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6G:
Hyper-Connecting the Connected & Connecting the Unconnected



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Outline

- What has 5G been and what might 6G be ?
- Some 6G technologies trends
- The global connectivity opportunity & challenge
- A light in digital darkness
- Conclusion

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Moving from 5G to 6G



Growth of Mobile Phone Subscribers & Data Traffic

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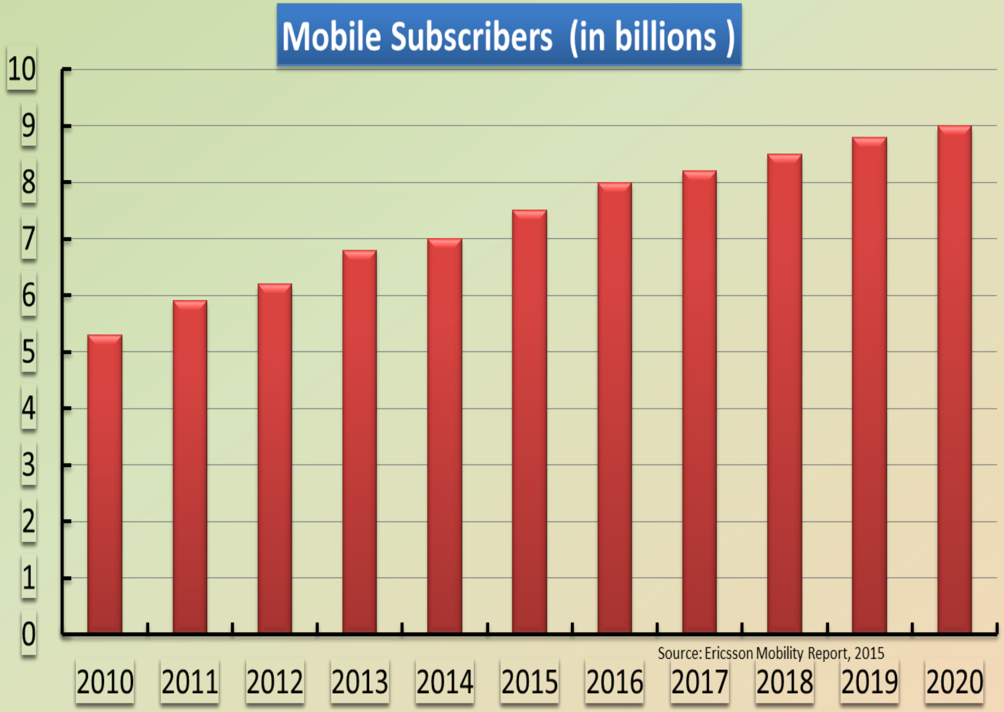
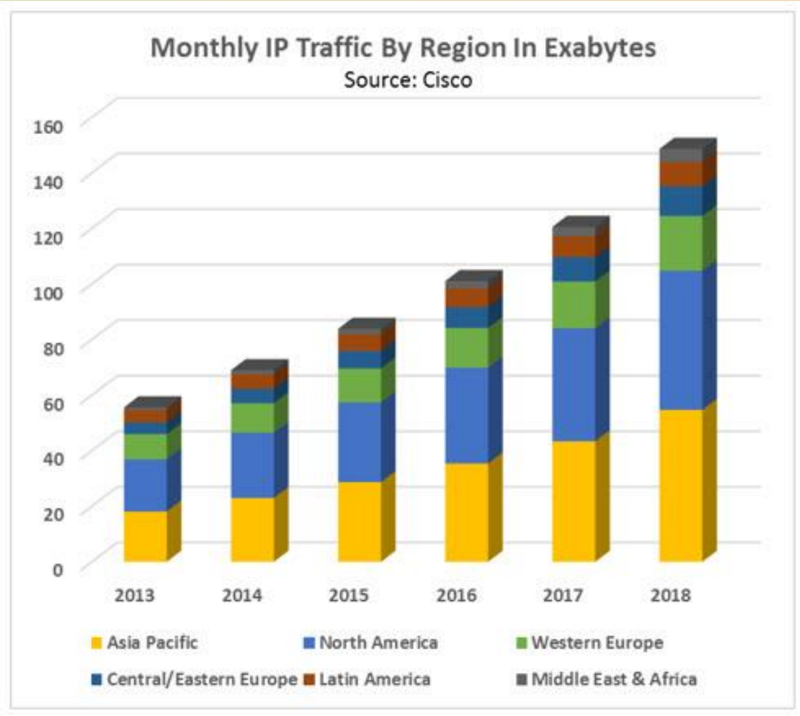


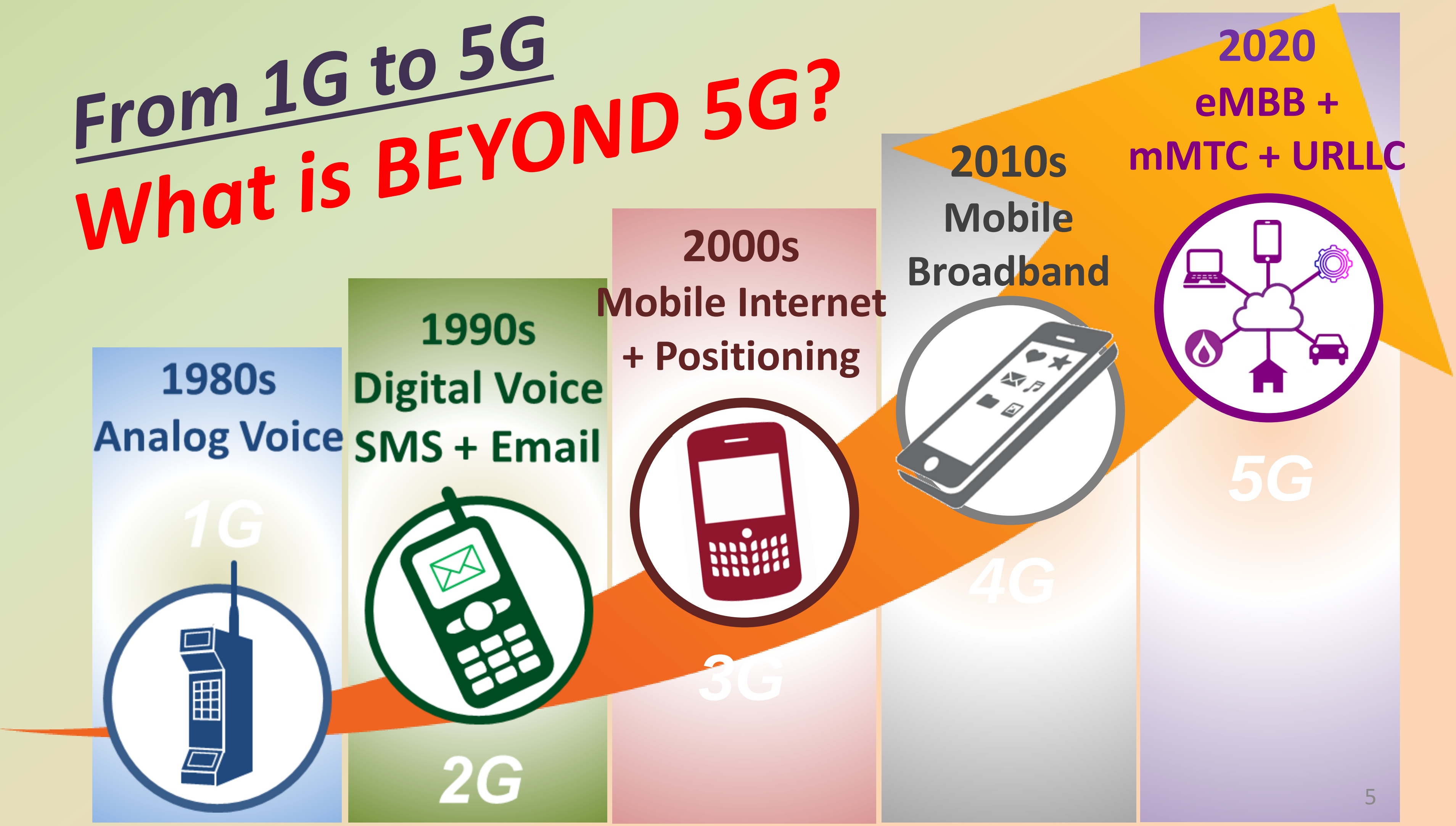


Mobile internet traffic growth is pushing the capacity limits of wireless networks !

Evolution of Generations

From 1G to 5G

What is BEYOND 5G?

