Hybrid network management
  - Access point selection
  - Handover
  - Mobility-aware load balancing
- ➢ Artificial Intelligence
- ➢ Parallel transmission LiFi
- ➢ Applications and Summary



Machine Learning

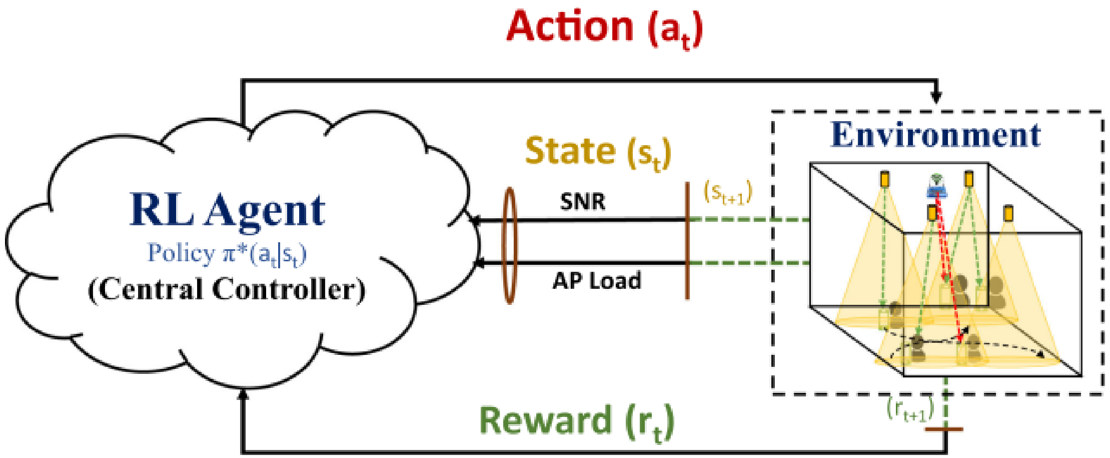
- **Supervised learning**
  - Trained by samples (i.e., known answers)
  - Used for classification, regression, prediction

- **Unsupervised learning**
  - Analyse correlation and relationships
  - Used for clustering, dimension reduction

- **Reinforcement learning**
  - Explore different options (trial and error)
  - Used to find the optimal solution

Apply RL in hybrid network management

- Method
  - State space
  - Action space
  - Reward

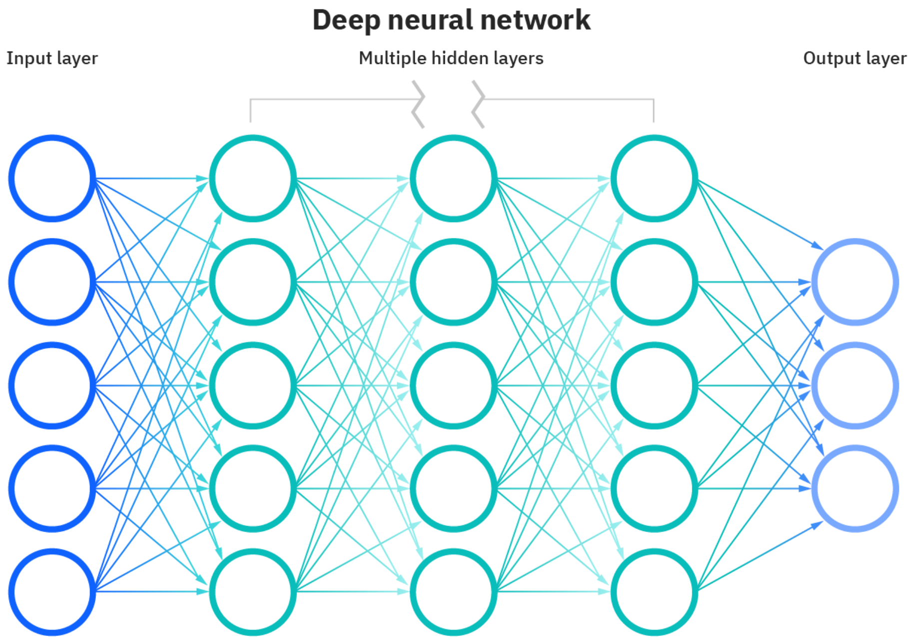


- Limitations:
  - Needs iterative actions to complete the training process
  - Needs ***retraining*** when the network environment changes (especially the user number)
- How about using deep neural network (DNN)?

