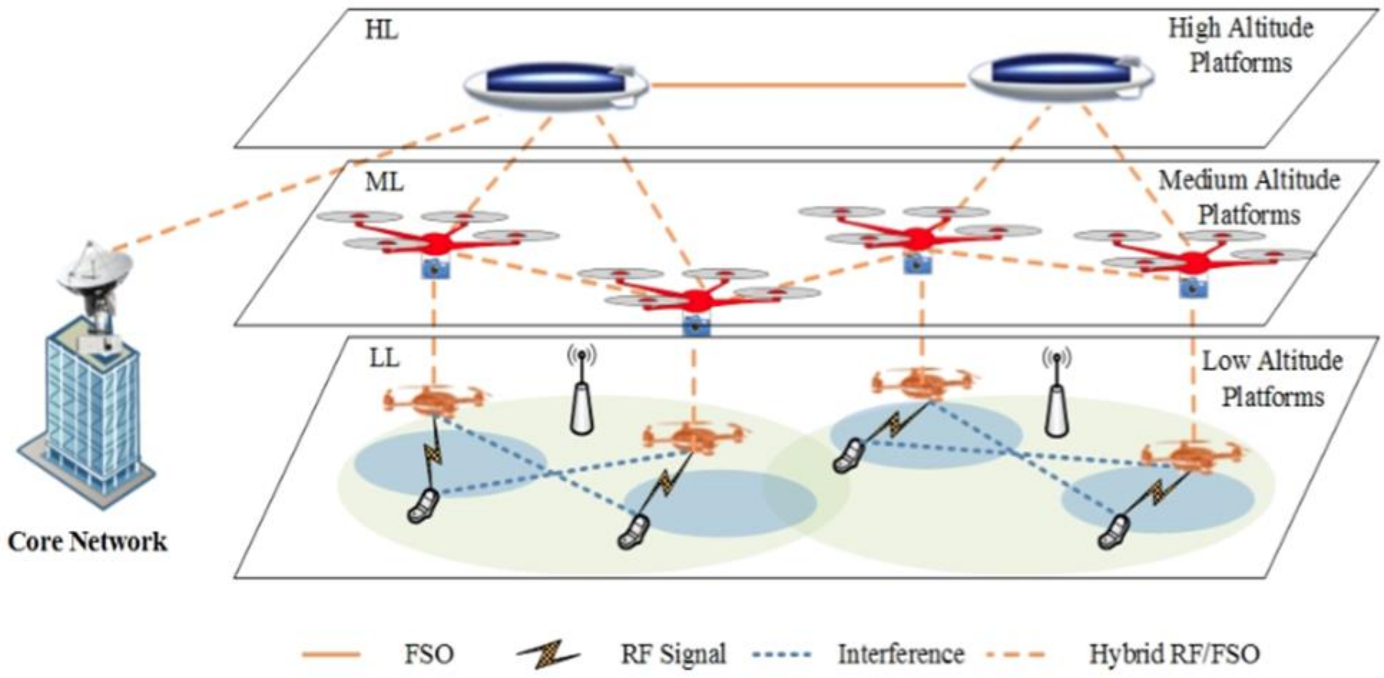


Networked-Flying Platforms:

Paving the Way Towards 5G and Beyond Access and Backhaul Wireless Networks

Muhammad Zeeshan Shakir

Agenda

- Introduction to 5G systems
  - Motivation to future systems: densification
  - Wireless fronthaul: Role of Network flying platforms
- Vertical FSO-based framework for fronthaul
  - Link budget, weather conditions and system losses
  - Performance evaluation in terms of data rate
  - Cost evaluation (capital) for various technologies
- Drone-small cell association problem
  - Problem formulation and numerical analysis
  - Two algorithms: distributed and central

– Airborne SON
  - Layered architecture for cellular network
  - Drone placement problem and SON

– 3-Takeaway Points

Network Flying Platforms:

Introduction to 5G systems

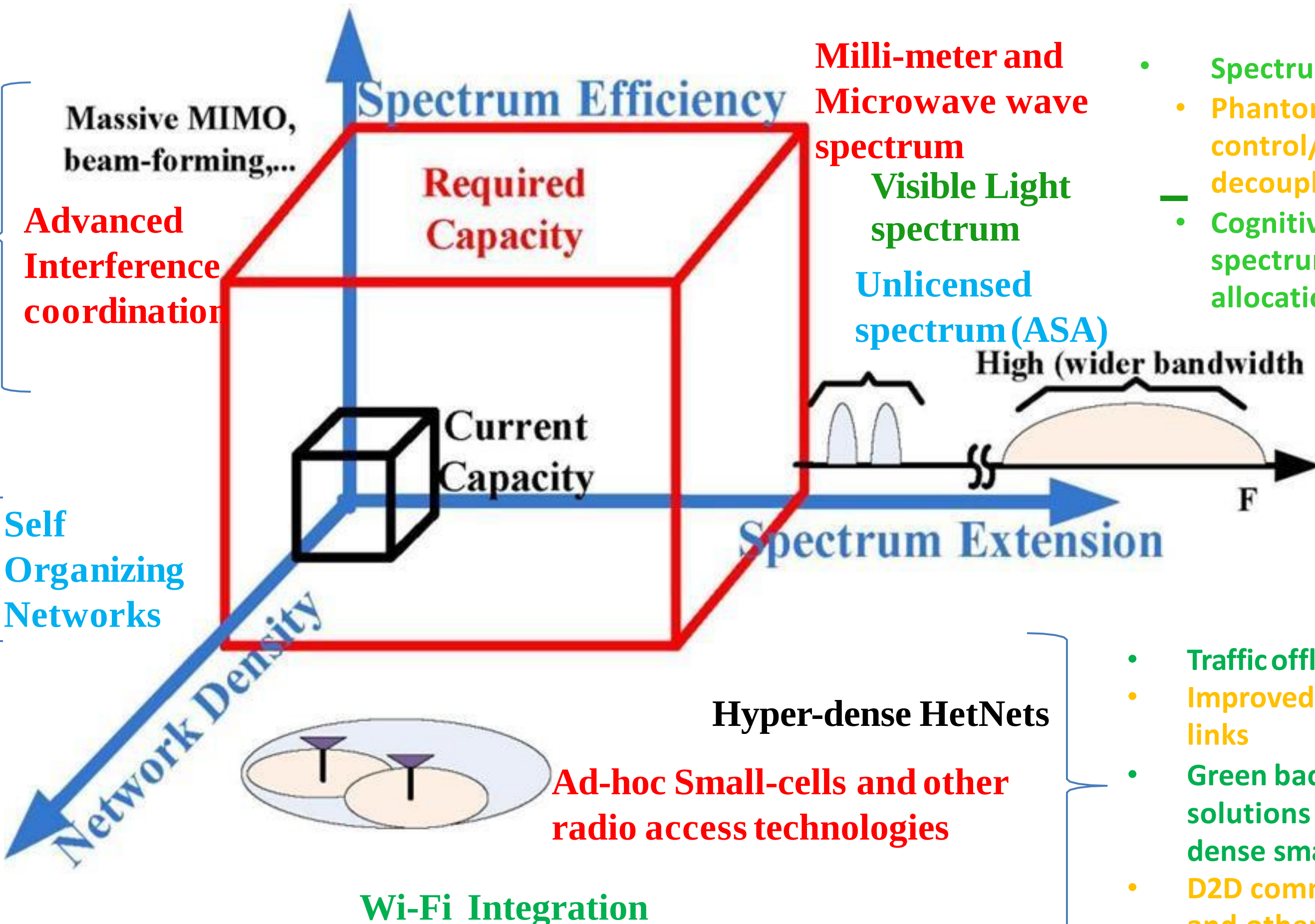
Nikola Tesla
(10 July 1856 – 7 January 1943)

"*When wireless is perfectly applied, the whole earth will be converted into a huge brain, which in fact it is, all things being particles of a real and rhythmic whole. We shall be able to communicate with one another instantly, irrespective of distance.*"
Nikola Tesla (1925)

Roadmap to 1000x: sustainable way!