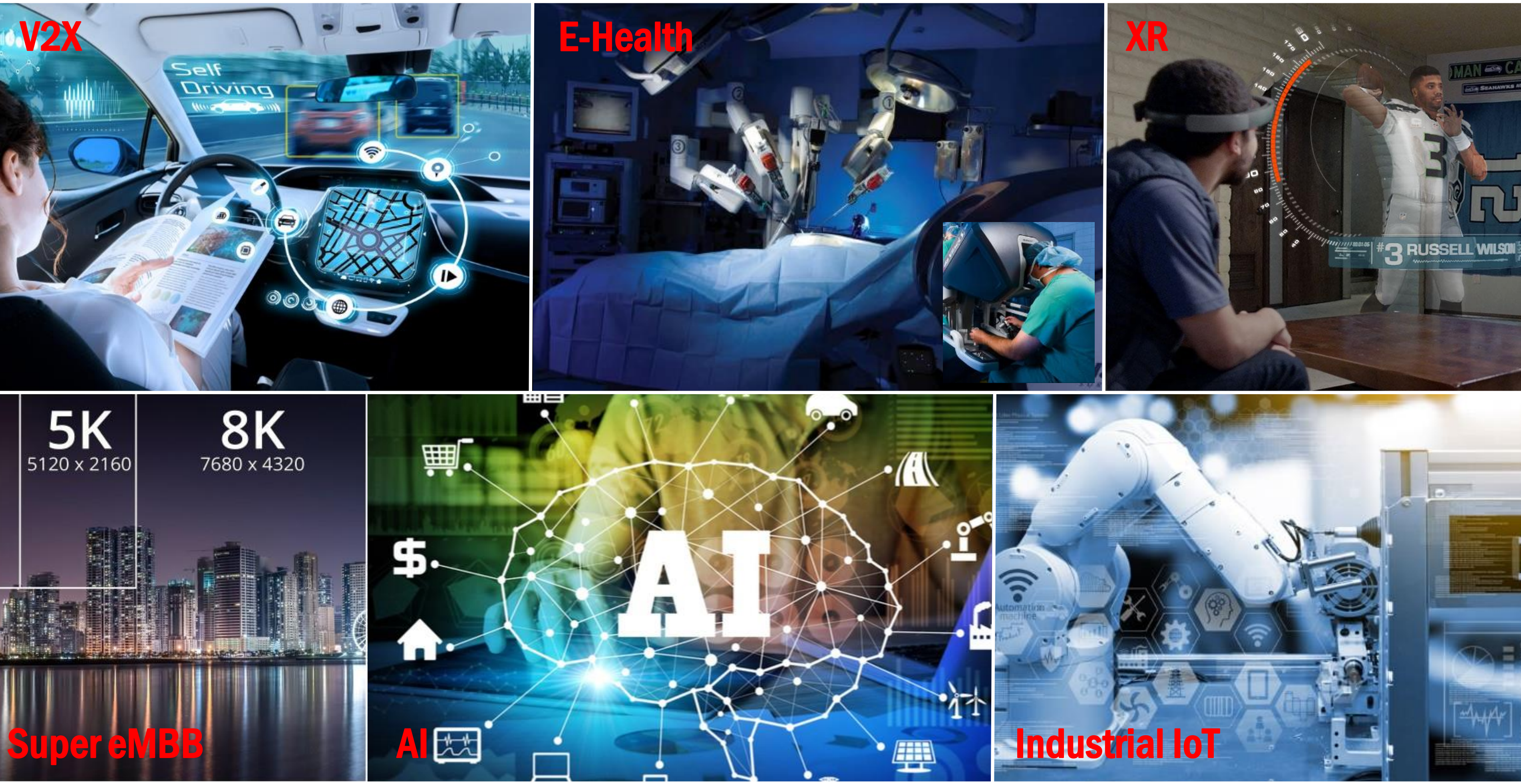


Background of 6G

- Current research progress towards 6G
  - 6Genesis Flagship Program (6GFP)
  - Terabit Bidirectional Multi-user Optical Wireless System (TOWS) for 6G LiFi
  - IEEE Future Network 'Enabling 5G and Beyond'
  - ITU-T Study Group 13: Network 2030
  - NASA: Project Loon
  - LG Electronics/KAIST: 6G Research Centre
  - First 6G Summit in Levi, Finland, March 2019
  - Carleton 6G Workshop, December 2018

  ....

6G Use Cases



S. Dang, O. Amin, B. Shihada, and M. –S. Alouini, "What Should 6G Be?", Submitted for publication (available at: https://www.researchgate.net/publication/332967955_From_a_Human-Centric_Perspective_What_Might_6G_Be and arxiv.org)

Some Trends/Projections

- 8.5 billions by 2030 & 11 billions by 2100
- As of 2018, 55% of the world's population lives in urban areas => expected to increase to 68% by 2050
- By 2030, the world is projected to have 43 megacities with more than 10 million inhabitants

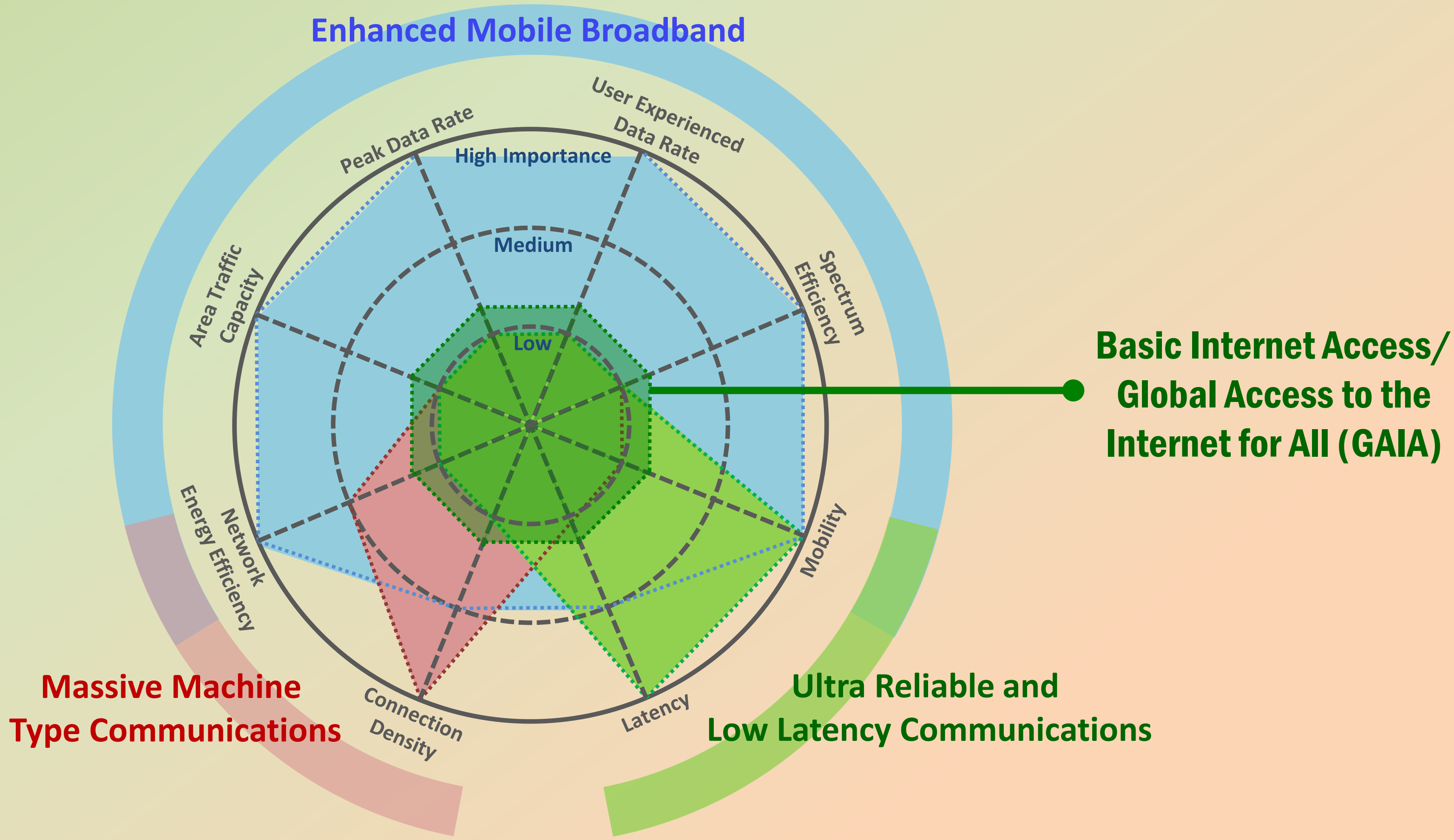
Sustainability Development Goals

- In 2016, the United Nations released 17 Sustainability Development Goals (SDGs) for the 2030 Agenda

SDG & 6G

- SDGs are expected to drive the evolution of 6G
- 6G should target:
  - Improved Efficiency
  - Digital Inclusion
  - More Safety and Security

Extra-User Case: "Basic" Connectivity



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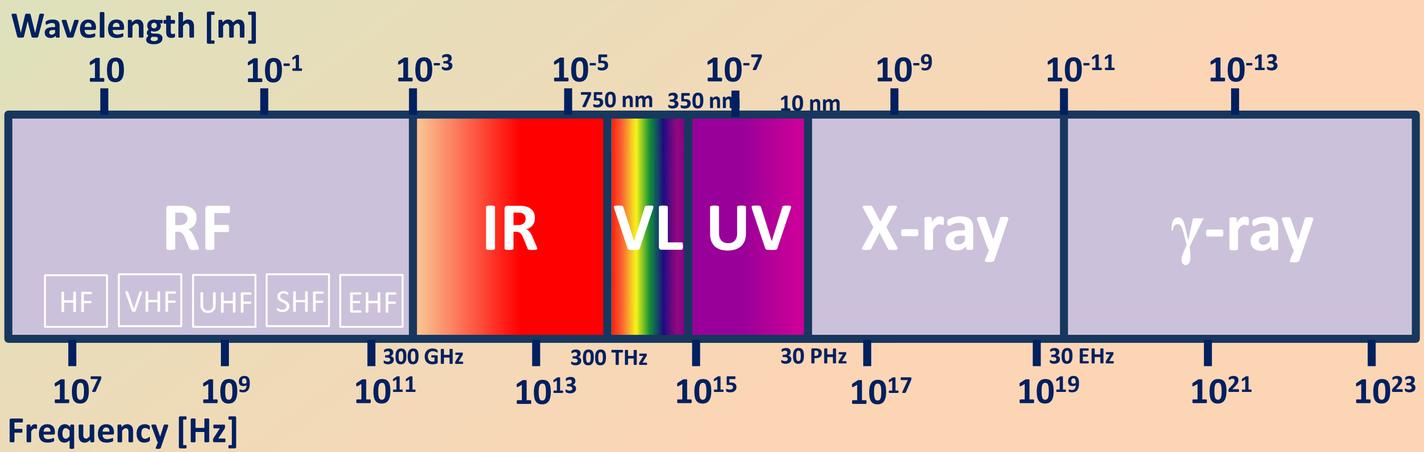
Some 6G Technologies Trends