[10] R. Ahmad et al. "Reinforcement Learning-Based Near-Optimal Load Balancing for Heterogeneous LiFi WiFi Network," IEEE Systems J., pp. 1-12, Jun. 2021.

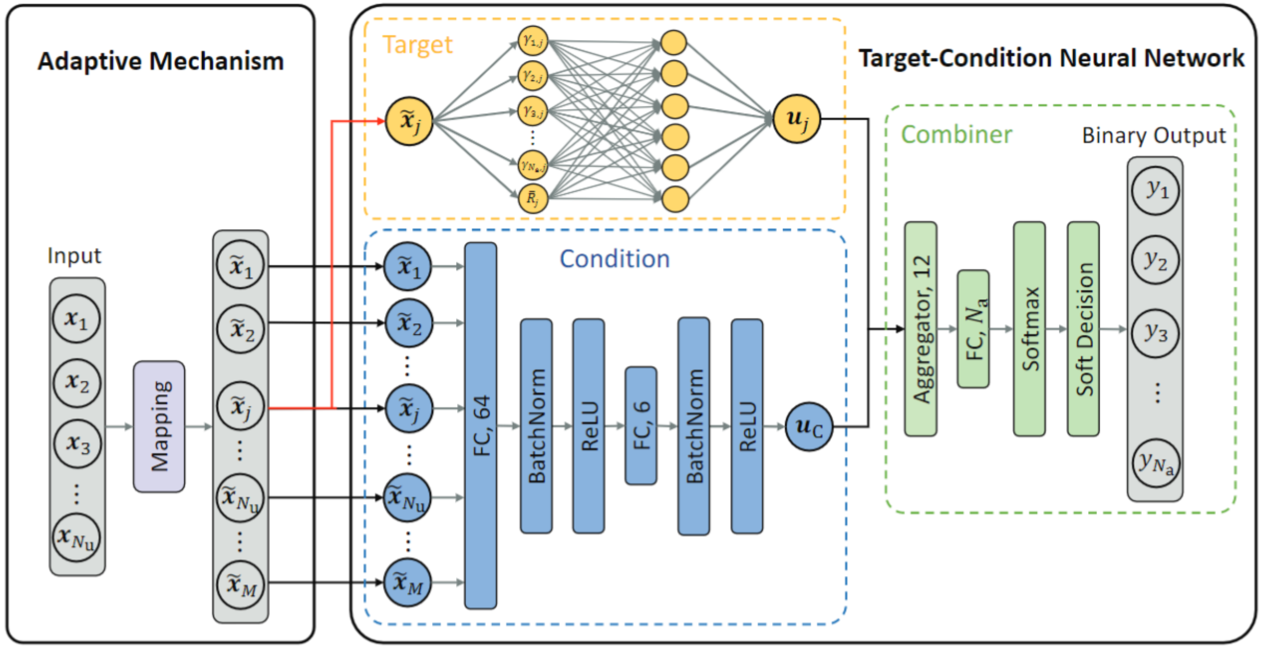
Apply DNN in hybrid network management

- A commonly used supervised learning method
- To apply DNN
  - Input nodes: $N \times N_{\mathrm{UE}}$ elements to express the parameters of each user
  - Output nodes: $N_{\mathrm{AP}} \times N_{\mathrm{UE}}$ elements to express the AP connection of each user
- However, in DNN, the numbers of input and output nodes are ***fixed***
- Question: is it possible to create an DNN that is ***adaptive to the user number***?