- Logical separation between idle mode and user DTX/DRX
- More antenna >> higher rate >>more time for sleep
- Higher capacity without desired densification

- Load balancing
- CoMP and other network coordination >> energy savings

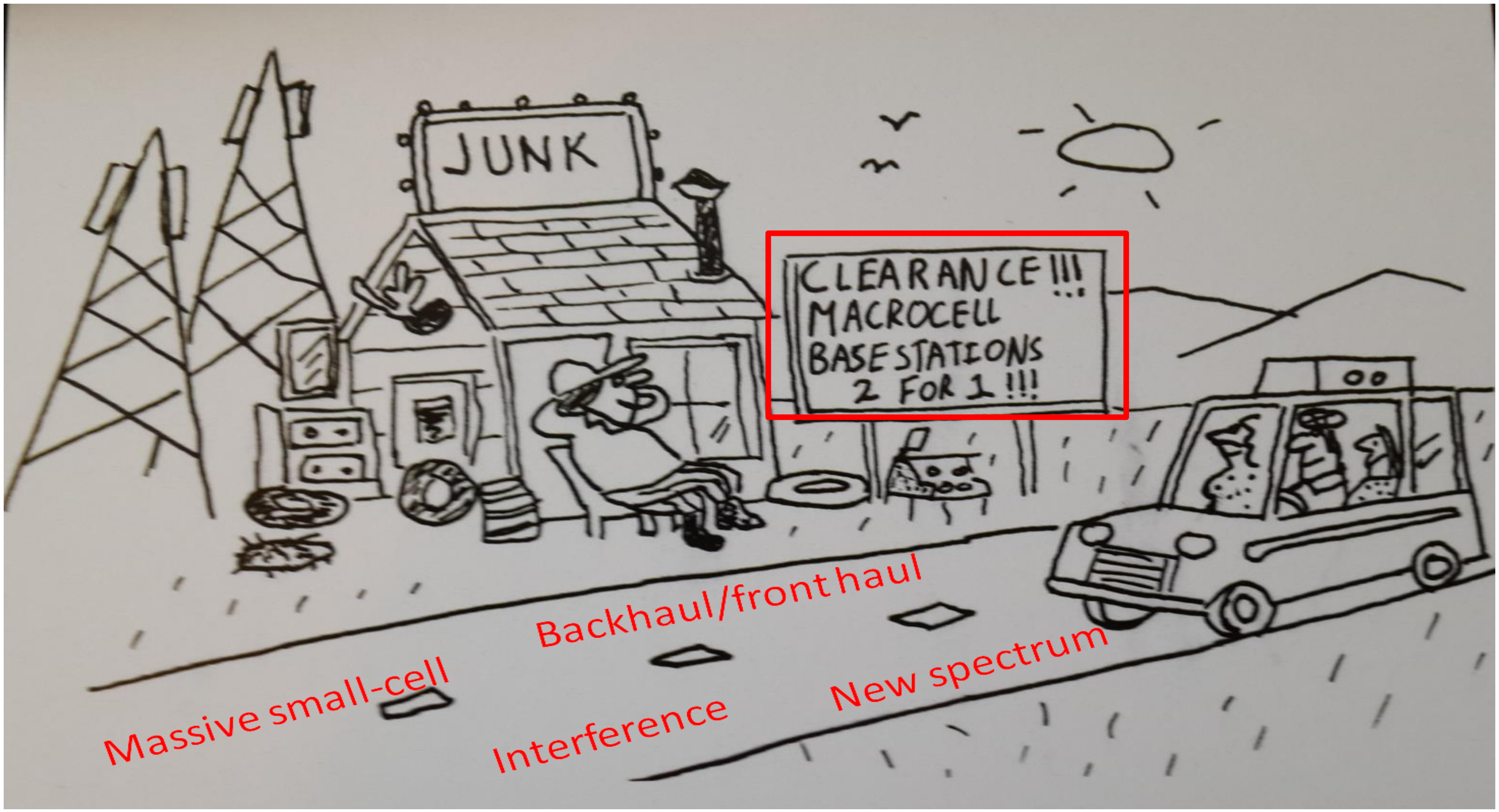


- Spectrum aggregation
- Phantom cell >> control/data plane decoupled
- Cognitive principles in spectrum and resource allocation

- Traffic offload
- Improved and reliable links
- Green backhaul solutions for hyper dense small cells
- D2D communications and other device centric services

2020: Beyond 4G, Radio Evolution for the Gigabit Experience, Nokia Siemens Networks, Aug. 2011

Network Densification: Pitfall

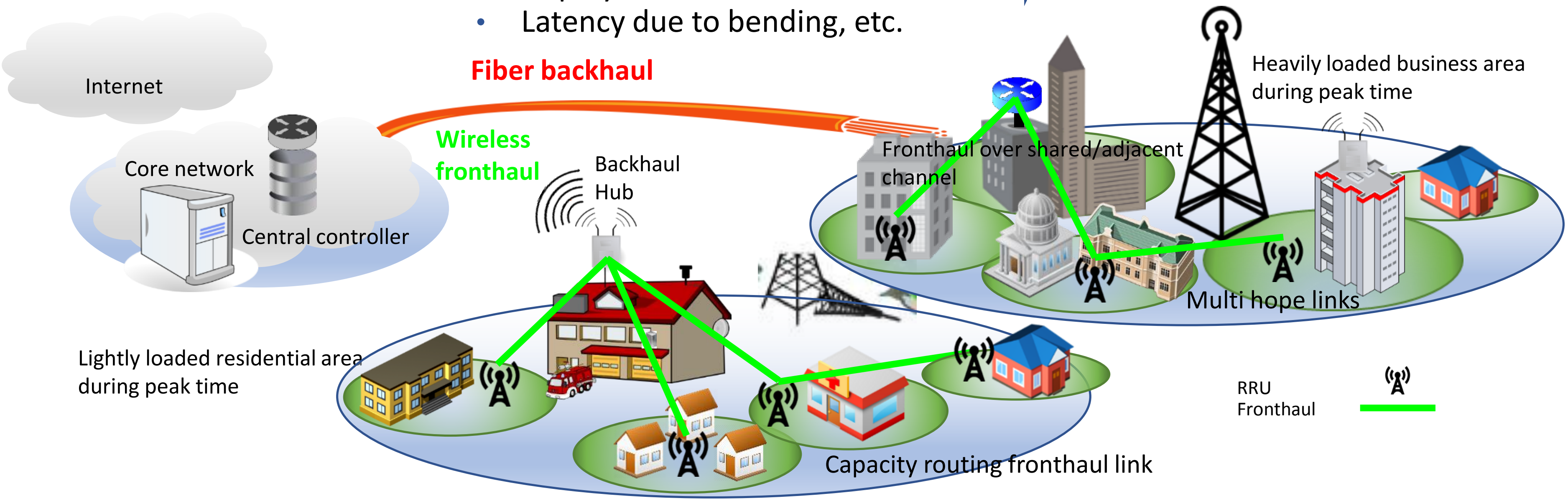


Source: Project: Post card from the near future, CTVR , Ireland, 2014.

Backhaul/fronthaul Dynamics: Ultra-dense HetNet

- RF NLOS backhaul/fronthaul
  - Placement of backhaul/fronthaul hubs (NP-Hard problem)
  - Data rate of Gbits/s could not be achievable
- Fiber
  - Deployment cost
  - Latency due to bending, etc.

