

# Robotic Aerial 6G Small Cells with Grasping End Effectors for mmWave Relay Backhauling

Jongyul Lee and Vasilis Friderikos

Centre for Telecommunication Research (CTR),  
Department of Engineering,  
King's College London, U. K.

{Jongyul.lee, Vasilis.Friderikos}@kcl.ac.uk

- 1. Introduction**
- 2. System Model**
- 3. Problem Formulations**
- 4. Numerical Investigations**
- 5. Conclusions**

- 
- » **Envisioning network densification:** To support the ever-increasing data traffic growth of ground users (GUs) in beyond 5G (B5G) or 6G networks, network densification is envisioned to play an important role in augmenting overall network capacity in the coming years.
  
  - » **Deployment of cost-effective wireless backhauling:** The deployment of cost-effective wireless backhauling connecting ultra dense small-cell base stations (BSs) will be of fundamental importance in providing the on-demand requirement of the GUs.
  
  - » **Small cell-BSs operated at low transmission power:** They can assist conventional macro-BSs to provide extra capacity, connectivity and reliable service, especially when using millimeter-wave (mmWave) spectrum, creating a heterogeneous network (HetNet) to cope with a high data traffic demand increase in urban ultra dense areas.
  
  - » **Efficient utilization and operation of mmWave communication:** They have the potential to provide the required gigabit-per-second traffic rate support for wireless backhaul networks in HetNet environments.
  
  - » **Unmanned Aerial Vehicles (UAVs):** it have been considered as a natural extension to the HetNet architecture represented by the small cell-BSs, which offer a highly cost-efficient solution to mitigate the expected data increase due to their flexible deployment.
- Note that it has been proven technically feasible for the UAV to mount wireless equipment operating as a mmWave aerial BS.

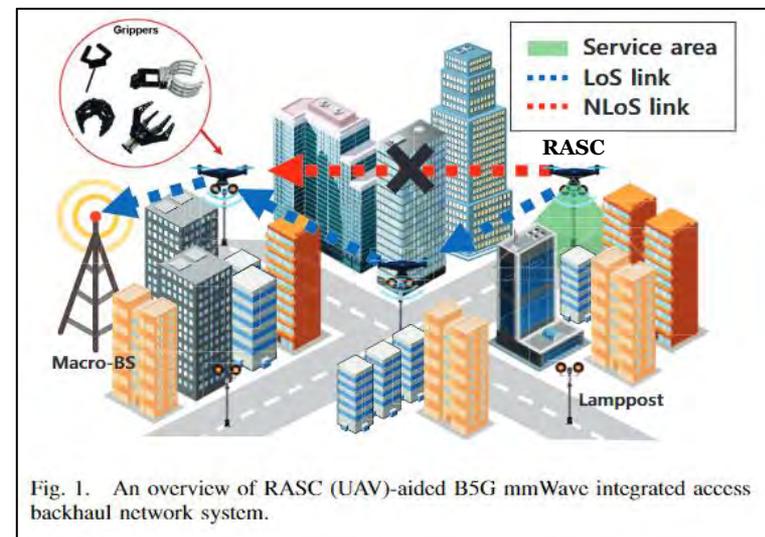
- 
- » **Limited on-board battery capacity and weather conditions:** since the UAV has inherently limited on-board battery capacity for flying/hovering, sustainable operation as an aerial BS limits the UAV deployment. Furthermore, the use of a UAV strongly depends on weather conditions such as rain and wind, as well as may cause significant levels of noise pollution in the surrounding area.
  
  - » **A set of previous works to overcome endurance issues of the UAV:** a multiplicity of solutions such as harvesting solar energy, applying a free space optics (FSO)-based charging system, or using a wired connection as a tether where energy and data feed the UAV whilst hovering, etc.
  
  - » **Robotic Aerial Small Cell (RASC):** the concept is proposed to cope with these issues. It is envisaged that the RASC can provide significant prolonged time of service by grasping in an energy neutral manner at tall urban furniture's such as lampposts using dexterous grippers.
  
  - » **Elimination of the enormous energy consumption:** using such robotic end effectors for grasping, the RASC eliminates the enormous energy consumption required for enabling hovering/flying of the UAV platform resulting in quickly depleting the limited capacity of the on-board battery.