From DNN to Target-Condition NN [11]

- Determine APS for a ***target*** user only (thus the number of output nodes is fixed for one user)
- Other users are considered as a ***condition***
- Map ***any*** number of ***condition*** users to a ***fixed*** number of users[1] through generating an image of the users



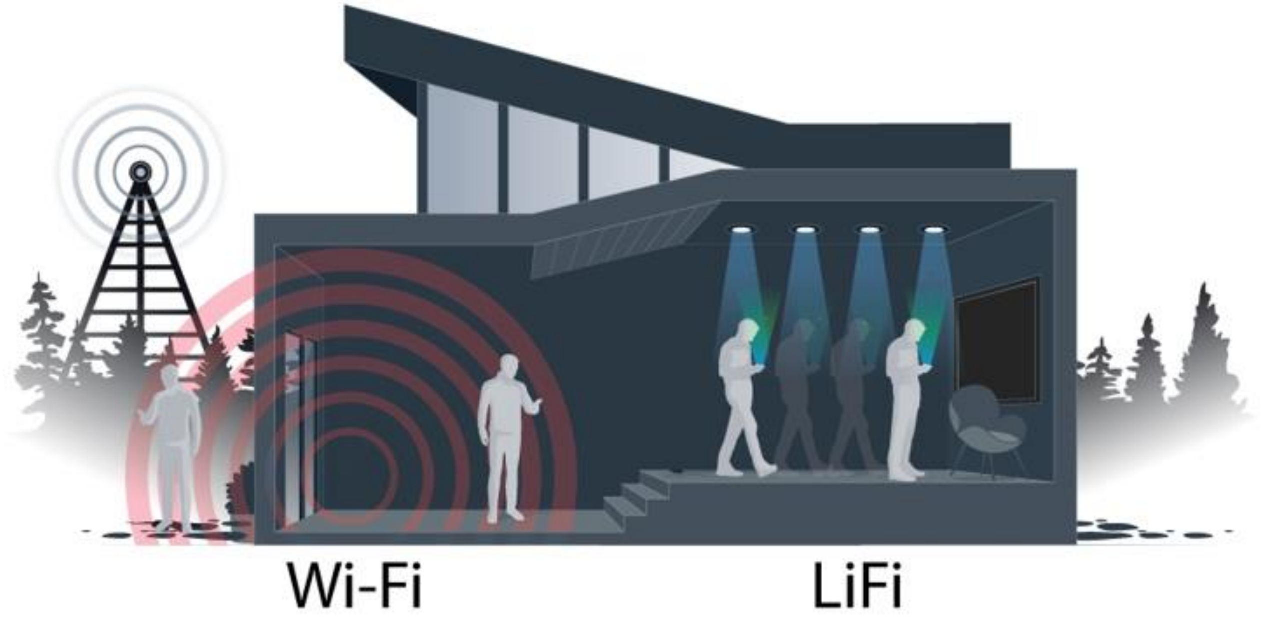
- This mapping process does not affect the APS for the ***target*** user!
- ***Does not need retraining*** when the user number changes!

[1] The maximum number of users that can be supported by the network.

[11] H. Ji, Q. Wang, S. Redmond, and **X. Wu**, "Adaptive Target-Condition Neural Network: DNN-aided load balancing for Hybrid LiFi and WiFi Networks," *(submitted to) IEEE Journal Sel. Areas Commun.*, 2022.

Outline

- ➢ Introduction to HyFi (Hybrid LiFi and WiFi networks)
- ➢ Hybrid network management
  - Access point selection
  - Handover
  - Mobility-aware load balancing
- ➢ Artificial Intelligence
- ➢ Parallel transmission LiFi
- ➢ Applications and Summary