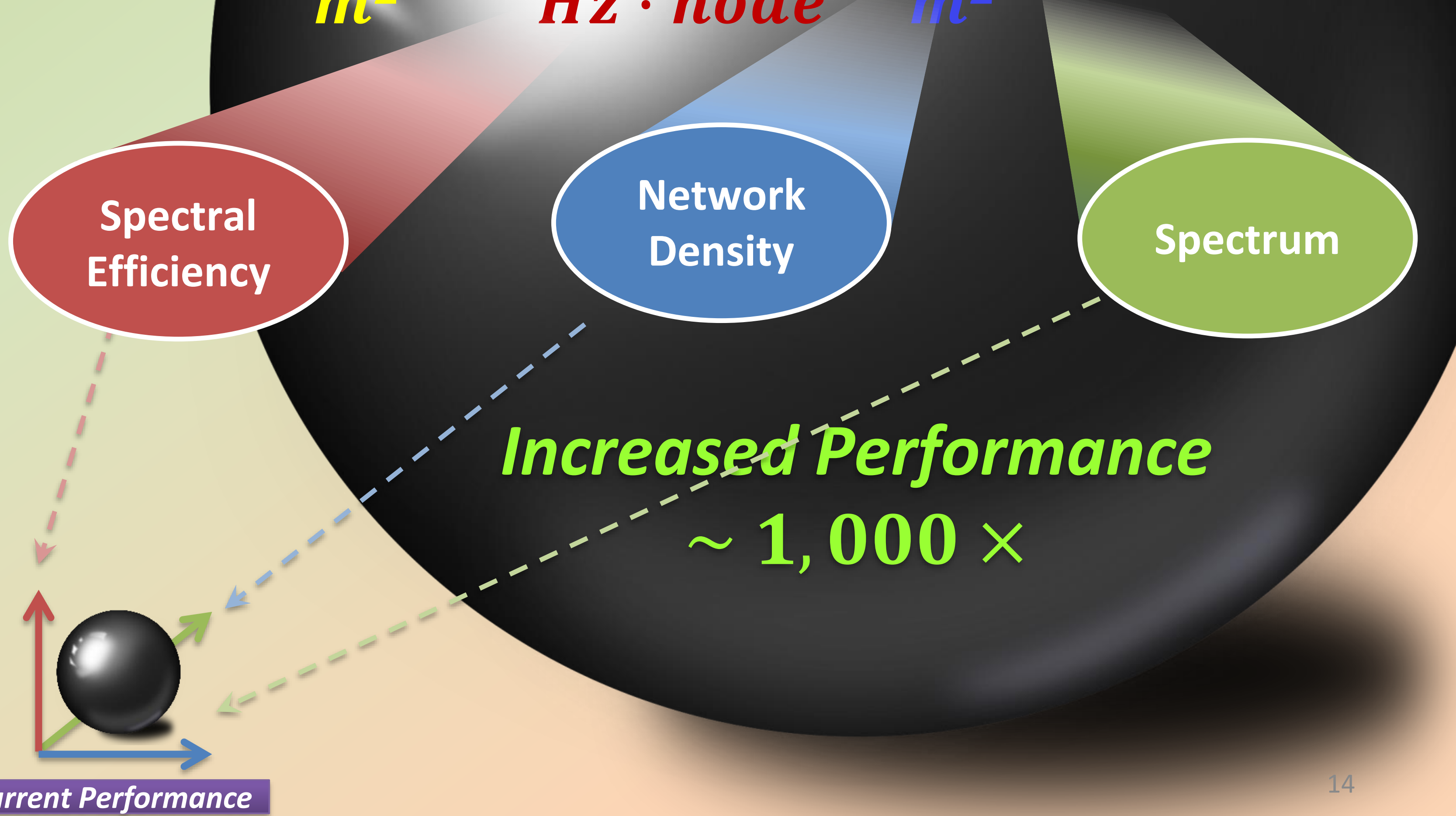
Spectrum

- RF spectrum typically refers to the full frequency range from 3 KHz to 30 GHz.
- RF spectrum is a national resource that is typically considered as an exclusive property of the state.
- RF spectrum usage is regulated and optimized
- RF spectrum is allocated into different bands and is typically used for
  - Radio and TV broadcasting
  - Government (defense and public safety) and industry
  - Commercial services to the public (voice and data)



Increasing the Area Traffic Capacity

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



Potential Enabling Technologies

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

Better Spectral Efficiency	Higher Network Densification	More Spectrum
❑ Massive MIMO	❑ Spectrum Sharing	❑ Carrier Aggregation
❑ Artificial Radio Space	❑ Cloud-RAN	❑ Mm-Wave (60GHz)
❑ Interference Management	❑ Small Cells	❑ THz Com
❑ Full Duplex Radio	❑ D2D	❑ Optical Wireless Com

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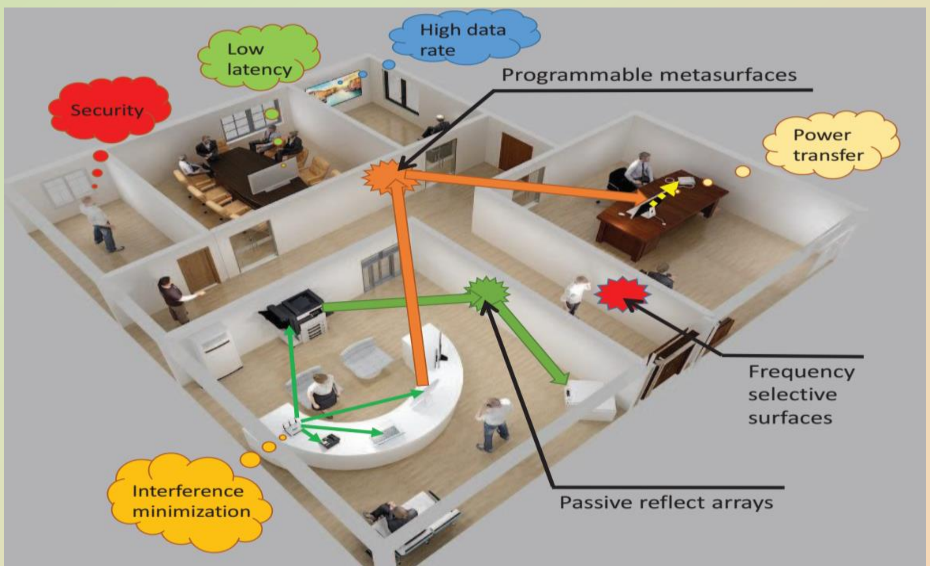
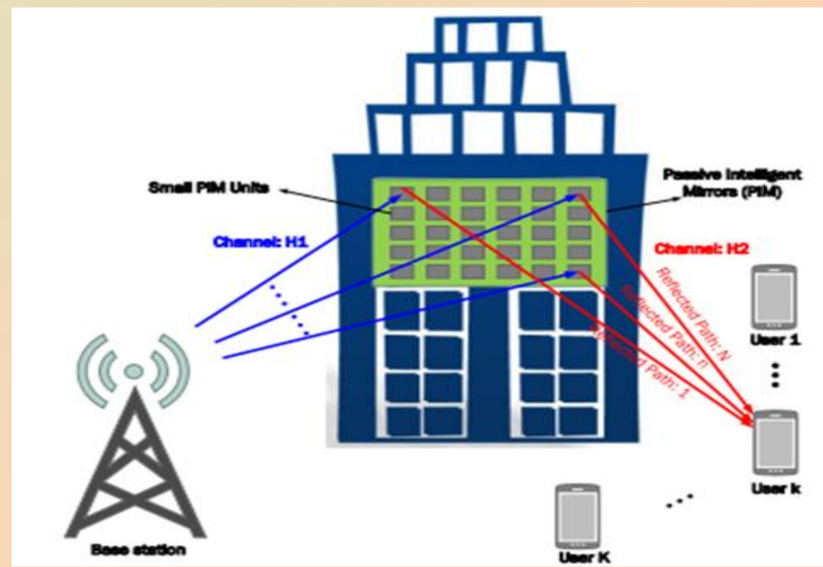
Smart Radio Spaces



Artificial Radio Space

- A new concept to assist reliable, secure, spectrum- and power-efficient communications in indoor and outdoor scenarios
- Using a metal/metamaterial surfaces or tunable reflect arrays consisting of low-cost low-power-consuming passive/active reflecting elements
- To make the propagation channel more favorable to satisfy various QoSs
- Easily placed in/on the wall/ceilings of the buildings





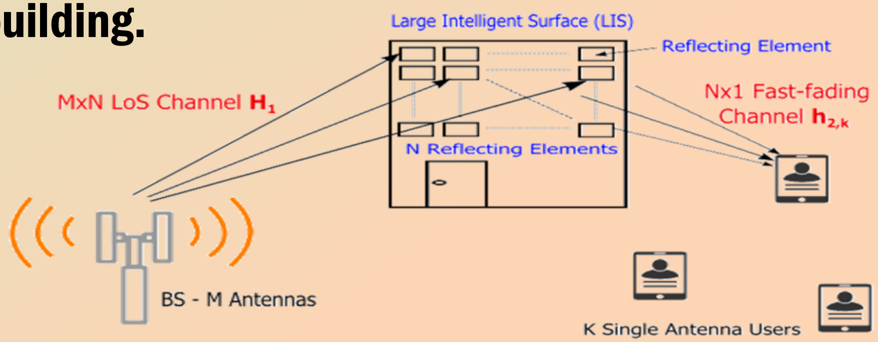
[1] C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, and I. Akyildiz, "A new wireless communication paradigm through software-controlled metasurfaces," *IEEE Commun. Mag.,* vol. 56, no. 9, pp. 162–169, Sep. 2018
[2] C. Huang, A. Zappone, M. Debbah, and C. Yuen, "Achievable rate maximization by passive intelligent mirrors," in *2018 IEEE ICASSP*, Calgary, Canada, Apr. 2018, pp. 3714–3718.

Reconfigurable Intelligent Surface (LIS) Assisted Wireless Communication

- A very new concept [2], [3], with the potential of significantly reducing the energy consumption of wireless networks while realizing Massive MIMO gains.
- Base station (BS) communicates with the users through a LIS.
- LIS is a planar array consisting of a large number of nearly passive, low-cost and low energy consuming, reflecting elements, with reconfigurable parameters.
- Each element induces a certain phase shift on the incident electromagnetic wave.
- Objective is to make the propagation channel more favorable for the users.
- Can be easily integrated into the walls of the building.

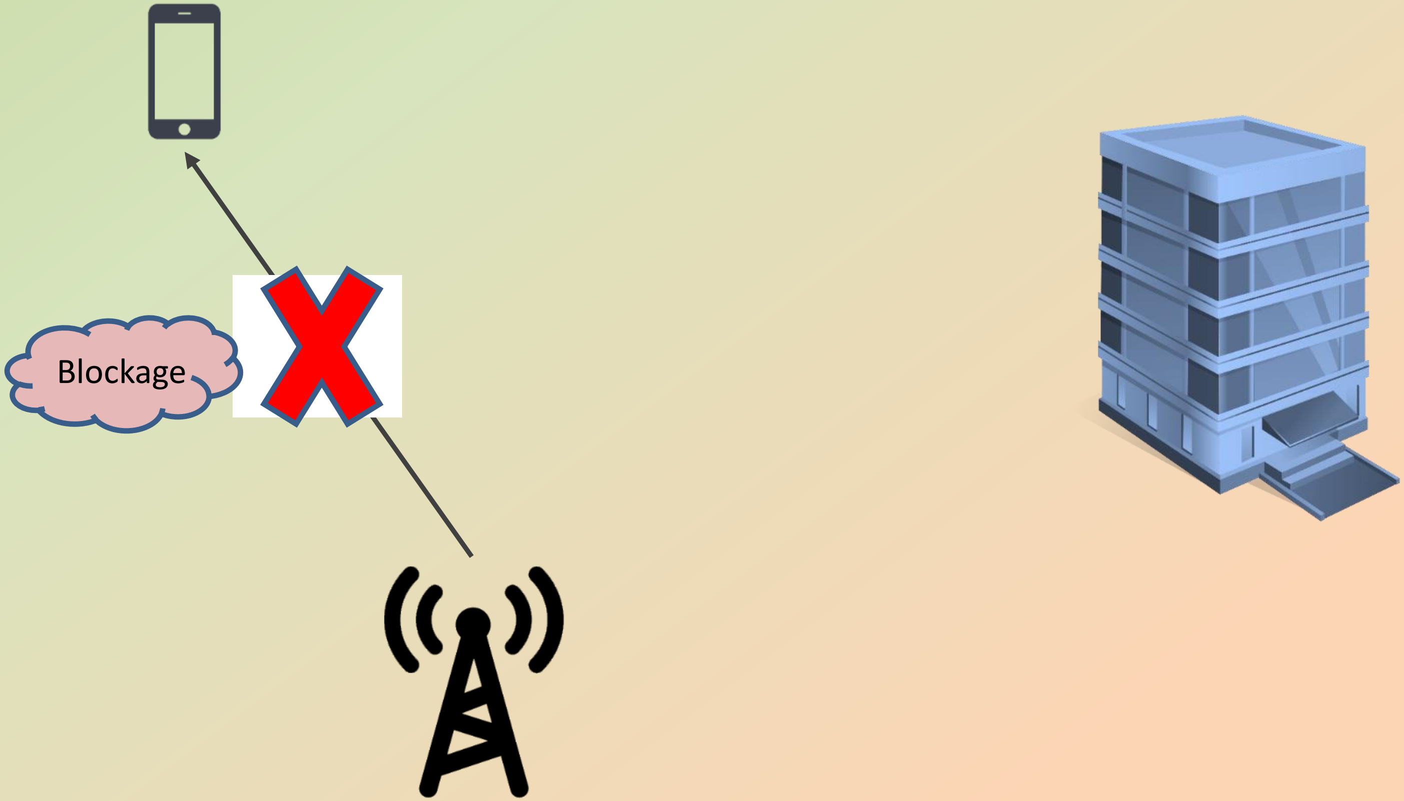
Current implementations:

- Reconfigurable reflect arrays,
- Liquid crystal metasurfaces,
- Programmable metamaterials.