Free space optical (FSO) communications: towards the speed of wireline links . . .



Real World Scenario: Wireless Backhaul

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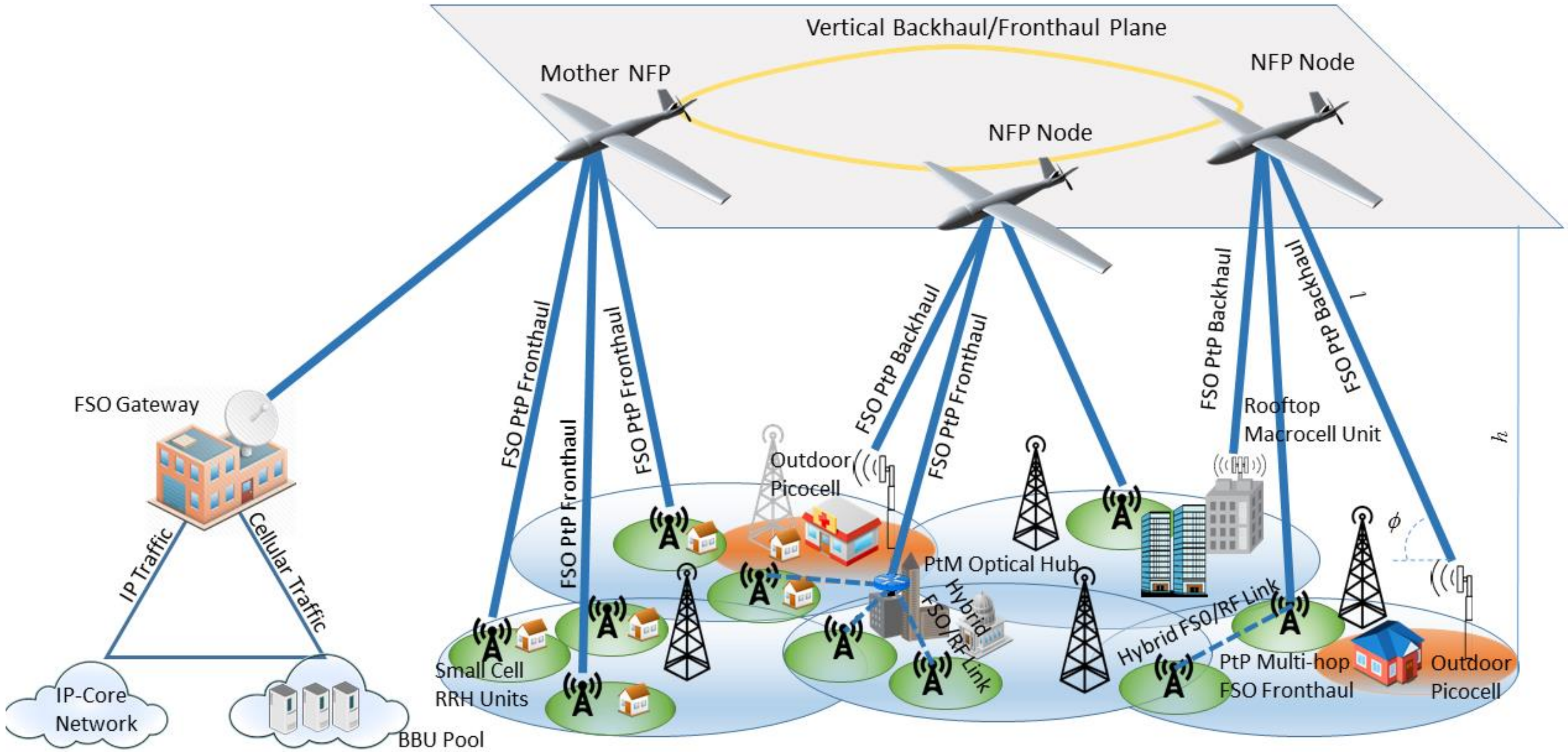
Network Flying Platforms:

Vertical FSO-based framework for fronthaul

Vertical FSO-based Fronthaul for Ultra-dense HetNets



M. Alzenad, M. Z Shakir, H. Yanikomeroglu, and M.-S. Alouini, “FSO-based vertical fronthaul/backhaul framework for 5G+ wireless systems,” in IEEE Communs. Mag., Oct. 2017, https://arxiv.org/abs/1607.01472

Spectrum for Vertical NFP-based Communications

Technology	Data rate	Channel modeling	Atmosphere	Wind
Free space optics (FSO):	• Up 10 Gbits/sec • LOS is required • Unlicensed • Reduced interference	• Link budget analysis • model for FSO satellite Comm • mathematical models	• Fog and visibility • Cloud thickness • Combination of weather	• Wind shear and wind speed dislocate the UAV • May lead to higher scintillation error due to UAV motion
RF (sub-6 GHZ)	• Mbits/sec • LOS/NLOS • Licensed and costly spectrum • Higher interference under NLOS	• Some suburban, rural models • FSPL+ NLOS/LOS • Limited models over subGHz and 5GHz	• Negligible atmosphere • Atmospheric particle absorption is very low over the lower electromagnetic spectrum	• Negligible signal fluctuations as compared with fading due to obstacles • Signal fluctuations due to wind, vegetation, etc.
Mm-wave/Tera hertz	• Few Gbits/sec to 10x Gbits/sec • LOS • Unlicensed/lightly licensed • Reduced interference – massive MIMO	• No vertical models • Trails ongoing	• Rain attenuation	• Doppler effect

Scattering Loss

- Scattering occurs when the FSO beam collides with the particles in the atmosphere which is the layer of gases that surround the planet Earth. Scattering can be classified into three categories, namely,
  - Rayleigh scattering;
  - Mie scattering;
  - Non-selective scattering.

Mie Scattering

- The Kruse model describes the attenuation due to Mie scattering as

$$L_{sca} = 4.34\ \beta_{sca} d = 4.34\ \left(\frac{3.91}{V} \left(\frac{\lambda}{550} \right)^{-\delta} \right) d,$$

where

- L_{sca} denotes the attenuation in dB
- β_{sca} stands for the scattering coefficient in km^{-1}
- d represents the distance along which the scattering phenomena occurs in km
- V denotes the visibility range in km,
- λ stands for the transmission wavelength in nm, $\delta = 0.585\ V^{(1/3)}$ for $V < 6$ km, $\delta = 1.3$ for $6 < V < 50$ km, and $\delta = 1.6$ for $V > 50$ km

M. Grabner and V. Kvicera, "Fog attenuation dependence on atmospheric visibility at two wavelengths for FSO link planning," in Proc. IEEE Antennas and Propag. Conf. (LAPC'2010), pp. 193–196, Loughborough, England, Nov. 2010.

Fog Attenuation

- Fog attenuation (L_{fog}) can be calcualted using Mie Scattering with the distance impacting the link with fog:

$$d = \Delta d_{fog} / \sin(\phi),$$

where Δd_{fog} is the fog layer thickness.

Table 1: Fog attenuation for different wavelengths and foggy conditions.

	Foggy conditions				
	Dense	Thick	Moderate	Light	Very light
Visibility (m)	50	200	500	770	1900
Wavelength (nm)	Attenuation dB/km				
650	327.61	80.19	31.43	20.16	7.92
850	309.21	73.16	27.75	17.46	6.52
1330	280.77	62.77	22.54	13.73	4.71
1550	271.66	59.57	20.99	12.65	4.22

Rain Attenuation

- The rainfall causes a non-selective scattering. The rain attenuation, L_{rain} (measured in dB) is given by

  $$L_{rain} = 1.076\ R_{rain}^{0.67} d_{rain},$$

  where R_{rain} denotes the rainfall rate in mm/hour and d_{rain} denotes the distance along which the rain affects the FSO beam in km, and given by

  $$d_{rain} = \Delta d_{rain}/\sin(\phi),$$

  where Δd_{rain} is the rain layer thickness and ϕ is the elevation angle.