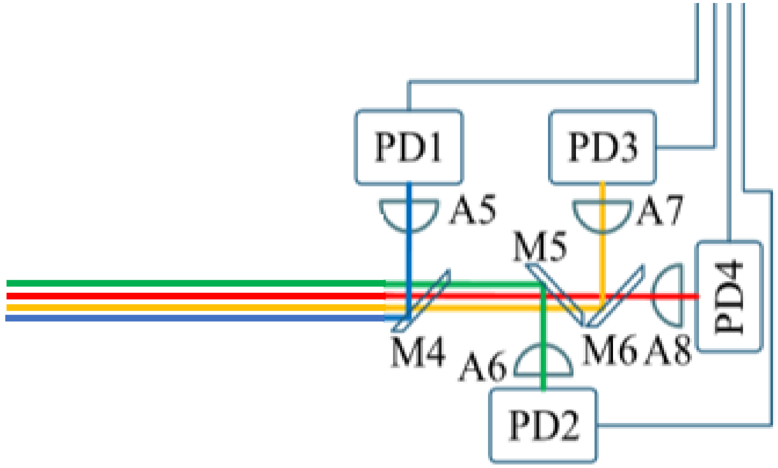
Serial Transmission vs Parallel Transmission

- Restricted by the conventional TCP, each user can only be served by one AP, i.e., serial transmission
- Enabled by the new multi-path TCP (MPTCP), each user can be served by multiple APs at the same time
- In contrast to serial transmission, parallel transmission will:
  - ***Boost link data rate***
  - ***Reduce handover***
  - ***Enhance network flexibility***
- Question: how to ***realize*** parallel transmission LiFi?

Parallel Transmission LiFi

Conventional LiFi WDM [1]:

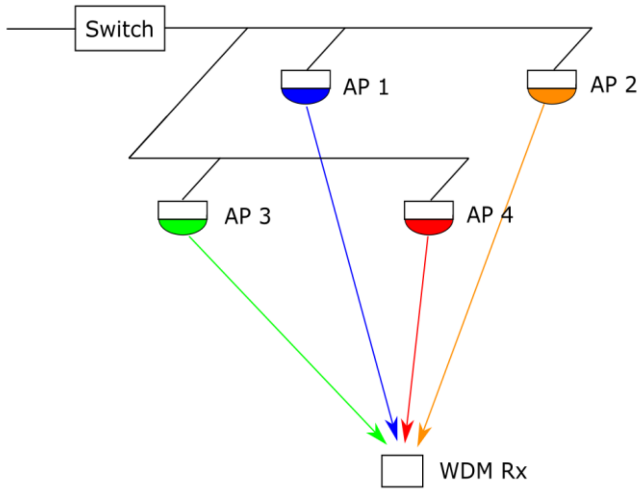
- Based on dichroic mirrors
- ***Not suitable*** for distributed transmitters
- ***Rely on*** precise alignment
- ***Difficult*** to support user mobility



Convectional LiFi WDM receiver

Challenges:

- **How?**
- Different APs serve one user at the same time
- Does not need alignment
- Support user mobility



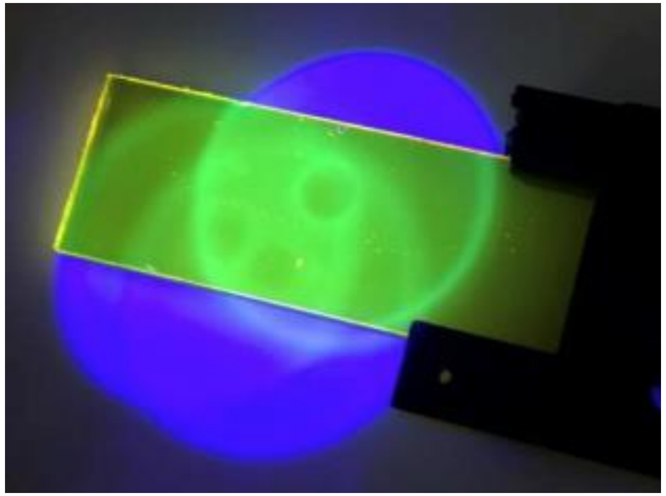
Concept of PT-LiFi

[1] R. Bian, I. Tavakkolnia and H. Haas, "15.73 Gb/s Visible Light Communication With Off-the-Shelf LEDs," *Journal of Lightwave Technology*, vol. 37, no. 10, pp. 2418-2424, May 2019.