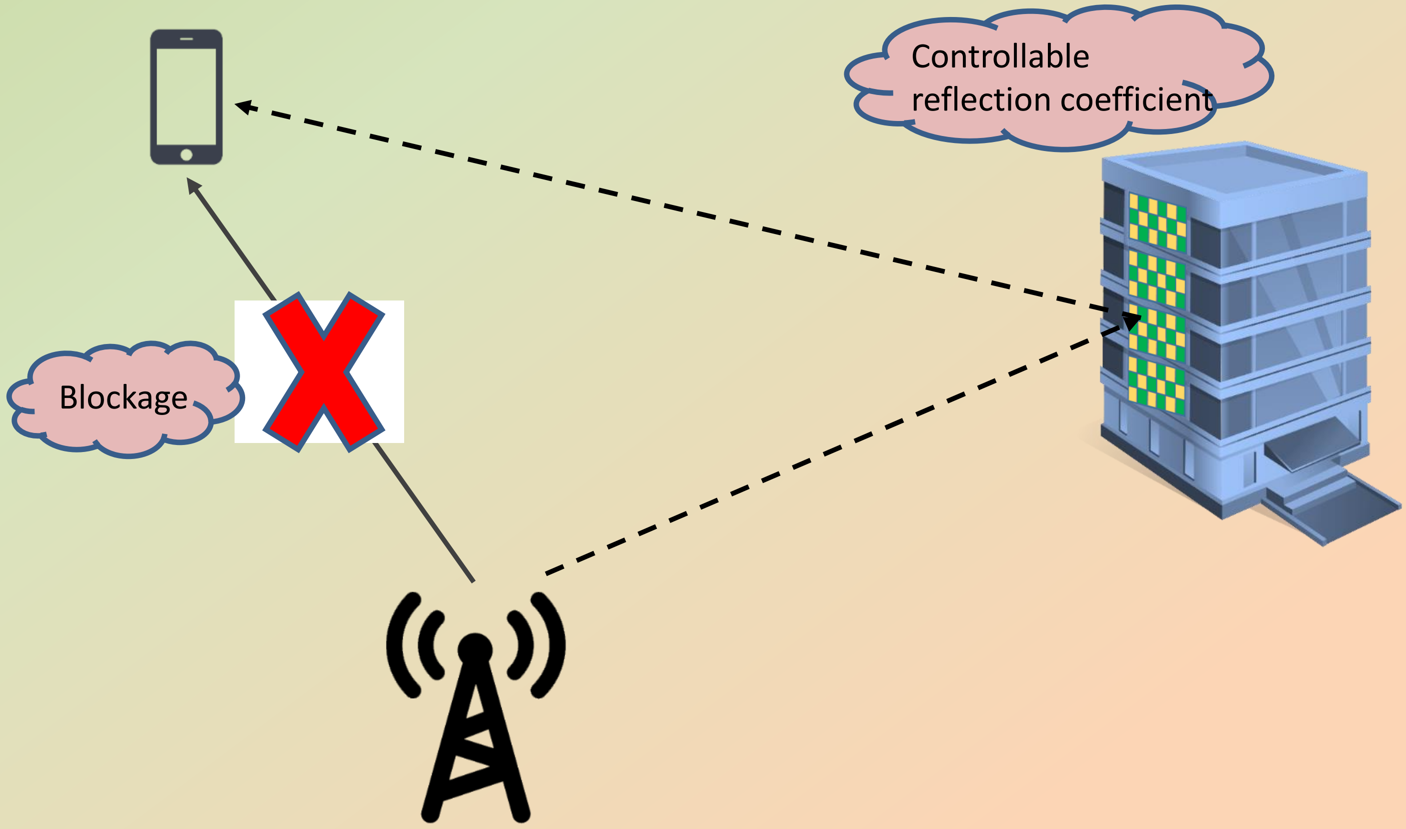
[3] M. Di Renzo, *et al.* "Smart radio environments empowered by AI reconfigurable meta-surfaces: An idea whose time has come", EURASIP Journal on Wireless Communications and Networking, 2019.
[4] Q. U. Nadeem, A. Kammoun, A. Chaaban, M. Debbah, and M. -S. Alouini, "Intelligent reflecting surface assisted multi-user MISO communication", IEEE Wireless Communications Magazine, Under Review.

Reconfigurable Intelligent Surfaces



M. Di Renzo, M. Debbah, D.-T. Phan-Huy, A. Zappone, M.-S. Alouini, C. Yuen, V. Sciancalepore, G. C. Alexandropoulos, J. Hoydis, H. Gacanin, J. de Rosny, A. Bounceur, G. Lerosey, and M. Fink, ‘‘Smart radio environments empowered by reconfigurable AI meta-surfaces: An idea whose time has come,’’ EURASIP J. Wireless Commun. Netw., 2019.

Reconfigurable Intelligent Surfaces



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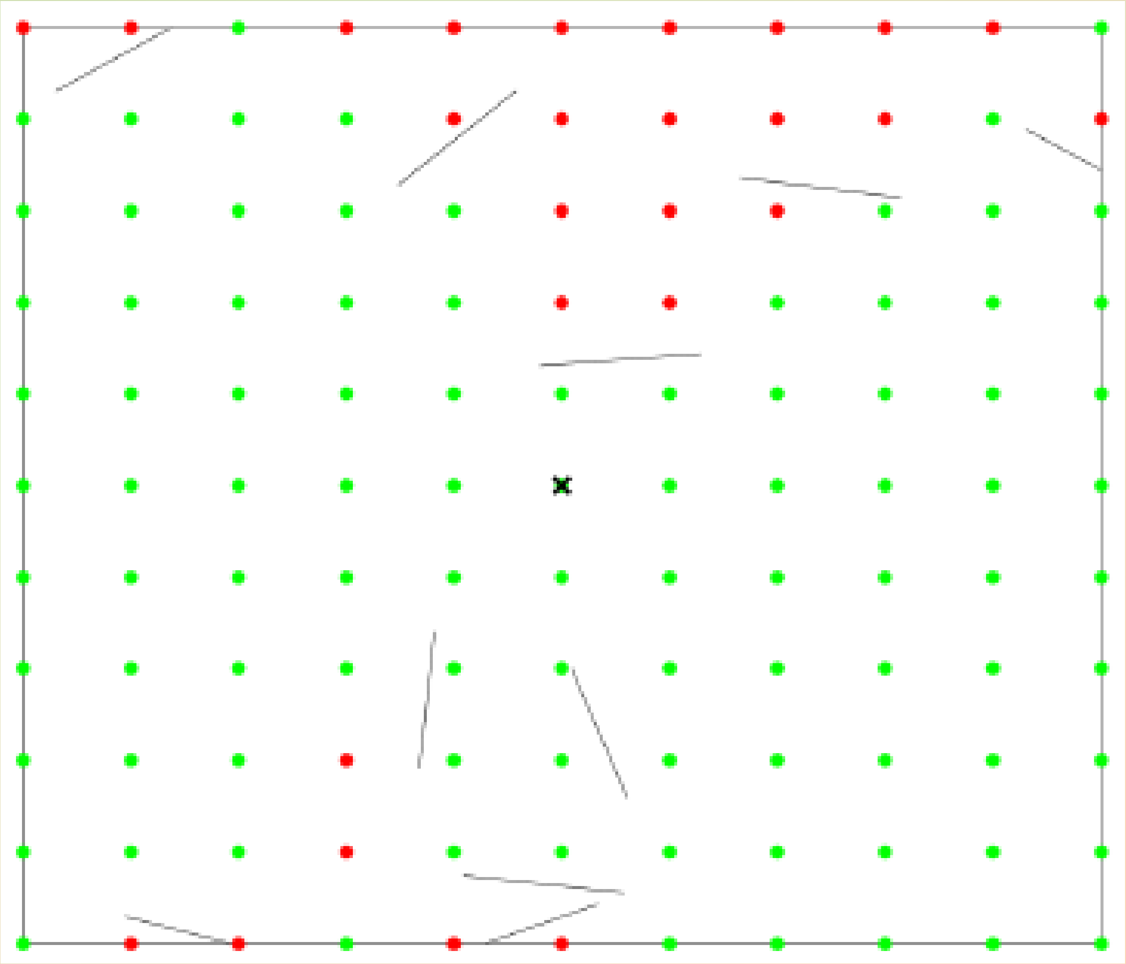
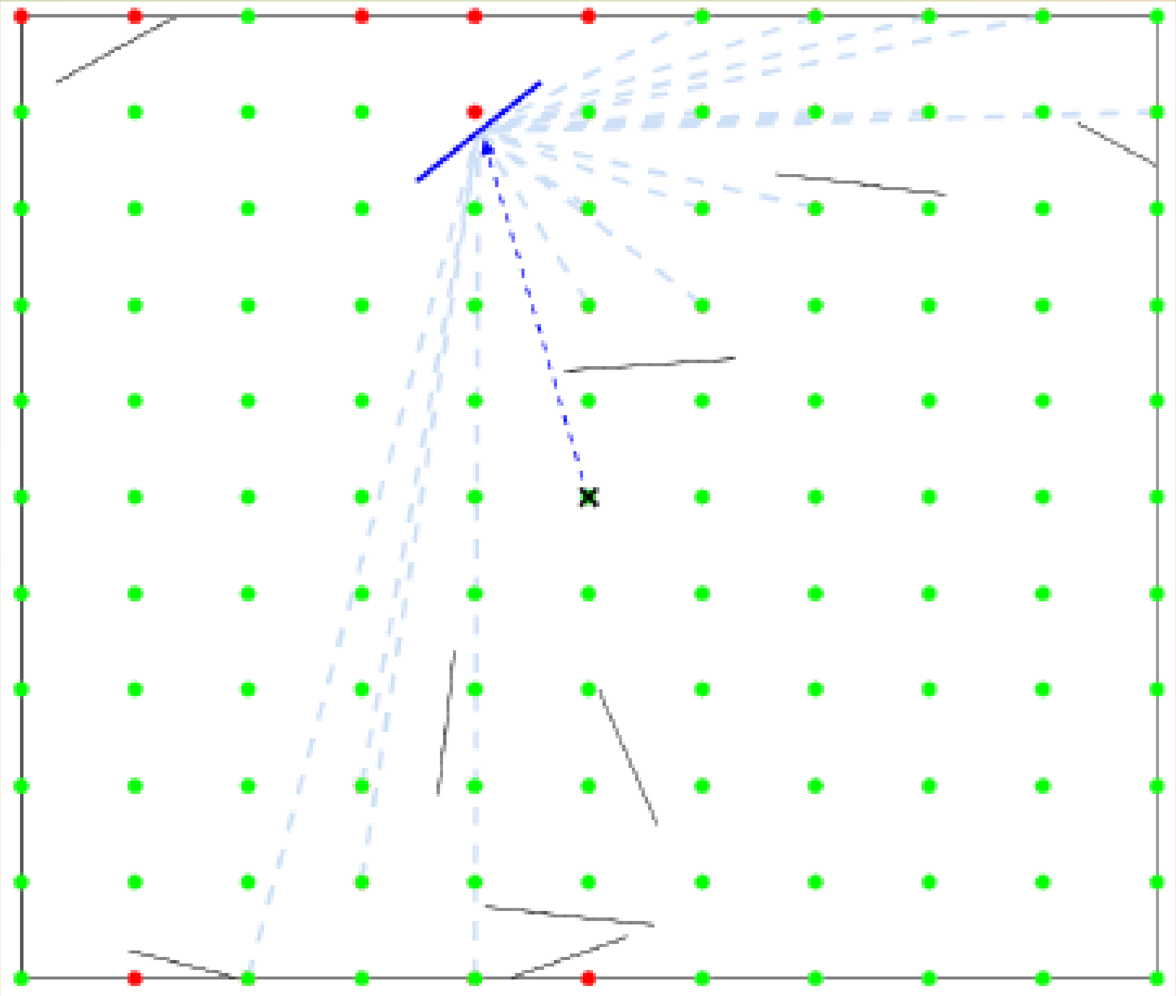
- **Potential Advantages:**
  - **Coverage for what was once unreachable (Not-Spots).**
  - **Interference cancellation.**
  - **Physical layer security enhancement.**