- For example, for d_{rain} =1 km, L_{rain} =1.08 dB, 6.09 dB, and 14.8 dB for rainfall rates of 1 mm/hour, 16 mm/hour, and 50 mm/hour, respectively.

S. S. Muhammad, P. Kohldorfer, and E. Leitgeb, "Channel modelling for terrestrial free space optical links," in Proc. IEEE 7th Int. Conf. Transparent Optical Networks, vol. 1, pp. 407–410, Barcelona, Spain, Jul. 2005.

Cloud Attenuation

- Clouds can be characterized by their height, number density (N_d), liquid water contents (LWC), water droplet size and horizontal distribution extent.
- Different empirical approaches have been proposed to model the cloud attenuation (L_{cloud}).
- We adopt the approach based on estimating cloud visibility range by dividing the atmosphere into layers. Then, for each layer, visibility range is estimated from their N_d and LWC, where visibility range is given by

$$V = 1.002(\mathrm{LWC})N_d^{-0.6473}.$$

M. Awan, Marzuki, E. Leitgeb, B. Hillbrand, F. Nadeem, and M. Khan, "Cloud attenuations for free-space optical links," in Proc. IEEE Wksps. Satellite and Space Commun. (IWSSC'2009), pp. 274–278, Siena-Tuscany, Italy, Sep. 2009.

Turbulence Loss

- The refractive index structure parameter $C_n^2(h)$ is an altitude dependent measure of the turbulence strength.
- According to the H-V model, the parameter $C_n^2(h)$ for the vertical link in the proposed system is given by

$$C_n^2(h) = 0.00594\left(\frac{v}{27}\right)^2\left(10^{-5}h\right)^{10}\exp\left(\frac{-h}{1000}\right) + 2.7\times10^{-16}\exp\left(\frac{-h}{1500}\right) + A\exp\left(\frac{-h}{100}\right),$$

where v denotes the rms wind speed and a typical value for constant A is $1.7\times10^{-14}\mathrm{m}^{-2/3}$. The attenuation caused by scintillation, L_{sci} (in dB) is then given by $L_{sci} = 2\sqrt{23.17(\frac{2\pi}{\lambda}10^9)^{\frac{7}{6}}C_n^2(h)\,l^{\frac{11}{6}}}$, where l is the path length.

B. Epple, "Impact of ground profile on scintillation index for high-altitude optical wireless links," in Proc. IEEE Conf. Global Commun. Wksps. (GC Wkshps'2010), pp. 1057–1061, Miami, FL, USA, Dec. 2010.

Geometrical and Optical Loss

- The geometrical loss in dB is given by

$$L_{\text{geo}} = 10\text{log}\left(\frac{\pi r^2}{\pi(\theta l/2)^2}\right),$$

  where r is the radius of the receiver's aperture, l is the length of the communication link, and θ is the divergence angle of the transmitter.

- Optical losses (L_{opt}) is caused due to the imperfect optical elements used at the FSO transceiver which reduces the optical efficiency of the FSO transmitter (η_t) and the receiver (η_r) and given by

$$L_{opt} = 10\text{log}(\eta_t \eta_r).$$

Data Rate of Vertical FSO Links

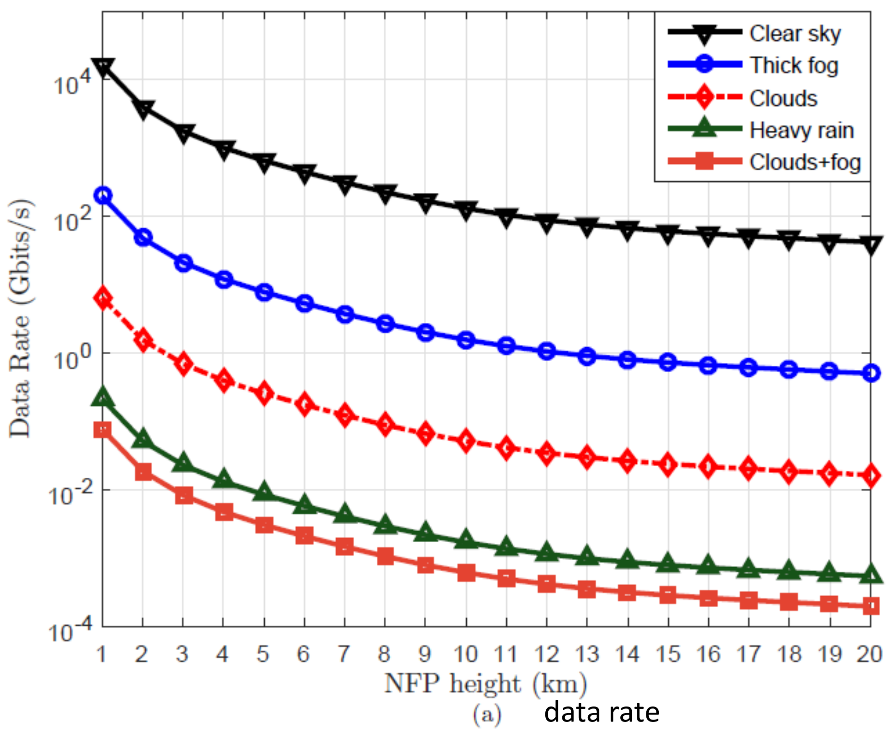
The achievable data rate R of a FSO link is given by

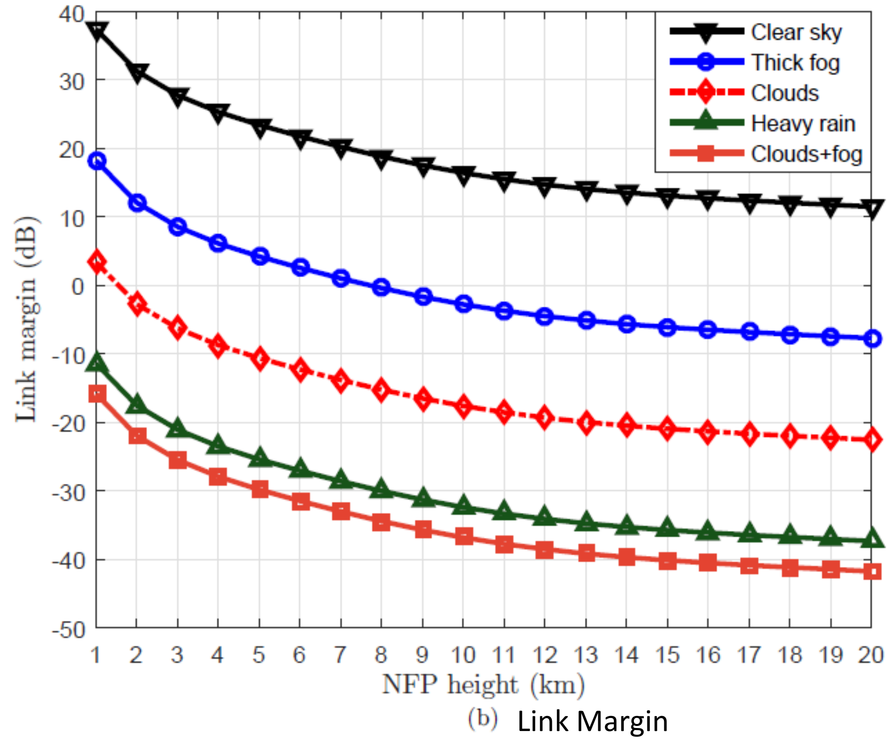
$$R = \frac{P_t \eta_t \eta_r 10^{\frac{-L_{poi}}{10}} 10^{\frac{-L_{atm}}{10}} A_R}{A_B E_p N_b} \quad \text{[bits/s]},$$