WDM receiver for PT-LiFi

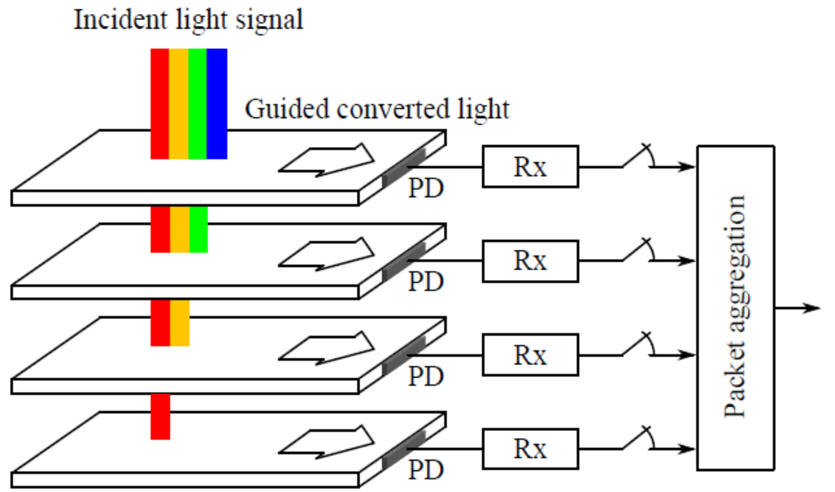
Florescent concentrator

- Absorb one wavelength and convert it to another wavelength
- Break the etendue limit
- Limited bandwidth (~40 MHz)



Novel WDM receiver [12]

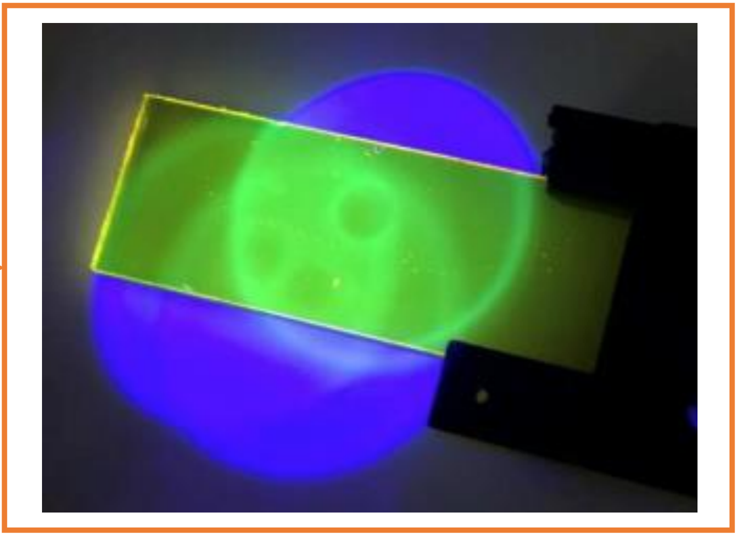
- Each concentrator absorbs a certain wavelength and let others go through



[12] **X. Wu** and D. C. O'Brien, "Parallel Transmission LiFi," *IEEE Transactions on Wireless Communications, vol. 19, no. 10, pp. 6288-6276, Oct. 2020.*