M. Di Renzo, M. Debbah, D.-T. Phan-Huy, A. Zappone, M.-S. Alouini, C. Yuen, V. Sciancalepore, G. C. Alexandropoulos, J. Hoydis, H. Gacanin, J. de Rosny, A. Bounceur, G. Lerosey, and M. Fink, ''Smart radio environments empowered by reconfigurable AI meta-surfaces: An idea whose time has come,'' EURASIP J. Wireless Commun. Netw., 2019.

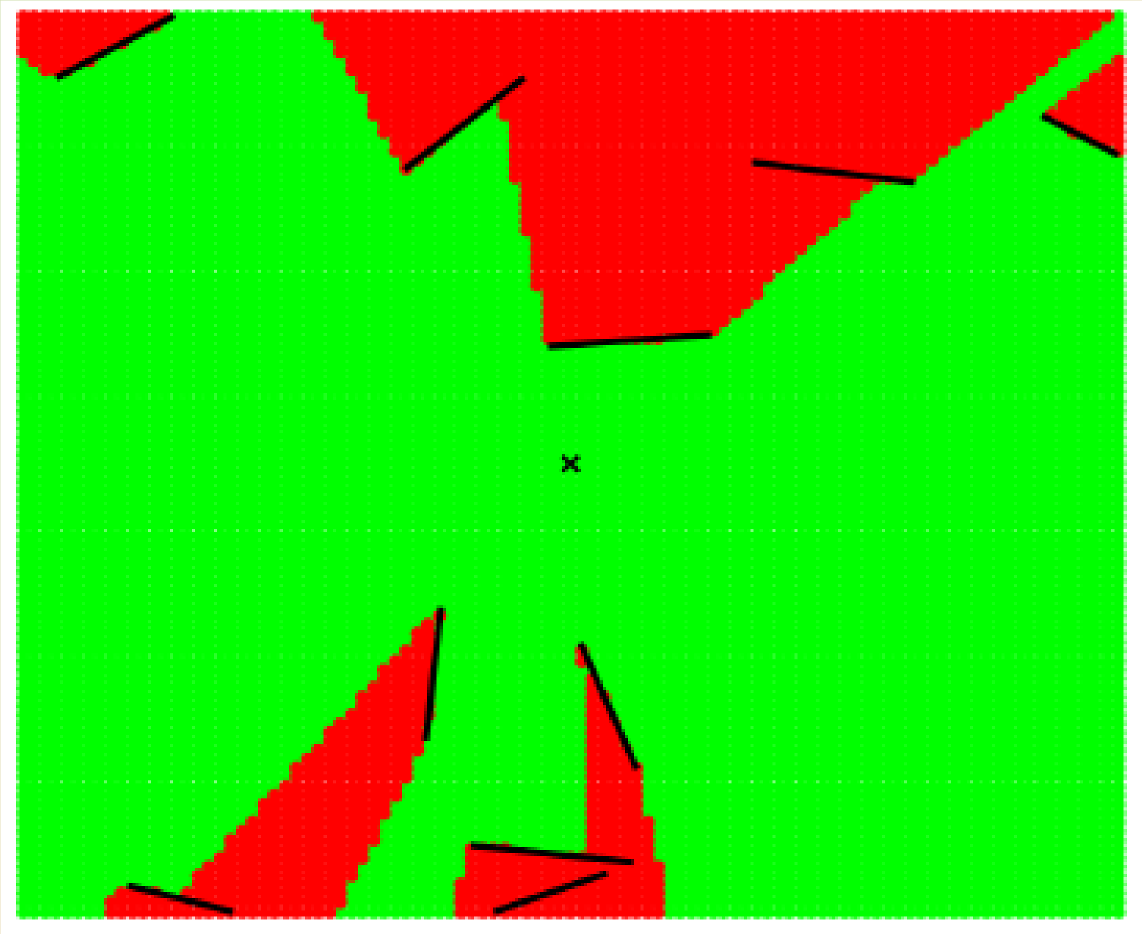
Elaborative Example (Before)



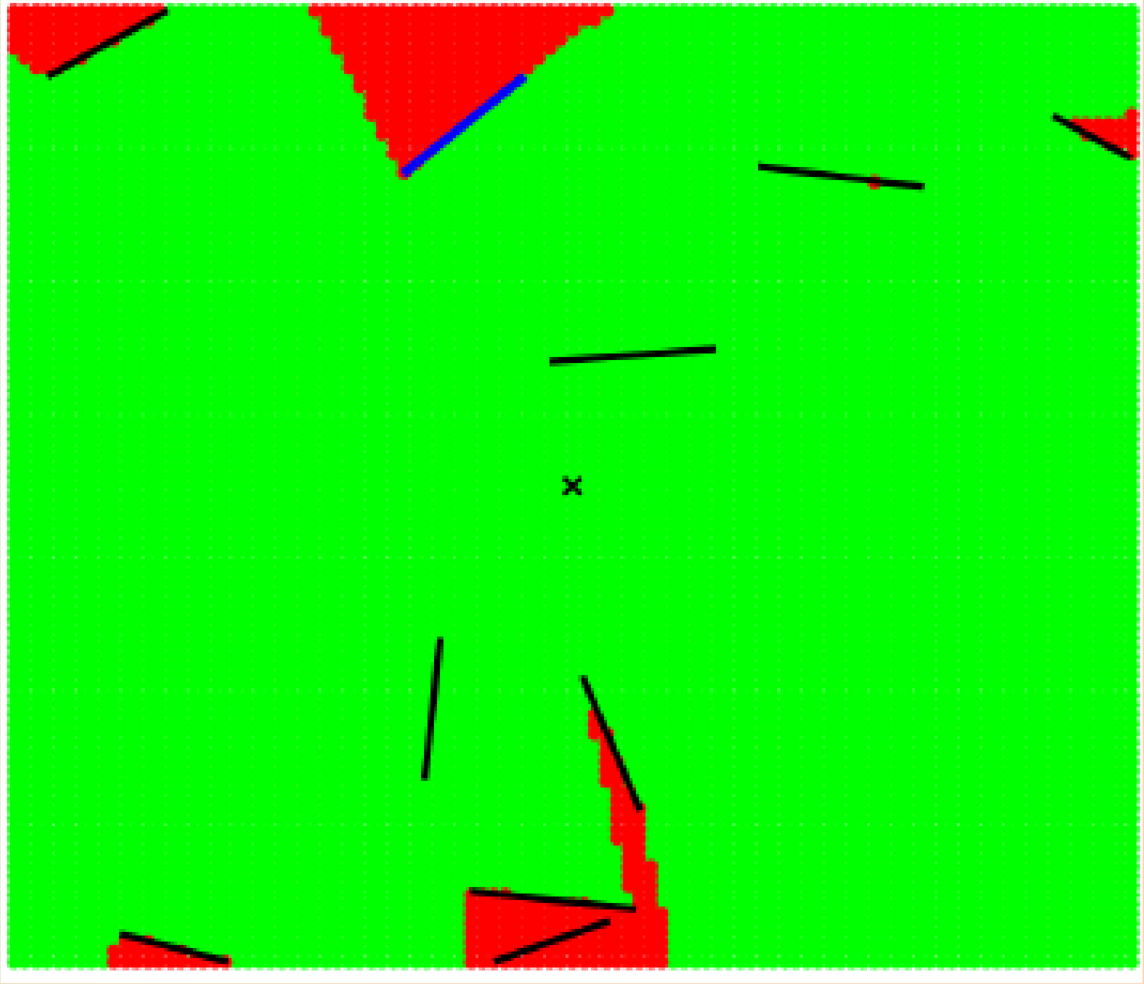
Elaborative Example (After)



Coverage (Before)