where

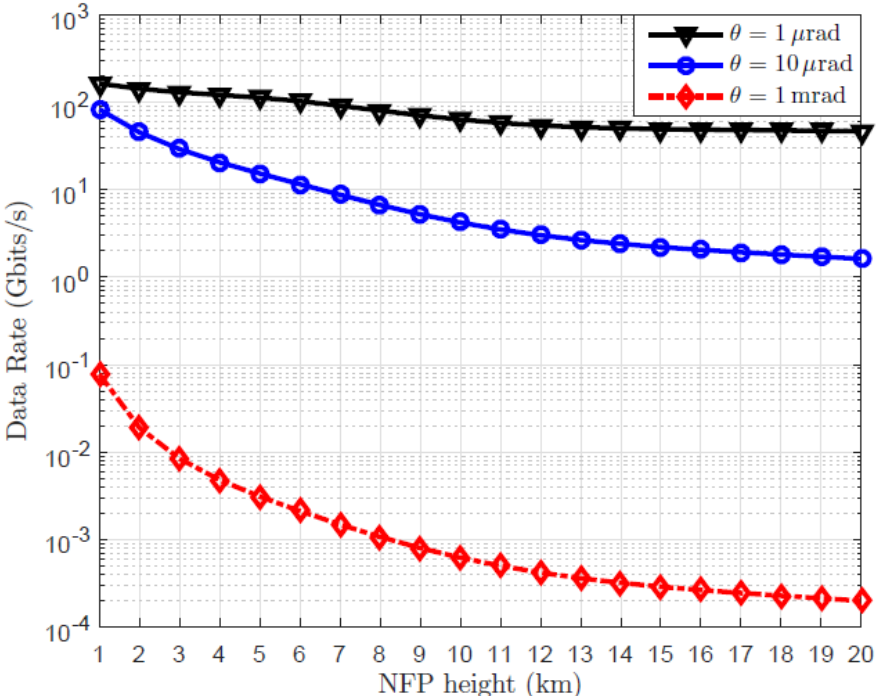
- P_t denotes the transmit power,
- η_t and η_r stand for the optical efficiencies of the transmitter and receiver, respectively,
- L_{poi} is the pointing loss measured in dB, $L_{atm} = L_{rain} + L_{fog} + L_{cloud} + L_{sci}$,
- $E_p = h_p c/\lambda$ denotes the photon energy
- N_b represents the receiver sensitivity in number of photons/bit.

Simulation Results (Data rate and Link Margin under weather conditions)

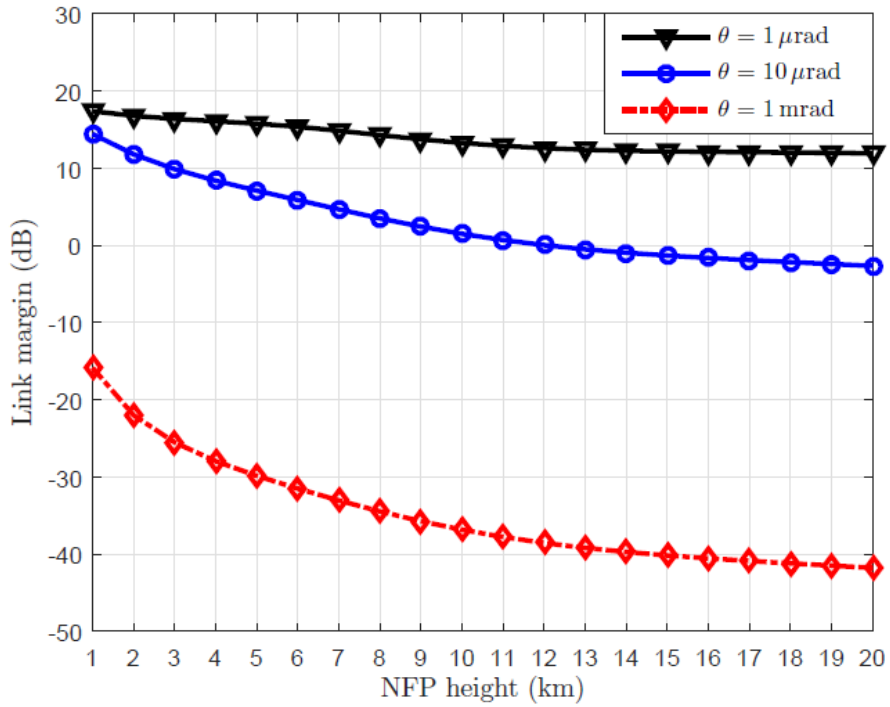




Simulation Results (under Fog and Cloud and varying Divergence angle)



(a) data rate



(b) Link Margin

Favourable Solutions for Vertical Fronthaul under different weather

Weather condition	Favourable Solutions
	• Adaptive transmit power control • Low altitude flights • Systems parameters such as Divergence angle • Hybrid FSO/RF system
	• Low or extreme high altitude flights (less than 5 km or more than 20 km (higher clouds are very thin)) • Site diversity (via multi hope communications between hubs)
	• Hybrid FSO/RF system • Site diversity • Low altitude flights • Increase transmit power Systems parameters such as Divergence angle

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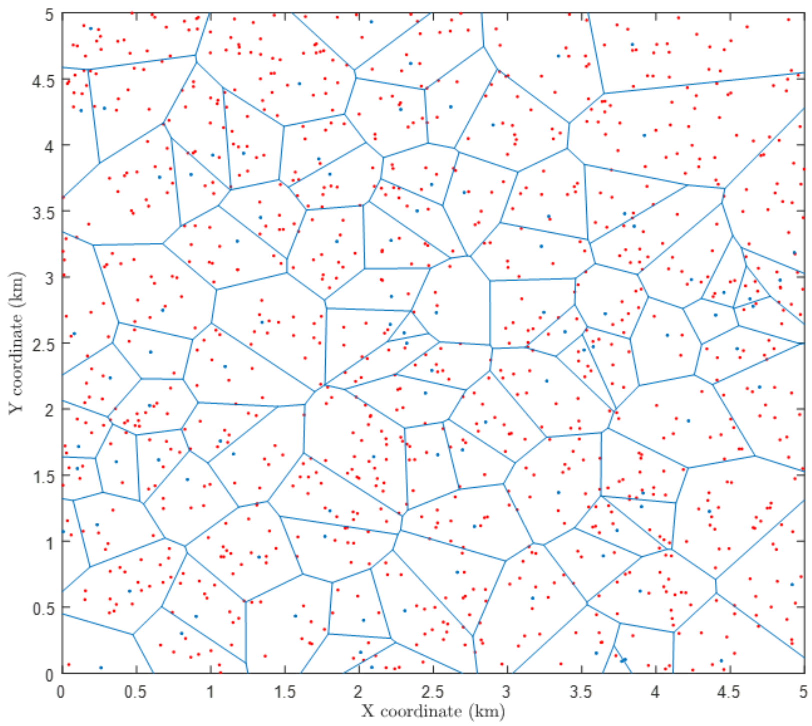
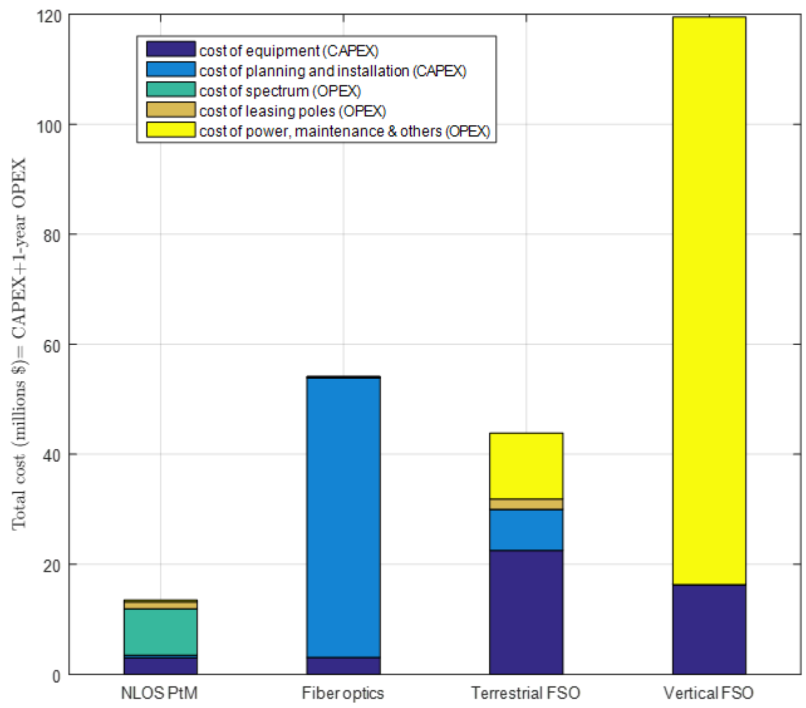
Total Cost of Ownership: Comparison for various backhaul/fronthaul