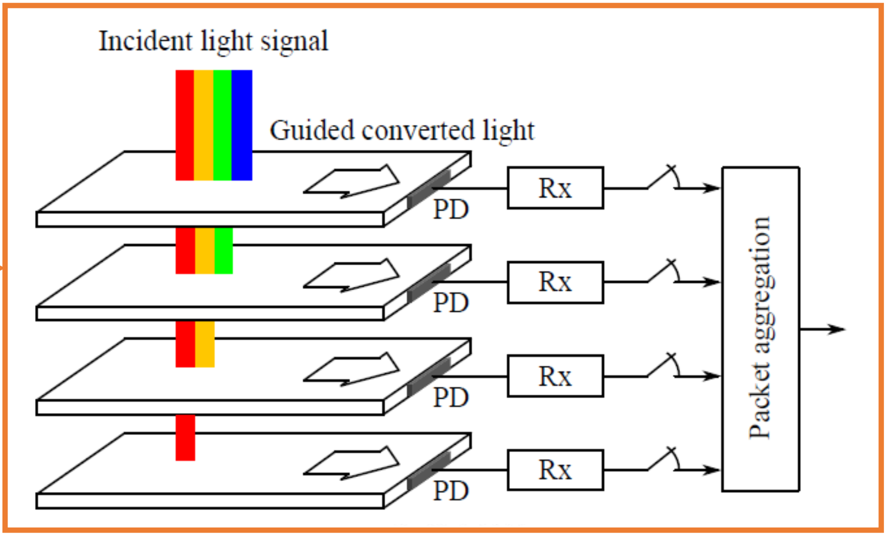
WDM receiver for PT-LiFi

Florescent concentrator



- Absorb one wavelength and convert it to another wavelength
- Break the etendue limit
- Limited bandwidth (~40 MHz)

Novel WDM receiver [12]



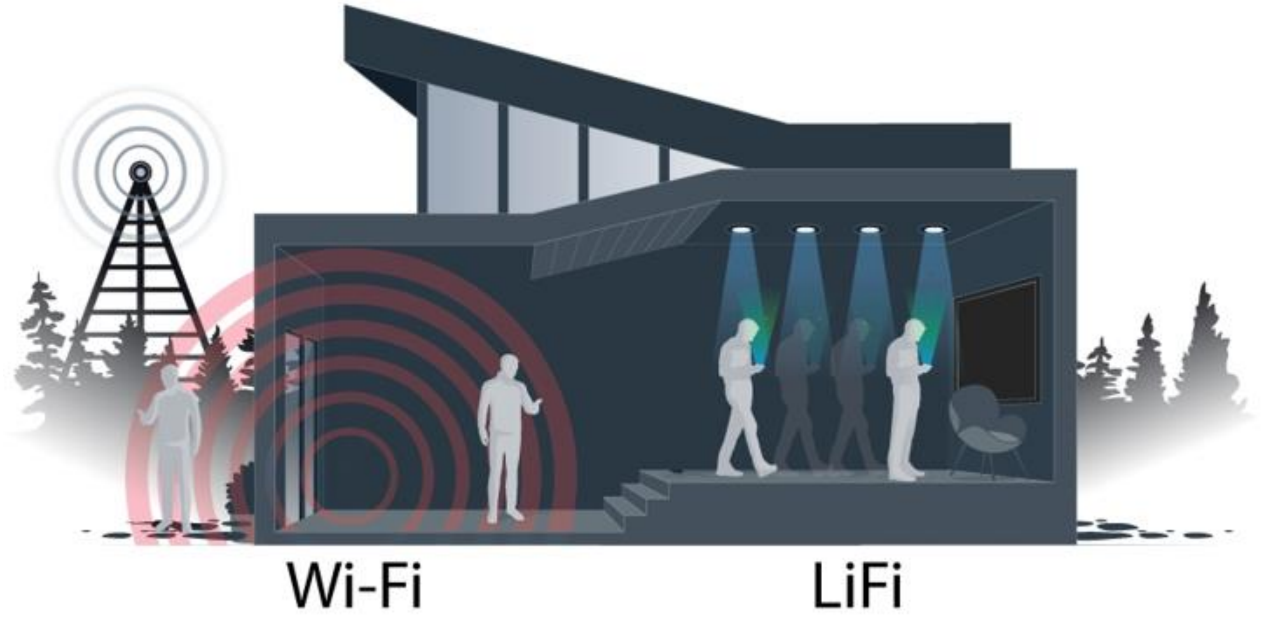
- Each concentrator absorbs a certain wavelength and let others go through
- Concentrators are ***stackable*** and thus the device size can remain the same

Parallel transmission LiFi can ***double*** the link capacity of conventional LiFi.