» **Fig. 1:** an overview of the RASC-aided mmWave backhaul network how the flexibility of the RASCs allows them to be deployed where needed including efficient locations of the RASCs that act as relay nodes.

» **No other works** have considered a novel framework where a network flow design is optimized by deploying multiple RASCs serving as small cell-BSs operated as a mmWave backhaul in a dense urban area.

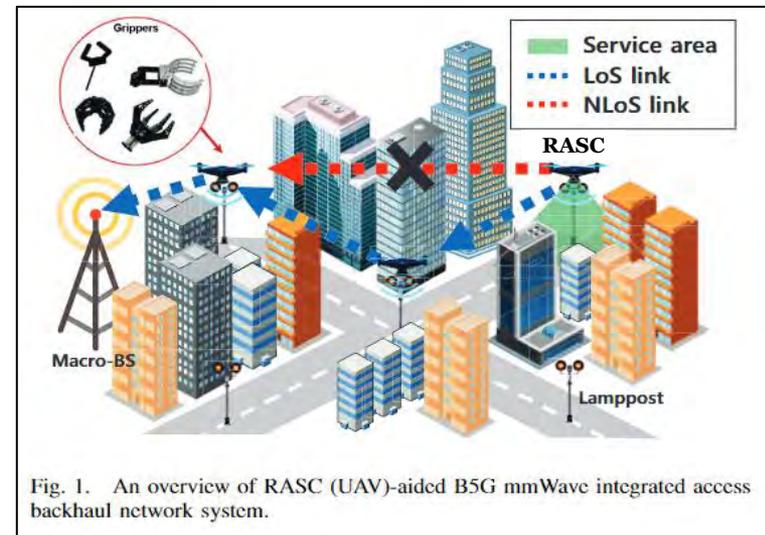
» **One of the major challenges** in the deployment of the HetNets is not only to efficiently deploy small cells but also to optimize the location of relay nodes to create high capacity backhauling in a given dense urban area.

» **No previous works** considered robotic small cells that can be deployed on demand and grasp at different tall urban landforms to be utilized as relay nodes to enhance the wireless backhaul network.



## · Contributions

- » **A network flow optimization problem:** operated with multiple RASCs deployed from a macro-BS using an integer linear programming (ILP) model by considering the mmWave multi-hop backhaul network.
- » **The goal of the proposed framework:** to minimize the network flow links and RASCs in an efficient manner.
- » **Augmentation of the formulation:** by considering the energy consumption of RASCs by using a MILP model is also augmented to reduce the total energy consumption when deploying RASCs.
- » Numerical investigations reveal that RASCs can drastically **reduce the amount of network densification** since only **a quarter to over half of the required number of small cells** is employed compared to **fixed relay nodes (small cells)** to support **the same amount of aggregate traffic backhauling rate in the network**.



# 2. System Model

## 2.1. Scenario

» A single **B5G terrestrial macro-BS** is considered in a given geographical area and a **set of RASCs (multiple RASCs) reside at the macro-BS** acting as a depot. The macro-BS is aware regarding areas of increased traffic demand (i.e., large number GUs) that require improvement for the network performance. In that sense, there are **clusters of users** where RASCs with grasping capabilities can be deployed.

» Once the aforementioned clusters are formed (i.e., areas where traffic demand is higher than a given threshold), then **RASCs serving as small cell-BSs for the clusters and mmWave relay nodes** are dispatched from the depot (i.e., macro-BS) to **create a multi-hop wireless network** by grasping at suitable lampposts.

» When a **RASC arrives at a lamppost**, it will utilize its **grippers (i.e., robotic arms)** to grasp and hence will eliminate any energy consumption for hovering and/or flying. Then, the RASC is on standby to serve and construct **the wireless mmWave backhaul links** towards the macro-BS as shown in Fig. 1.

» It is assumed that **sufficient radio-frequency (RF) chains** are available at the RASC building a **link** so that the link is used by **multiple flows**. Since the urban environment scenario with many obstacles for the blockage effect such as high-rise buildings is assumed, LoS connection (link) is only desirable for mmWave communication. Also, the service lasts for a given duration  $t$ .