(a)

A snapshot of the typical Poisson distributed HetNet



(b)

Deployment cost of several backhaul/fronthaul solutions

Network Flying Platforms:

Drone-small cell association problem

NFP-SCs Association

- Design association problem of NFP hubs and SCs
- Consider network centric case - serve maximum possible SCs
- Consider practical constraints
- Present efficient solution to the association problem

S. A. W. Shah, T. Khattab, M. Z. Shakir, M. O. Hasna, "A distributed approach for networked flying platform association with small cells in 5G+ Networks," in Proc. IEEE GLOBECOM'2017, Singapore, Dec. 2017. https://arxiv.org/pdf/1705.03304.pdf

S. A. W. Shah, T. Khattab, M. Z. Shakir, M. O. Hasna, "Association of networked flying platforms with small cells for network centric 5G+ C-RAN," in Proc. IEEE PIMRC'2017, Montreal, Canada, Oct. 2017. https://arxiv.org/pdf/1707.03510.pdf

NFP-Small cell Association Problem formulation

$$\max_{\{A_{ij}\}} \quad \sum_{i=1}^{N_{SC}} \sum_{j=1}^{N_D} A_{ij} \tag{1a}$$

subject to

$$\sum_{i=1}^{N_{SC}} \sum_{j=1}^{N_D} r_{ij} \cdot A_{ij} \leq R \tag{1b}$$

$$\sum_{i=1}^{N_{SC}} b_{ij} \cdot A_{ij} \leq B_j, \qquad \forall j \tag{1c}$$

$$\mathrm{SINR}_{ij} \cdot A_{ij} \geq \mathrm{SINR}_{\min}, \qquad \forall i, j \tag{1d}$$

$$\sum_{i=1}^{N_{SC}} A_{ij} \leq N_{l_j}, \qquad \forall j \tag{1e}$$

$$\sum_{j=1}^{N_D} A_{ij} \leq 1, \qquad \forall i \tag{1f}$$

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Distributed Maximal Cells Algorithm (DMCA)

Step 1

- Every SC creates a list of NFPs that satisfy $\mathrm{SINR}_{\min}$
- Out of the list, each SC selects the NFP such that $\min(b_{ij} + r_{ij})$

Step 2

- Each NFP selects the SCs with $\min(b_{ij} + r_{ij})$
- Before association, NFP validates B_j and N_{l_j} constraints

Step 3

- If R limit has not exceeded and resources are available
- Mother NFP associates the remaining SCs using same rule

Step 4

- If R limit has exceeded
- Mother NFP disassociate the SCs having max. data rate

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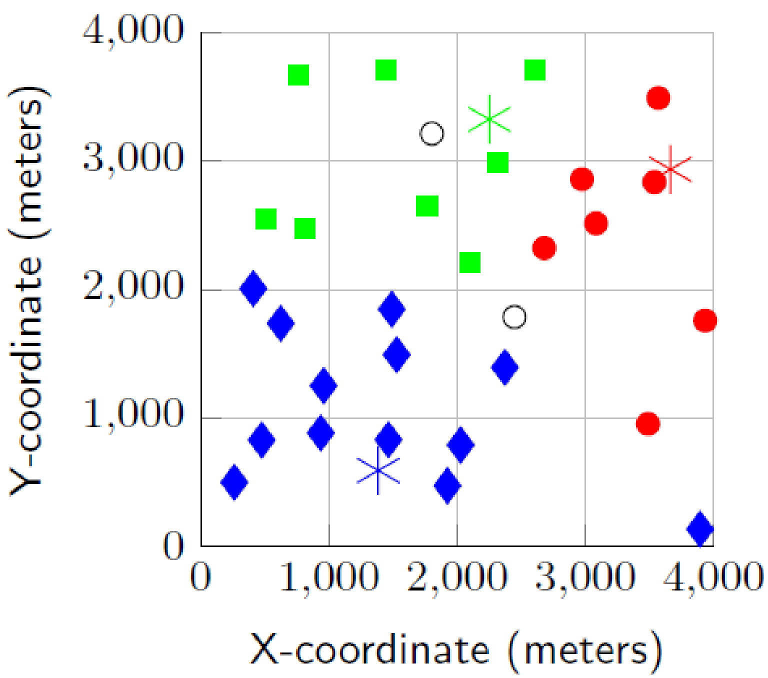
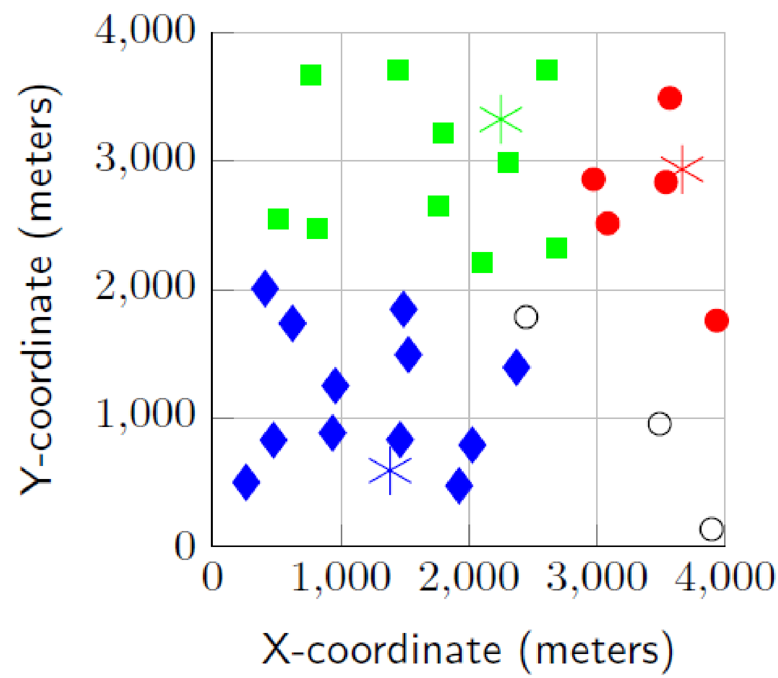
Centralized Maximal Cells Algorithm (CMCA)

- Create a list of NFP-SC links that satisfy SINR constraint
- Out of the list, select the pair such that $\min(b_{ij} + r_{ij})$
- Verify the R, B_j and N_{l_j} constraints and associate
- If B_j and N_{l_j} constraints are not verified then NFP j links are removed from list
- When SC i is associated with NFP j, remaining pairs of SC i are removed from list
- If R is exceeded, process stops