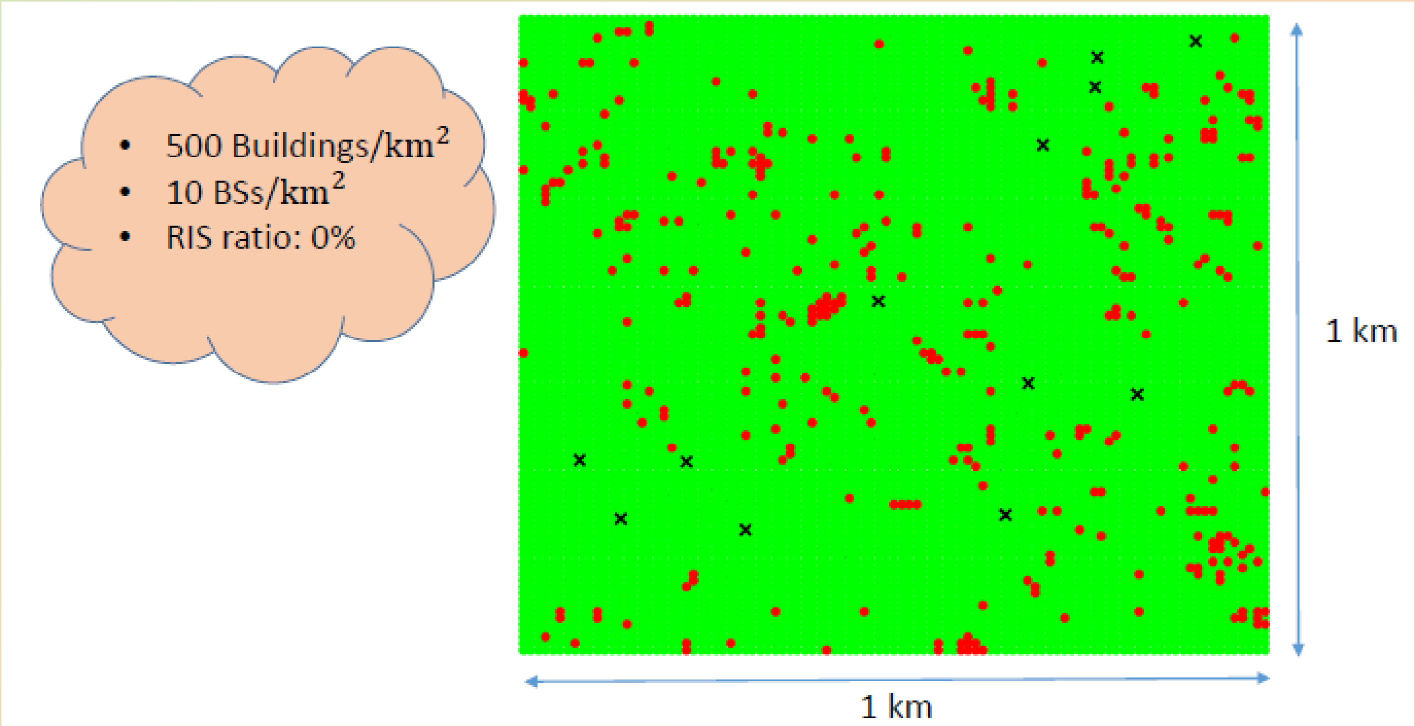


Coverage (After)



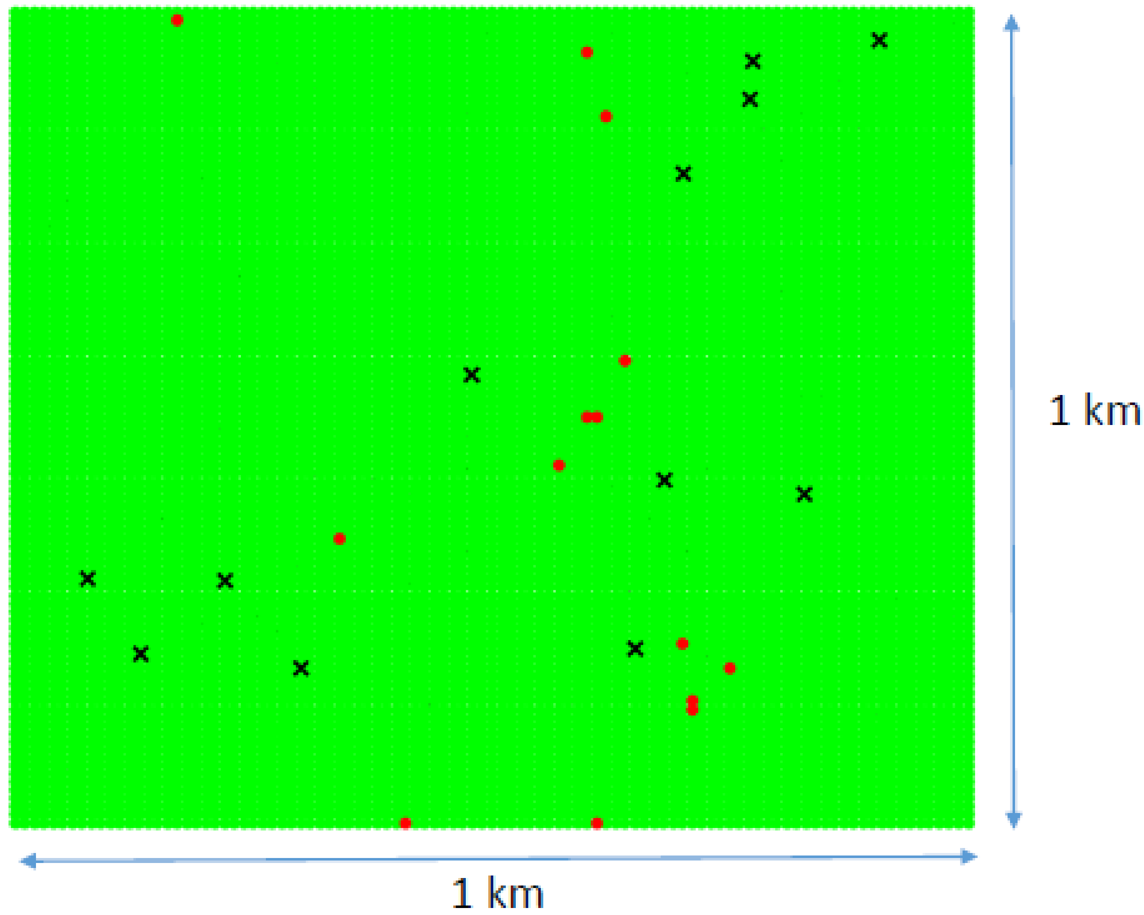
Some Questions of Interest

- Observation:
  - Location of the RIS and its orientation highly affect its influence on the performance of the wireless network.
- Questions:
  - What is the optimal set of buildings/objects to be selected for RIS deployment ?
  - What is the optimal ratio of buildings that need to be equipped with RIS ?



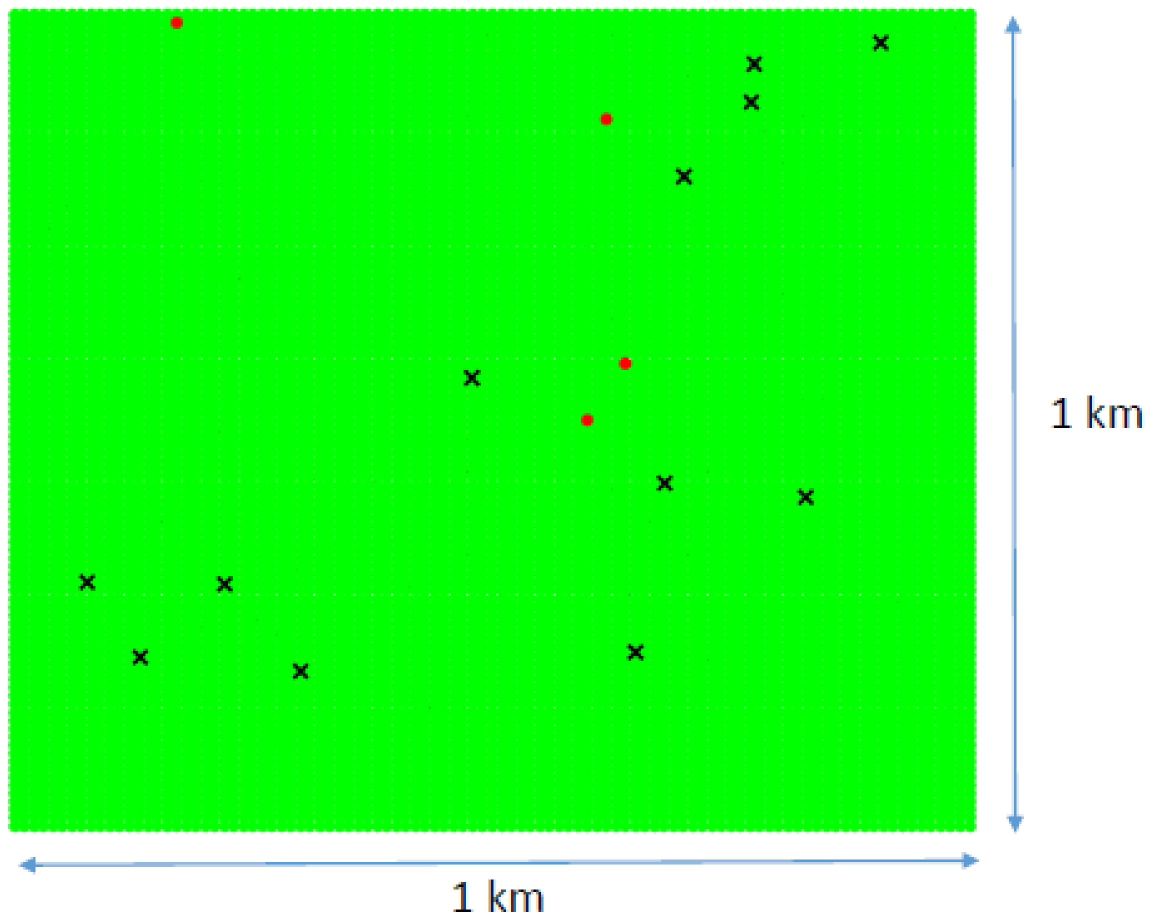
RIS Ratio (5 %)