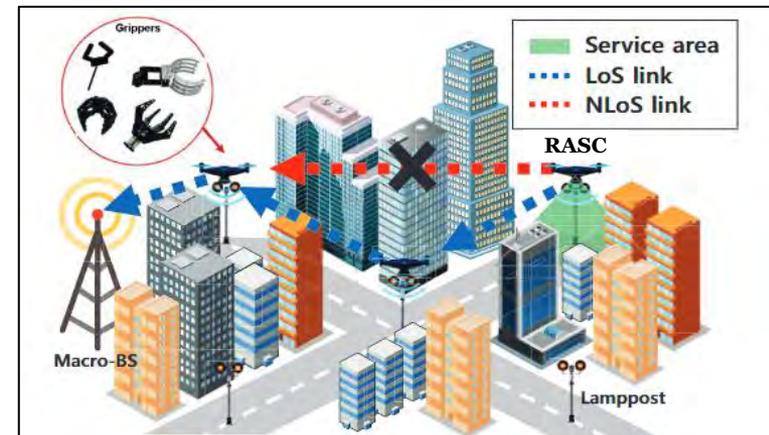


Fig. 1. An overview of RASC (UAV)-aided B5G mmWave integrated access backhaul network system.

### 2.2. Transmission Model

---

- » The utilization of **mmWave communications** at **28 GHz** frequency
- » The mmWave links are realized by employing **fixed beamforming** with high-gain antenna arrays mounted on the RASC where each antenna array covers a 90 degrees sector in the horizontal plane.
- » The mmWave signals are generally **less prone to mutual interference** due to **the directional nature of the propagation beamforming** resulted from the use of narrow beamwidth antennas. Furthermore, **the strong directional signals** (with the blockage effect and the many obstacles such as high-rise buildings in the urban environment) reduce **the overall impact of interference**.
  
- » In the urban wireless backhaul network, **nodes** (at **the top of the lampposts** that the RASC grasps) are located on a **height from 5 m to 12 m** (which is the typical range for the size of lampposts in UK), which is **unlikely for a physical object to disturb their links**, i.e., Non-LoS (NLoS) links.
- » Hence, it is assumed that **no more than two physical links** along the constructed path **interfere with each other** for simplicity: **Signal to Noise Ratio (SNR) and LoS condition for the link** are only considered.
- » For a detailed **mmWave link capacity generation** as a function of the distance between nodes, the macroscopic **pathloss** is applied as discussed in the reference below(\*) in order to calculate the beamforming gains.

\*M. R. Akdeniz et al, "Millimeter wave channel modeling and cellular capacity evaluation," *IEEE journal on selected areas in communications*, Vol. 32, No. 6, pp1164–1179, 2014.

## 2. System Model

### 2.3. Energy Consumption Model for Rotary Wings of a UAV

» **RASC controlled with rotary wings**, the constant velocity  $v$ , and grippers (robotic arms).

» **Propulsion energy**: The propulsion power with a function of the velocity  $v$  in meter per second (m/s) is approximately given by  $P_{\text{trav}}(v)$  described in the reference(\*). Subsequently, the propulsion energy in Joule (J) to fly between nodes is denoted as  $E_{\text{trav}}^{ij} = P_{\text{trav}}(v) t_{\text{trav}}^{ij}$ ,  $\forall i, j (i \sim j) \in V$  (set of nodes), ( $t_{\text{trav}}^{ij}$  represents the traveling time that the RASC spends flying, i.e.,  $t_{\text{trav}}^{ij} = d_{ij} / v$ ,  $d_{ij}$  is the Euclidean distance between nodes).

» **Grasping Energy**: The grasping power of RASC depends on its size and weight, as well as the type of the gripper. The electromagnetic solenoid-based grippers can be deemed as suitable for attaching to ferromagnetic surfaces such as lampposts. Hence, the grasping energy consumed during the duration  $t$  is given by  $E_{\text{grasp}} = P_{\text{grasp}}[t]$ , where  $P_{\text{grasp}}$  is the grasping power. Note that this can be considered as an upper bound while the RASC is perching since energy neutral grippers of the RASC that could be applied require no energy consumption for hovering and/or flying.

» **Communication Energy**: The communication energy of the RASC is given by  $E_{\text{comm}} = (P_0 + \eta_p P_{\text{Tx}})[t]$ .