Simulations: NFP-SC Associations



B&B association



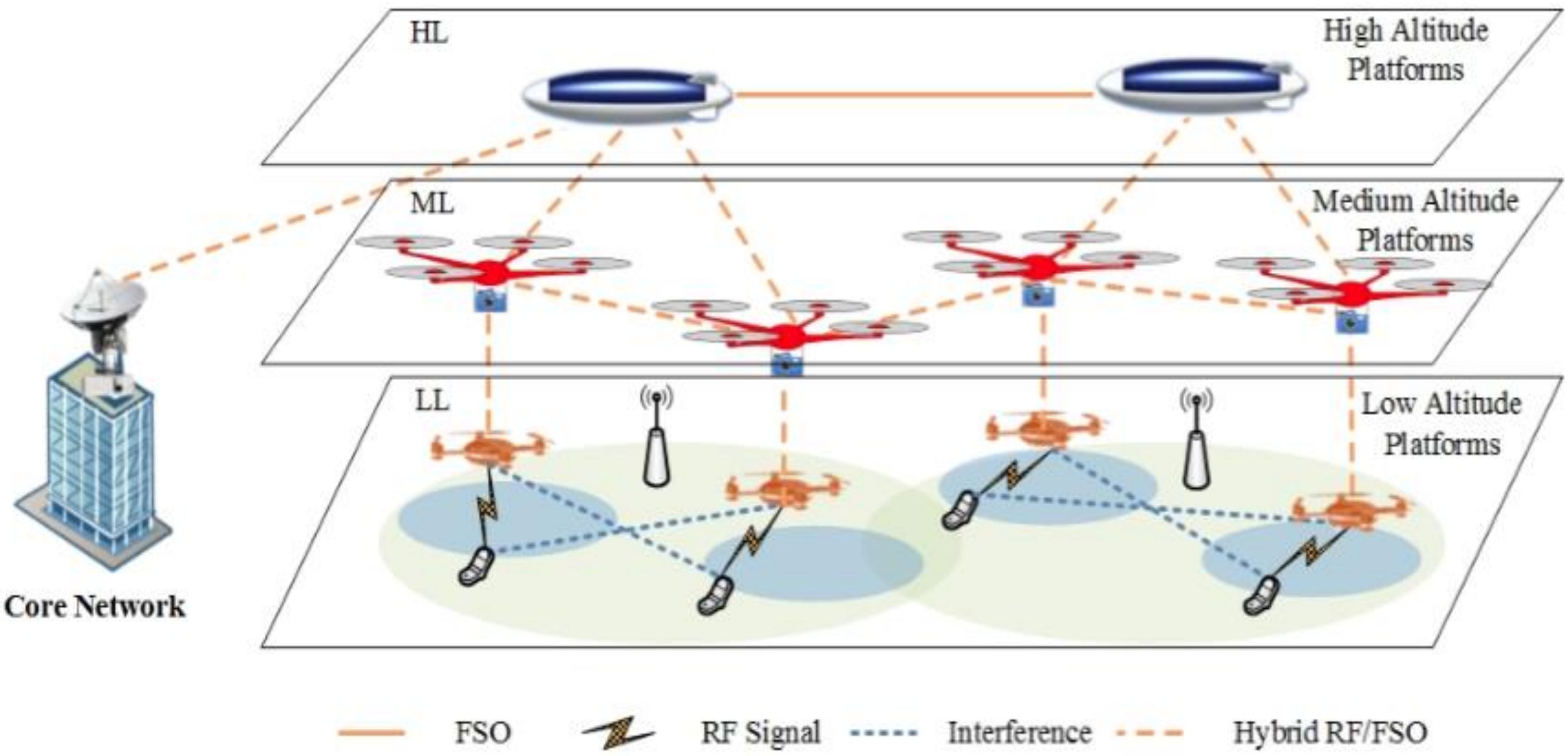
Algorithm DMCA and CMCA association

○ Unassociated SCs ● Associated SCs ✳ NFPs

Network Flying Platforms:

Airborne Self-organising networks

Airborne Self Organising Networks A-SON



Functionalities of Layers

- **Higher Layer (HL)**: NFPs operating in the HL belong to High Altitude Platform (HAP) category and are responsible for **optimizing the resources in transport networks for lower layers.**
- **Medium Layer (ML)**: NFPs in the ML belong to the Medium Altitude Platform (MAP) category and are responsible for r**elaying the network between the lower and higher layer**. NFPs in the medium layer are dual role playing i.e., in addition to relaying, MAPs are performing surveillance to ensure safe and secure operation of the architectures.
- **Lower Layer (LL)**: NFPs operating in the LL are typical low altitude platforms (LAPs**) flying at relatively lower altitudes and responsible for network optimization including NFP placement and association based on resource allocation, interference management, etc.**

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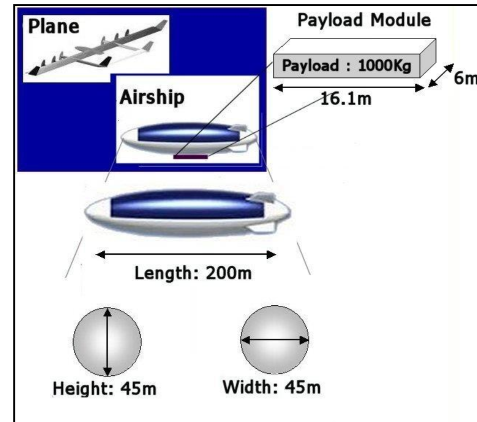
Classification of NFPs

- **HAP:** operate at the HL providing Line of Sight (LOS) connectivity over a wide geographical area (30km radius):
    - planes or airships, manned or unmanned, payload of a few kilograms to a few tones, stay aloft a few hours to a few years providing backhaul and control/fleet coordination services for other aerial platforms at lower layers.
- **MAP:** operate at the ML and can be used as a relay between a HAP and a LAP:
    - *mostly UAVs with long endurance capabilities as well as manned aerial vehicles, can stay airborne for several hours and are usually destined for military missions. MAP coverage area is expected to be of up to 5km radius.*
- **LAP:** tethered balloons, drones, operate at the LL. LAPs provide LOS communications with favorable radio conditions:
    - *have the ability to rapidly deploy a fleet of LAP with modular communication payload capabilities. LAP are optimally distributed to offer capacity and expand coverage via resource and interference management.*



Spoil for choice over platform selection?