[12] **X. Wu** and D. C. O'Brien, "Parallel Transmission LiFi," *IEEE Transactions on Wireless Communications, vol. 19, no. 10, pp. 6288-6276, Oct. 2020.*

Outline

- ➢ Introduction to HyFi (Hybrid LiFi and WiFi networks)
- ➢ Hybrid network management
  - Access point selection
  - Handover
  - Mobility-aware load balancing
- ➢ Artificial Intelligence
- ➢ Parallel transmission LiFi
- ➢ Applications and Summary



Applications

Communication based

- High data rate (4K, VR, holographic display)
- High density (airport, stadium)

Functional

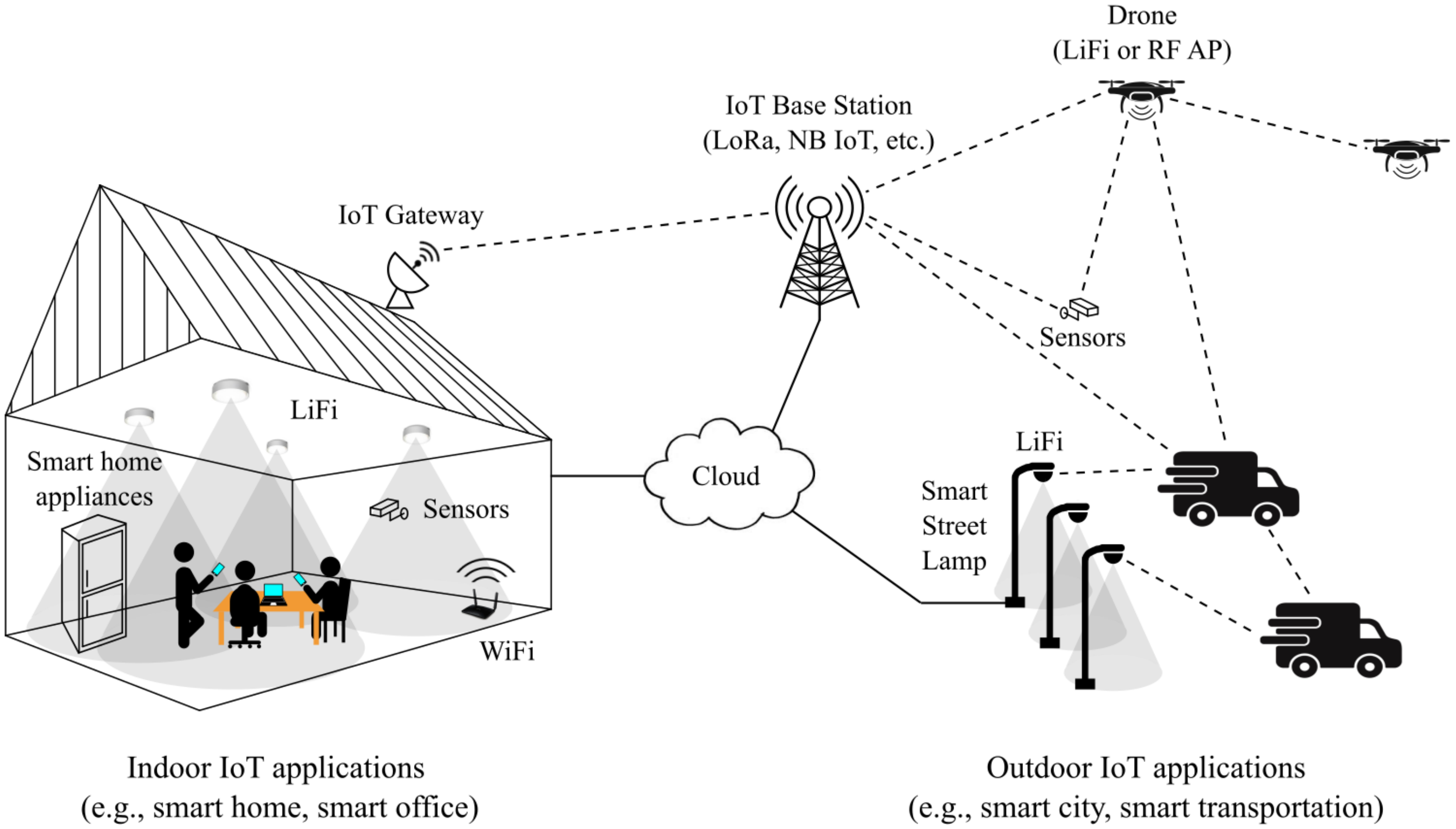
- Indoor positioning (localization, navigation)
- Physical layer security (secure communication)