( $P_0$  = the minimum active power,  $\eta_p$  = a linear transmission factor,  $P_{\text{Tx}}$  = the transmission power as discussed in the reference(\*\*))

\*Y. Zeng, J. Xu, and R. Zhang, "Energy minimization for wireless communication with rotary-wing uav," *IEEE Transactions on Wireless Communications*, Vol. 18, No. 4, pp2329–2345, 2019.

\*\*M. Höyhtyä, O. Apilo, and M. Lasanen, "Review of latest advances in 3gpp standardization: D2d communication in 5g systems and its energy consumption models," *Future Internet*, Vol. 10, No. 1, 2018.

$$y_{ijf} = \begin{cases} 1, & \text{if flow } f \text{ uses a link} \\ & \text{between a node } i \text{ and a node } j, \\ 0, & \text{otherwise.} \end{cases} \quad (6.1)$$

$$x_{ik} = \begin{cases} 1, & \text{if a RASC } k \text{ travels from the macro-BS and} \\ & \text{stays at a node } i \text{ for the network flow,} \\ 0, & \text{otherwise,} \end{cases} \quad (6.3)$$

» Decision variables (6.1) and (6.3): **The variable  $x$  and  $y$  are binary.**

$$\sum_{j \in \mathcal{V}} y_{ijf} = 1, \quad \forall i \in \mathcal{V}_e, \quad \forall f \in \mathcal{F}, \quad (6.2a)$$

$$\sum_{i(i \neq 0) \in \mathcal{V}} y_{i0f} = 1, \quad \forall f \in \mathcal{F}, \quad (6.2b)$$

$$\sum_{j(i \neq j) \in \mathcal{V}_b} y_{ijf} = \sum_{j(i \neq j) \in \mathcal{V}_b} y_{jif}, \quad \forall i \in \mathcal{V}_b \setminus \{0\}, \quad \forall f \in \mathcal{F}, \quad (6.2c)$$

» Constraints (6.2): **Network flow path in the wireless backhaul network.**

» Objective function (6.6) is to minimize **the number of hops for the network flow** while minimizing the number of RASCs.

$$\sum_{k \in \mathcal{K}} x_{ik} \leq 1, \quad \forall i \in \mathcal{V} \setminus \{0\}, \quad (6.4a)$$

$$\sum_{i \in \mathcal{V} \setminus \{0\}} x_{ik} \leq 1, \quad \forall k \in \mathcal{K}, \quad (6.4b)$$

$$\sum_{k \in \mathcal{K}} x_{ik} \geq y_{ijf}, \quad \forall i \in \mathcal{V} \setminus \{0\}, \quad j \in \mathcal{V}_b, \quad \forall f \in \mathcal{F}. \quad (6.4c)$$

» Constraints (6.4): **Multiple RASCs to connect/bridge the network flow.**

$$S_{ij}^{\text{eff}} = \min[\log_2(1 + 10^{0.1 * (\text{SNR} - \alpha)}), S_{ij}^{\text{max,eff}}], \quad \forall i, j \in \mathcal{V}, \quad (6.5a)$$

$$c_{ij} = B \cdot S_{ij}^{\text{eff}}, \quad \forall i, j \in \mathcal{V}, \quad (6.5b)$$

$$\sum_{f \in \mathcal{F}} \mathcal{V}_{\text{th}}^f[t] y_{ijf} \leq c_{ij}, \quad \forall i, j \in \mathcal{V}, \quad (6.5c)$$

» Constraints (6.5): **Modelling link capacity on the network flow.**

$$(P1): \min_{X, Y} \sum_{i \in \mathcal{V}} \sum_{j \in \mathcal{V}} \sum_{f \in \mathcal{F}} y_{ijf} + \sum_{i \in \mathcal{V}} \sum_{k \in \mathcal{K}} x_{ik} \quad (6.6)$$

$$\text{s. t. } (6.2a) - (6.2c), (6.4a) - (6.4c), (6.5a) - (6.5c), \quad (6.7)$$

$$x_{ik} \in \{0, 1\}, \quad \forall i \in \mathcal{V} \setminus \{0\}, \quad \forall k \in \mathcal{K}, \quad (6.8)$$

$$y_{ijf} \in \{0, 1\}, \quad \forall i, j(i \neq j) \in \mathcal{V}, \quad \forall f \in \mathcal{F}, \quad (6.9)$$