Platform Name	AirShip AirPlane AirBaloon AirCopter (S/P/B/C)	Manned Unmanned (M/U)	Max Altitude (approximately) (m)	Platform length (m)	Platform width (Wing Span) (m)	Platform weight (kg)	Range (km)	Max Payload (kg)	Endurance (hrs)
Lower Layer - LAP									
Amazon Drone	C	U	122			25	16	2.26	0.5
Aerovironment Dragon Eye	P	U	150	0.9	1.1	2.7		0.5	0.37
SkyHook (Helikites)	B	U	2286	7.31	5.48		Fixed	40	Tethered
Zepellin-NT	S	M	2600	75	19.5	8790	900	1900	24
MD4-1000 (DHL)	C	U	3000	1.03	1.03	2.9	20	1.2	0.8
Skyship 600 (Charly)	S	M	3050	59	15.2	3757	1019	2343	52
Desert Star (Helikites)	B	U	3352	10.05	6.7		Fixed	100	Tethered
MRI P2006T	P	M	4200	8.7	11.4	850	926	380	6
Protonex	P	U	4250		8.2	50	600	25	9
Medium Layer - MAP									
Schiebel Camcopter S-100	P	U	5486	3.11	1.24	110	180	34	6
ScanEagle	P	U	5944	1.6	3.1	16		7.1	15
Airlander 10	S	M	6100	92	43	20000		10000	504
General Atomics Prowler II	P	U	7600	5	10.75	250	2000	270	48
FOTROS	P	U	7600	6.2	17		2000		30
EADS SDE Eagle 1	P	U	7620	9.3	16.6	1000	1000	250	24
Solar Impulse 2	P	M	8534	22.4	72	2300		408	117
MQ-1 Predator	P	U	8839	8.53	17	1233	400	487	24
Anka - A	P	U	9144	8	17.3	1400	4896	200	24
Silver Arrow Sniper	P	U	9145	9.4	18	1250	200	400	26
Higher Layer - HAP									
IAI Heron	P	U	10000	8.5	16.6	900	350	250	52
Predator B (MQ-9B)	P	U	15000	11	20	2223	1852	1700	14
G520 Strto 1	P	M	16000	13.82	33	3300	3670	1400	8
Northrop Grumman Global Hawk	P	U	18000	14.5	39.9	6781	22779	1360	32
Zephyr 6	P	U	18288		18	30		2.27	30
Aurora Flight Sciences Perseus	P	U	19812	7.62	21.79	1936		99.79	24
Stratobus	S	U	20000	100	30			250	5 years
M-55 Geophysica	P	M	21000	22.86	37.46	13995	4965	7000	6.5
ISIS (Integrated Sensor is Structure)	S	U	21500	137.16				2700	10 years

Optimisation of Airborne SON

- NFP-LL placement to capture maximum UEs can be formulated as:

$$\max \sum_{n=1}^{N} \sum_{u=1}^{U} d_{n,u}$$

$$\text{subject to} \sum_{u=1}^{U} d_{n,u} \leq 1, \qquad \forall n \in \{1, \ldots, N\}$$

$$d_{n,u} = \begin{cases} 1 & RSS_{n,u} > RSS_{-n,u} \\ 0 & otherwise \end{cases} \qquad \forall u \in \{1, \ldots, U\},$$

- where *N* is the number of LAPs in NFP-LL, *U* is the number of UEs, and $d_{n;u}$ is 1 if the u^{th} UE is served by LAP *n*, otherwise it will be zero. $RSS_{n,u}$ denotes the received signal strength of UE *u* from LAP n. $RSS_{n,u}$ denotes the strengths of received signal from other nodes of NFP and the Macrocells, if exists.

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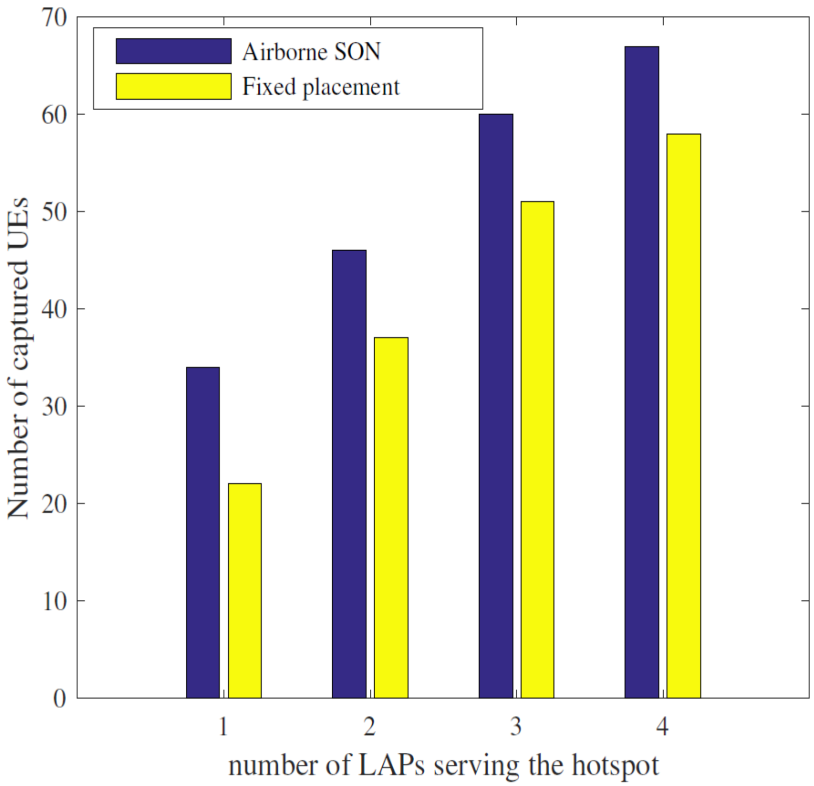
Simulation of LL A-SON

- We modeled an NFP where the LL provides service to a demand hotspot.
- The UEs in the system are served by the macrocell and the NFP-LL assists the macrocell by capturing UEs.
- The NFP optimizes its LL for a given number of LAPs.
- Due to weather conditions, battery failure or surveillance duty the system may lose LAP.



Network Flying Platforms:

Challenges, future directions and some ongoing/past research/trials

Challenges and Future Direction

Although airborne systems have attracted industry and academia's attention in the last couple of years, there still exists several challenges and open research directions:

- **Standardization:** Airborne cellular networks are yet to be standardized. The existing networking standards cannot fully address the challenges of airborne networks and proper standards for airborne communication and networking is required.

- **Surveillance:** Airborne cellular network would offer complementary connectivity services to expand the coverage or inject the capacity under some unknown situations, therefore their successful operation would depend on advanced surveillance mechanisms to detect amateur flying platforms and combat to avoid any further disruption in cellular services.

- **Ethics and privacy:** NFPs and swarm of NFPs may face two-fold challenges in order to comply with regulatory issues related to privacy and ethics. NFPs should be able to protect the privacy of the connected users while following the flying ethics as per regulations and avoiding no-flying zone.

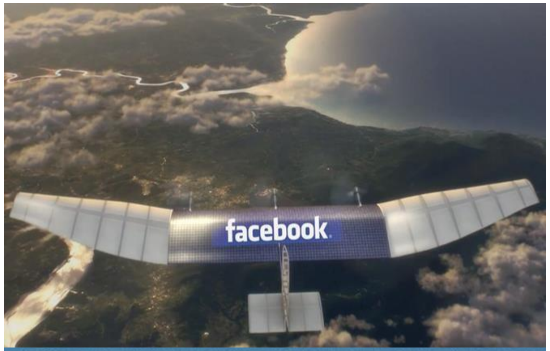
- **Testbed and verification:** Various projects in Europe and United States study and test the performance of future Internet and connectivity architecture, resource allocation techniques, waveforms, and integration of future technologies using advanced testbeds. To the best of our knowledge, none of the existing testbed validation and experimentation provide an environment for testing the proposed airborne SON.

3-Takeaway Points – **it's a blue-sky**

- ➢Hybrid FSO/mm-wave medium should be considered as a potential solution to meet the demands of 5G+ networks using NFP communications.
- ➢Brownfield solution: NFPs can join the key players of 5G communications for immediate impact of the technology with right combination.
- ➢Interdisciplinary research efforts are required to make the story successful. Wind turbulence, regulatory alignments, security/privacy, operational and capital expenses are to be done.

Flying platforms for 5G and Beyond: Some ongoing/past developments

- Sep 2017: Droneway between Isle of Lewis and Mainland by EE.
- Feb 2016: Intel testing drones over AT&T LTE Networks, Verizon starts 5G Trials with Samsung
- Jan 2016: Project Skybender: Google's secretive 5G internet drone tests revealed
- Jul 2015: Facebook launches Aquila solar-powered drone for internet access



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Recent References: NFPs for 5G and Beyond

NFPs for Wireless fronthaul

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Thank You and Questions!

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