Advanced

- Consumer IoT (smart home, wearables)
- Industrial IoT (smart factory, smart grid, smart city)

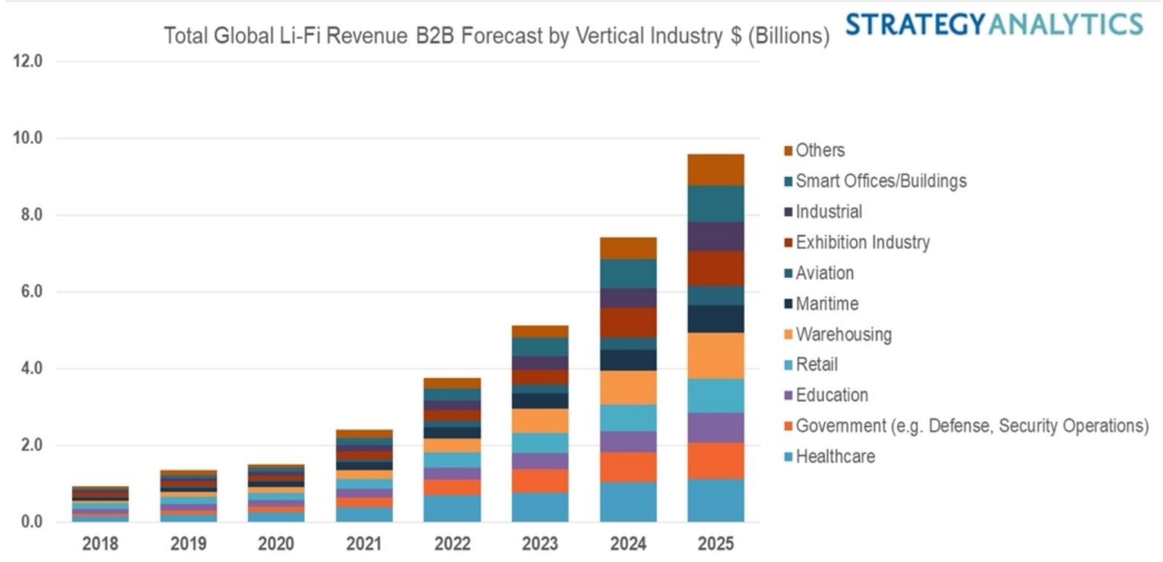
Application scenarios

- In addition to provide high speed transmission, HyFi can well support IoT and be applied in both indoor and outdoor scenarios.



Summary

- Along with the looming spectrum crunch in RF, LiFi has emerged in recent years as a promising technology for indoor wireless communications.
- At the mean time, WiFi continues its wide deployment in daily life.
- The coexistence of LiFi and WiFi is gaining momentum with the roll-out of LiFi commercial products from companies such as pureLiFi and Signify.
- Located in the same local area, LiFi and WiFi can be readily managed through a central control unit, forming HyFi.
- Combining the high data rate of LiFi and the ubiquitous coverage of WiFi, HyFi is able to provide greater network performance than a single wireless technology.
- Research on implementing HyFi in realistic environments and optimizing the network performance is still underway.



Thank you for your attendance!

xiping.wu@ucd.ie