- 500 Buildings/km^2
- 10 BSs/km^2
- RIS ratio: 5%



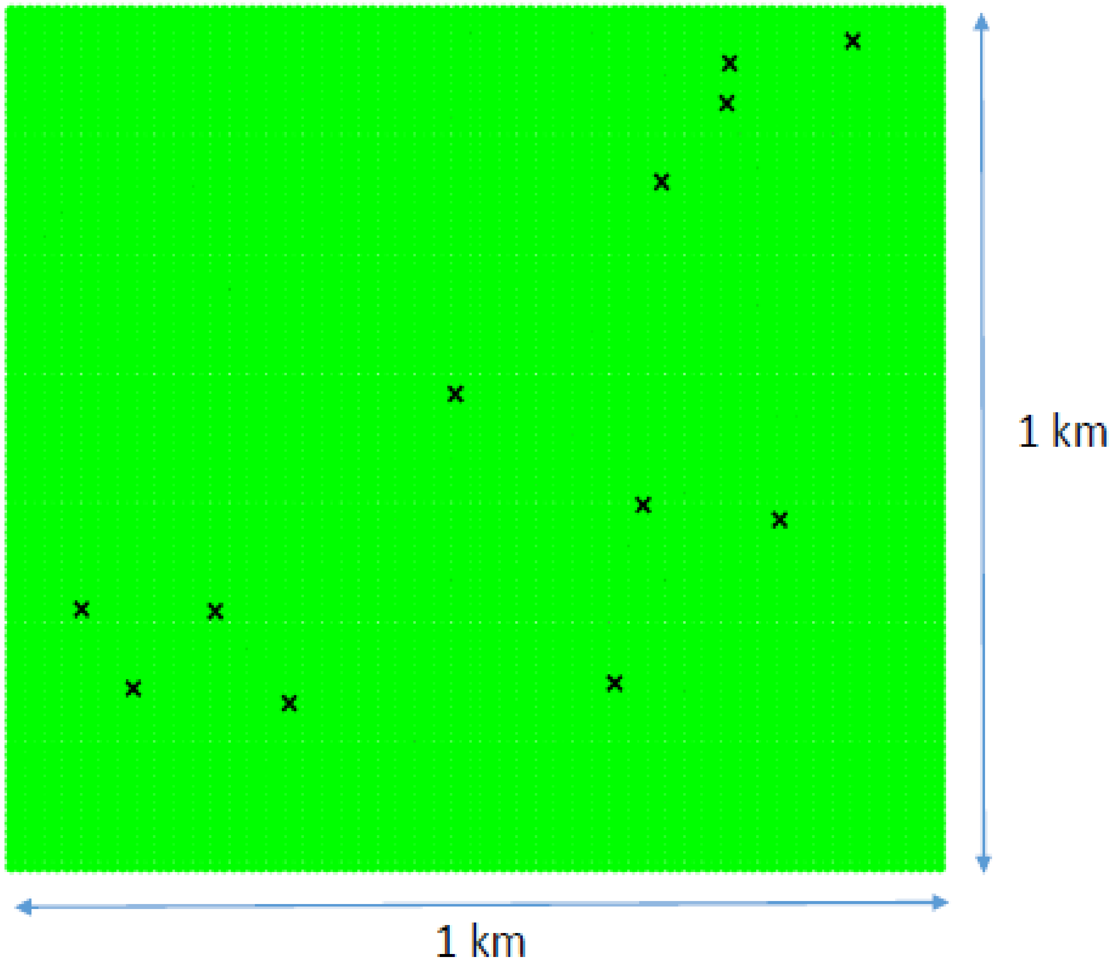
RIS Ratio (10 %)

- 500 Buildings/km^2
- 10 BSs/km^2
- RIS ratio: 10%

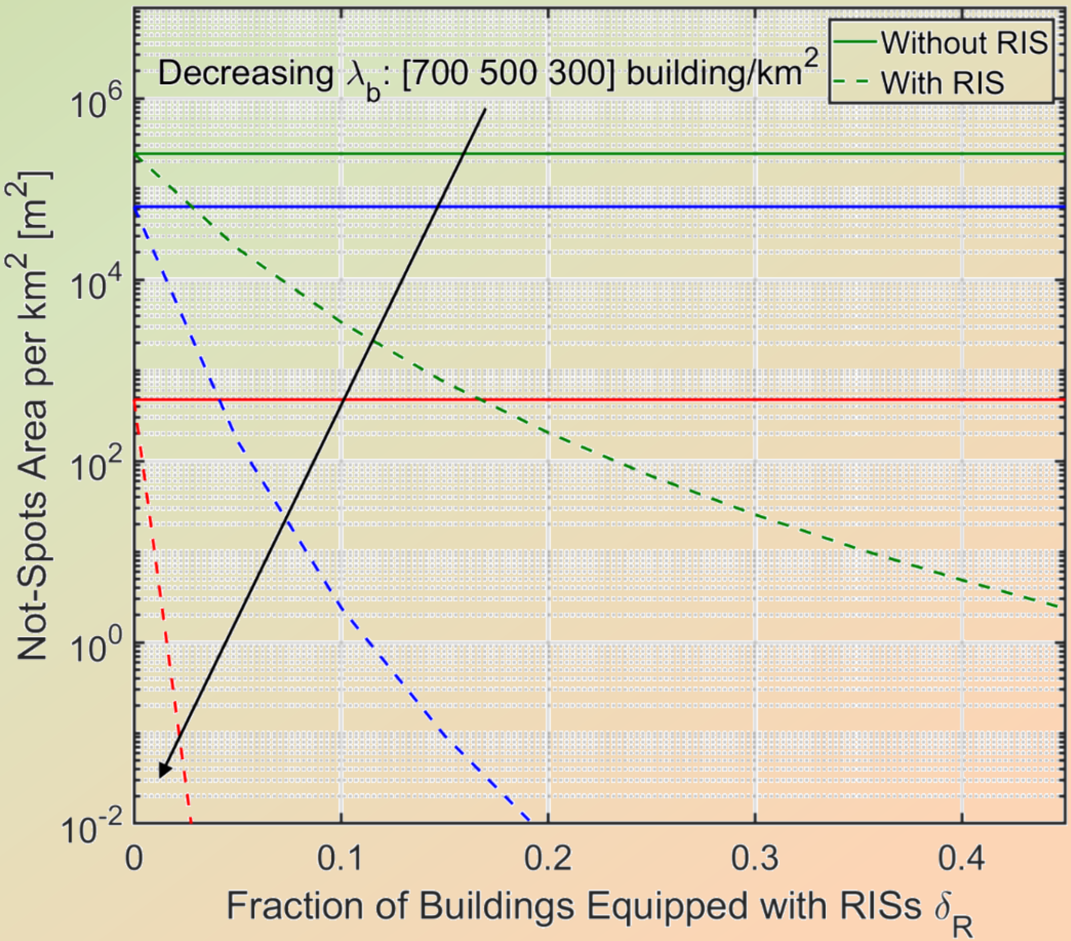


RIS Ratio (40 %)

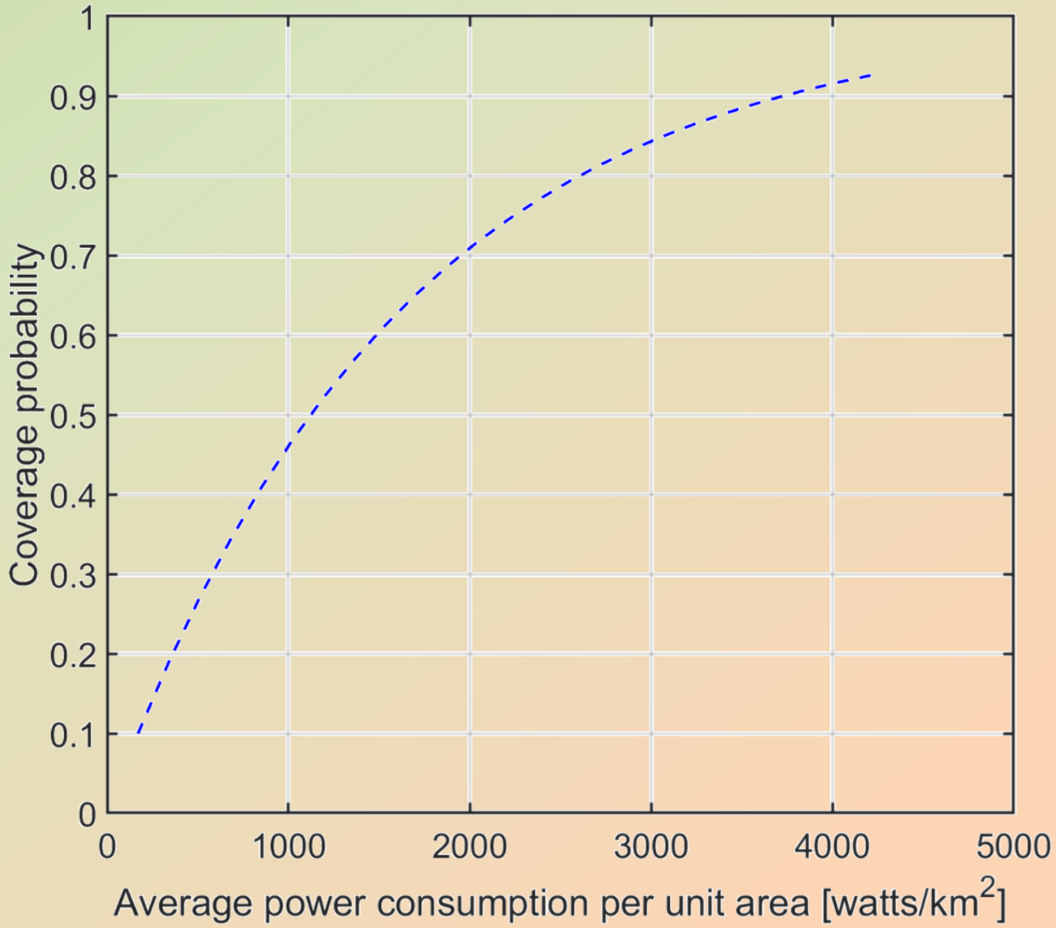
- 500 Buildings/km^2
- 10 BSs/km^2
- RIS ratio: 40%