» An optimization model **(P1) for the flow of the backhaul network with multiple RASCs** can be formulated.

$$E_{ik}^{\text{total}} \geq 0, \text{ energy consumption of a RASC } k \quad (6.10)$$

when it is activated at a node  $i$ ,

$$E_{jik}^{\text{fly}} = x_{ik} E_{\text{trav}}^{ji}, \quad \forall i, j \in \mathcal{V}, \quad \forall k \in \mathcal{K}, \quad (6.11a)$$

$$E_{ik}^{\text{act}} = x_{ik} E_{\text{grasp}} + \sum_{f \in \mathcal{F}} y_{ijf} E_{\text{comm}}, \quad \forall i, j \in \mathcal{V}, \quad \forall k \in \mathcal{K}, \quad (6.11b)$$

$$E_{ik}^{\text{total}} = E_{jik}^{\text{fly}} + E_{ik}^{\text{act}}, \quad \forall i, j \in \mathcal{V}, \quad \forall k \in \mathcal{K}, \quad (6.11c)$$

$$(P2): \min_{E, X, Y} \sum_{i \in \mathcal{V}} \sum_{j \in \mathcal{V}} \sum_{f \in \mathcal{F}} y_{ijf} + \sum_{i \in \mathcal{V}} \sum_{k \in \mathcal{K}} x_{ik} + \sum_{i \in \mathcal{V}} \sum_{k \in \mathcal{K}} E_{ik}^{\text{total}} \quad (6.12)$$

s. t. (6.2a) – (6.2c), (6.4a) – (6.4c), (6.5a) – (6.5c), (6.8), (6.9), (6.11a) – (6.11c), (6.13)

$$E_{ik}^{\text{total}} \geq 0, \quad \forall i \in \mathcal{V} \setminus \{0\}, \quad \forall k \in \mathcal{K}, \quad (6.14)$$

» In order to prevent **the use of inefficient energy consumption of RASCs** when they are dispatched from the macro-BS, **an additional variable and constraints** on the energy consumption of the RASC are derived.

» Decision variables (6.10): The variable  $E$  is continuous.

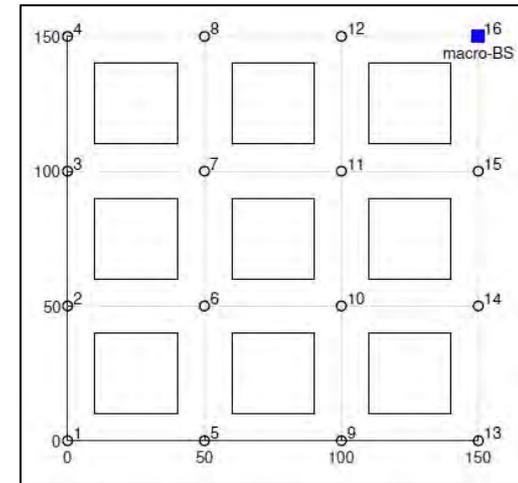
» Constraints (6.11) on the energy consumption of the RASC.

» An optimization model (P2) for the flow of the backhaul network with multiple RASCs can be formulated.

» The objective function (6.12) is to **minimize the number of hops for the network flow** while minimizing the **number of RASCs and the energy consumption of RASCs**.

# 4. Numerical Investigations

- » Right Fig: a Manhattan grid model aiming at a typical downtown urban environment for RASC deployment
- » The street width: 10 m (the edge part) or 20 m (the street along the intersection)
- » **15 lampposts at 10 m height** are considered and uniformly distributed at 50 m apart along the intersection of the streets. These lampposts constitute **the set of candidate locations for hosting the RASCs** where they will fly to and grasp via the embedded dexterous **end effectors** eliminating energy consumption for hovering and/or flying.
- » A macro-BS is located on the corner of the very top right.
- » The number of **hotspots** is varied in the given area creating traffic flows denoted as  $N_E$ . Those hotspots are randomly distributed to the vicinity of lampposts in the given area.
- » All **required achieved throughput ( $\gamma_{th}$ )** at hotspot areas is identical.
- » The velocity of the RASC is 10.21 m/s that consumes minimum energy with maximum endurance.



Parameter	Value
Deployment area	Manhattan grid model (150m × 150m)
Number of blocks (buildings)	9 (30m × 30m)
Number of lampposts (nodes) including a macro-BS ( $N_V$ )	16
Number of required flows above the threshold at respective hotspot area ( $N_E$ )	1, 2, 3
Maximum number of RASCs ( $N_K$ )	15
Required throughput in the hotspot area ( $\gamma_{th}$ )	(0.5, 3) bps/Hz
Duration ( $t$ )	1800 s
Carrier frequency	28 GHz
Bandwidth ( $B$ )	1 GHz
Minimum active power ( $P_b$ )	6.8 W [121]
Linear transmission factor ( $\eta_p$ )	4 W [121]
Transmit power ( $P_{TX}$ )	24 dBm [123]
Grasping power ( $P_{grasp}$ )	10 W [120]
Propulsion power ( $P_{trav}$ )	[119] in detail
Velocity ( $v$ )	10.21 m/s [119]
Maximum spectral efficiency ( $S^{\max,eff}$ )	4.8 bps/Hz [112]
Loss factor ( $\alpha$ )	3 dB [112]

# 4. Numerical Investigations

## 4.1. Flow Optimization Analysis

» Right Fig: **the minimum number of small cells** with varying the required achieved throughput ( $\gamma_{th}$ ) and the number of required flows ( $N_E$ ) and compares the RASC deployment of the proposed **(P1) and (P2) solutions** in the case of  $N_E = 1$  to 3 with **the Fixed Small Cells (FSCs)** deployment.

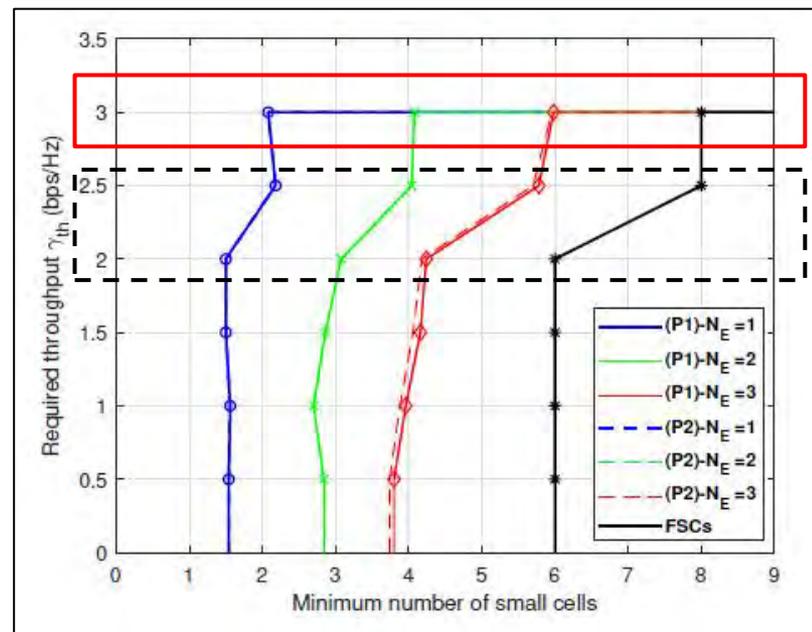
» **FSCs**: as infrastructure with wireless equipment may cause a **highly expensive installation cost**. Also, they are deployed as **immovable** but set to be connected to cover the given whole area for enabling the traffic flow from the hotspot areas to the macro-BS regardless of  $N_E$  for the wireless backhaul.

» **All schemes steeply increase the number of small cells** at  $\gamma_{th} = 2.5$  bps/Hz due to **the link capacity**.

» The proposed optimal scheme **(P1) and (P2)** use more efficient implementation in constructing backhaul links than the FSCs throughout the entire simulations.

» **On average the number of RASCs** required are **2.08** (blue line), **4.08** (green line) and **5.98** (red line) for the case of  $N_E$  range from 1 to 3 respectively when end-users at hotspots require a minimum rate of **3 bps/Hz** ( $\gamma_{th}$ ).

» However, for the same achievable rate **the number of FSCs** (black line) **ranges from 6 to 8** and this is **regardless of increase of the value  $N_E$**  (i.e., the number of hotspots).



# 4. Numerical Investigations

## 4.1. Flow Optimization Analysis

» Right Fig: toy examples of (P1) solution and the FSCs when  $N_E = 3$  and  $\gamma_{th} = 3$  bps/Hz.

» Left figures both in Fig. (a) and (b): the result of **(P1) solution**.

» Right figures both in Fig. (a) and (b): the result of **FSC**.

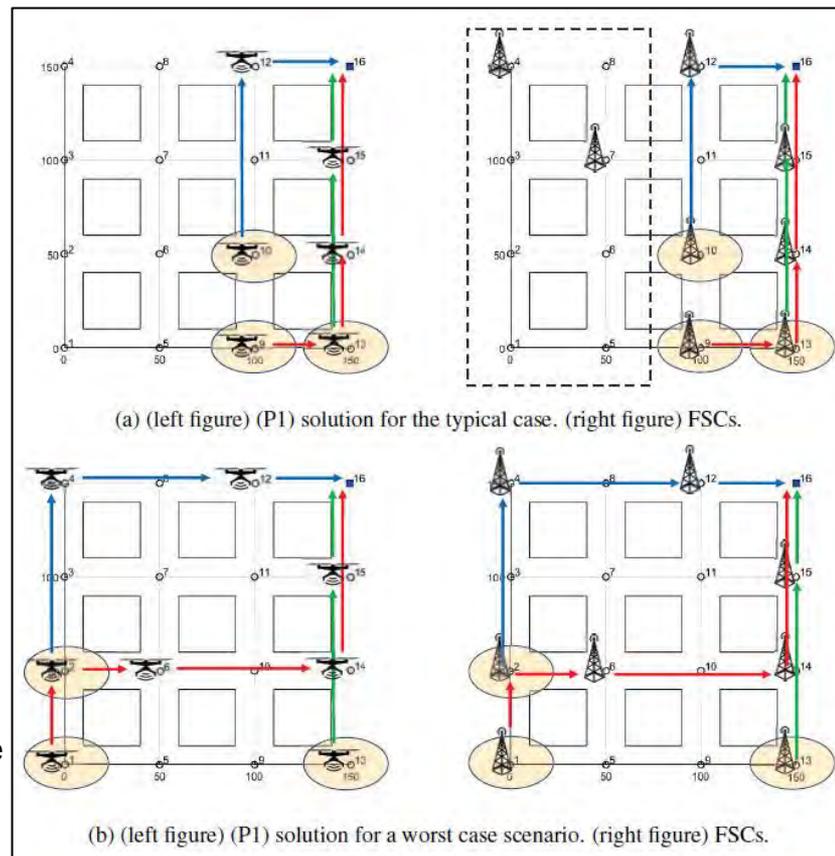
» **Yellow circles**: hotspot areas.

» **Red, green, blue arrows**: flow direction.

» Fig (a): **6 RASCs** are only deployed for the flow starting from the **3 hotspot areas** for the typical case. Whereas **6 FSCs** are deployed for the same 3 hotspot areas whilst **2 additional FSCs** cover the rest of the given urban area as described in the black dotted box, i.e., **the total number of the FSCs is 8**.

» Fig (b): **8 RASCs** are deployed for a worst-case scenario in the location of hotspots. Whereas **8 FSCs** with identical allocations are also deployed to cover the given entire urban area.

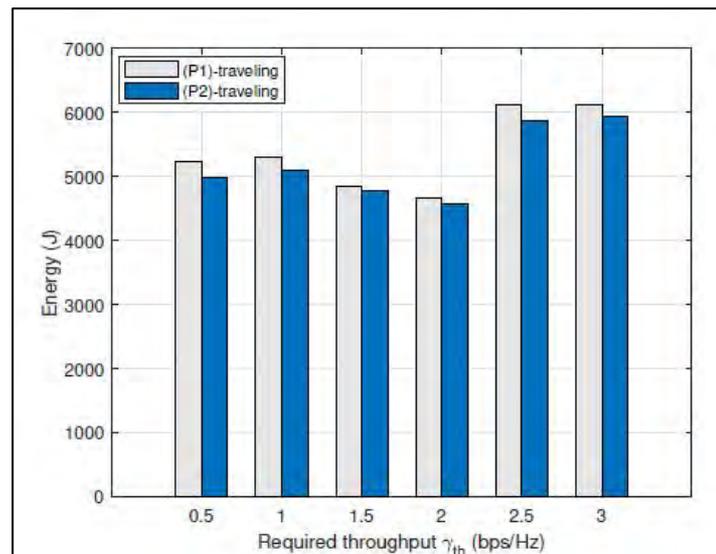
» **The maximum number of RASCs** required for the deployment **does not exceed the number of FSCs** in the given same urban area.



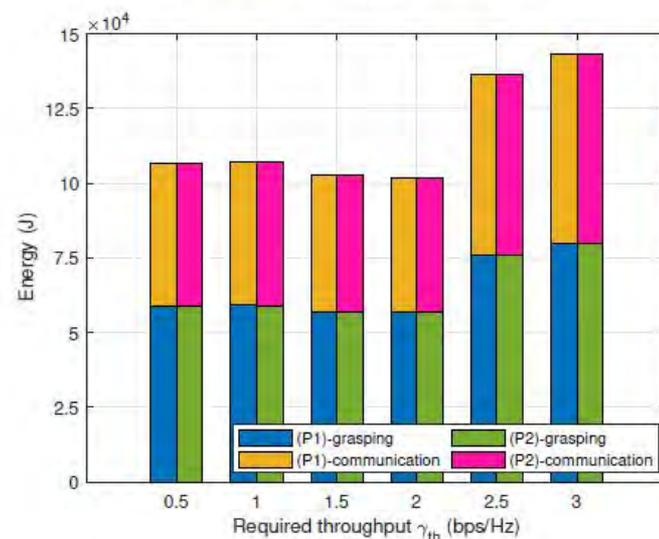
# 4. Numerical Investigations

## 4.2. Energy Consumption of RASC for Deployment

- » Right Fig: the energy consumption of RASCs for the optimal scheme (P1) and (P2).
- » **One duration  $t$**  is only considered → **the traveling energy** in the investigations is consumed for **the initial route** where the RASCs travel from the macro-BS to the nodes for the wireless backhaul.
- » **The energy consumption in both figures has a slight increase from  $\gamma_{th} = 2.5$  due to the link capacity.**
- » **The grasping energy and communication energy** of both schemes (P1) and (P2): **amount to the majority of their total energy** since the RASCs consume **longer time for service than the traveling time** to arrive at the nodes, i.e.,  **$t = 1800s$  and tens of seconds to fly.**
- » However, **the traveling energy** in essence requests **a high propulsion power** → the grasping and communication energy of both schemes show almost similar values; **a delicate difference.**
- » Ex) **the communication energy** of (P1) and (P2) obtain approximately **47.6kJ** and **47.9kJ**, respectively for the case of  $\gamma_{th} = 1$ . However, the scheme (P2) outperforms the scheme (P1) by gaining up to **5% avg** (maximum 32.5%) of **the traveling energy** throughout the entire simulations.
- » The transition of their trajectory over time variation will be studied as future work.



(a) Traveling energy consumption.



(b) Grasping and communication energy consumption.

- 
- » **A novel optimization framework** to compute an optimal **network flow** implemented by **multiple robotic aerial small cells (RASCs)** serving users at hotspot areas and acting as **relay nodes** to create a **wireless millimeter wave (mmWave) backhaul network**.
  - » The proposed framework **allows for creation of backhaul links** so that **the required flow** is optimized **from the hotspot areas to the macro-BS** when there are multiple RASCs **perched at lampposts**.
  - » The proposed framework **outperforms the deployment of the conventional fixed small cells (FSCs)** for supporting **the same throughput demand** by providing **25% to 65% lower number of RASCs** than that of the FSCs.
  - » This implies that due to their efficient on-demand deployment and the fact **that RASCs do not consume energy for hovering and/or flying when perching**, they can be seen as a **considerably attractive alternative to FSC installation**.

# **Thank you for watching this video**

## **Q & A**

**Department of Engineering**  
**Centre for Telecommunications Research (CTR)**  
Jongyul.lee@kcl.ac.uk