Reduction of Not-Spots

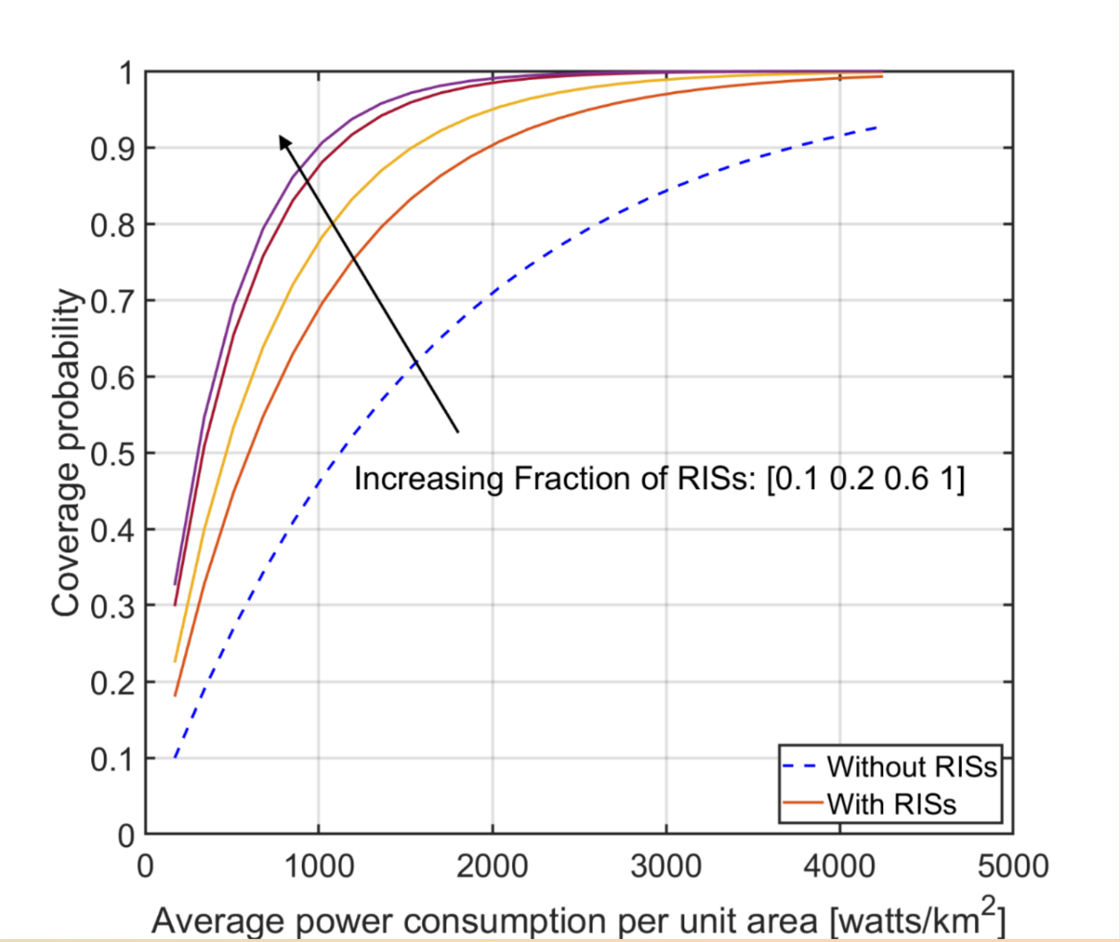


Coverage Probability (Before)

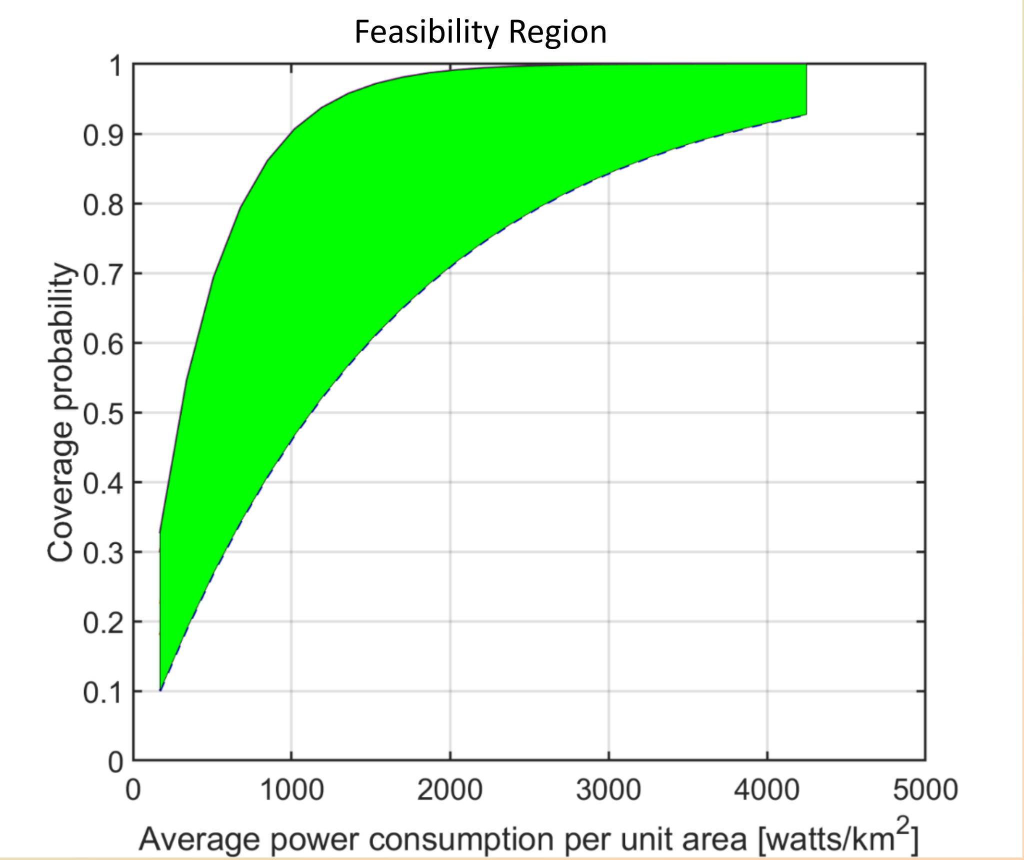


Coverage Probability (After)

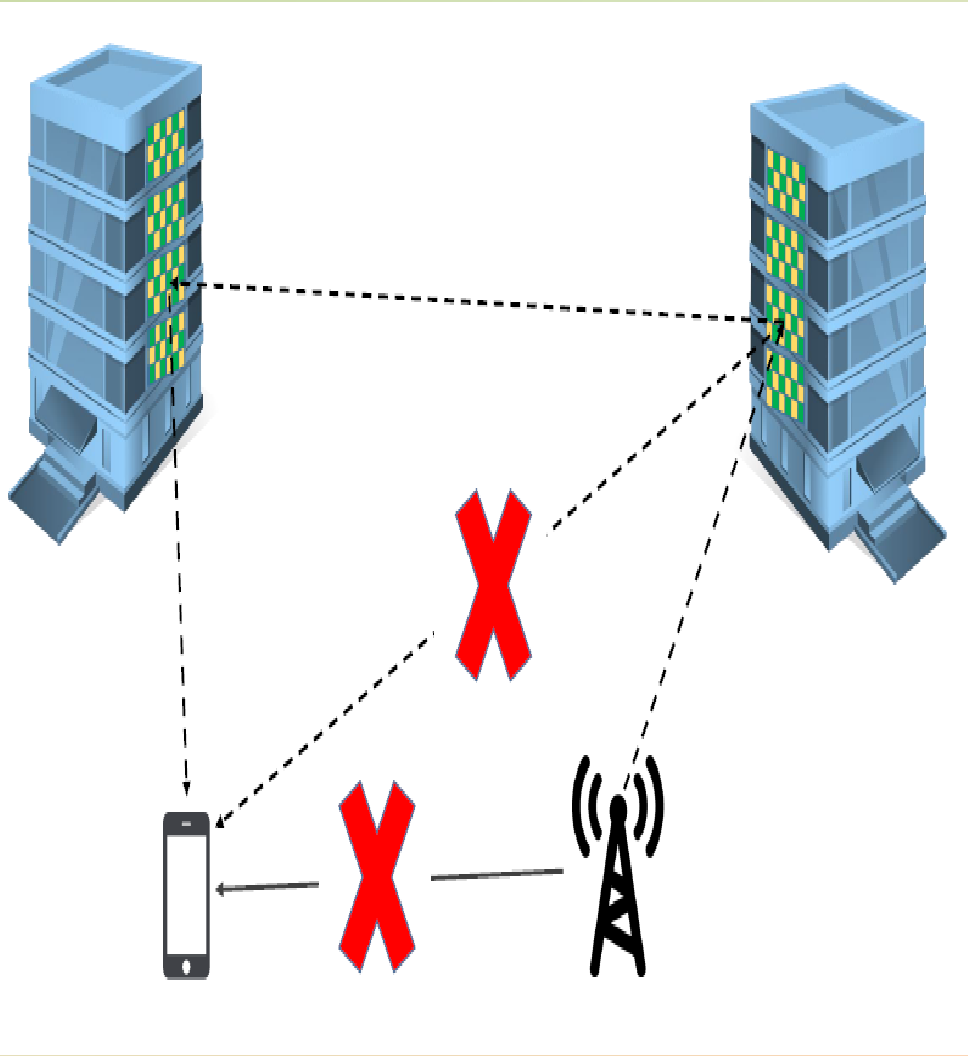
Reconfigurable Intelligent Surfaces



Feasibility Region

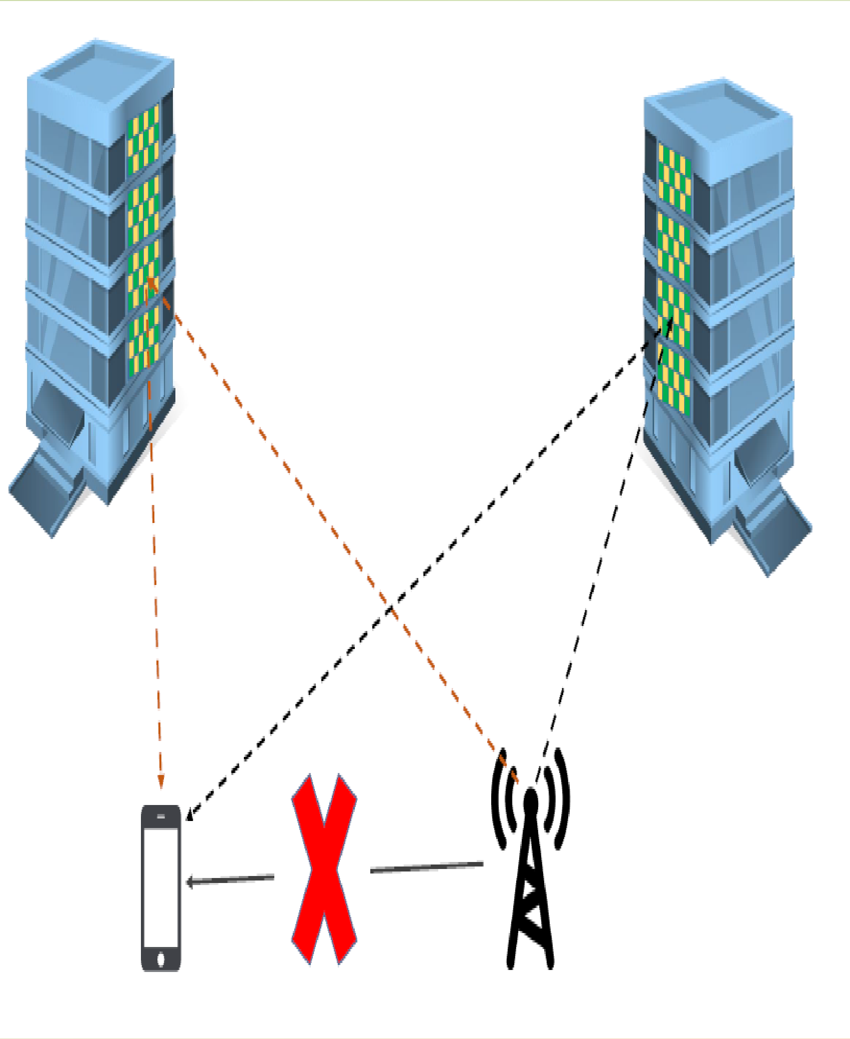


Multi-hop RIS-Assisted Communication



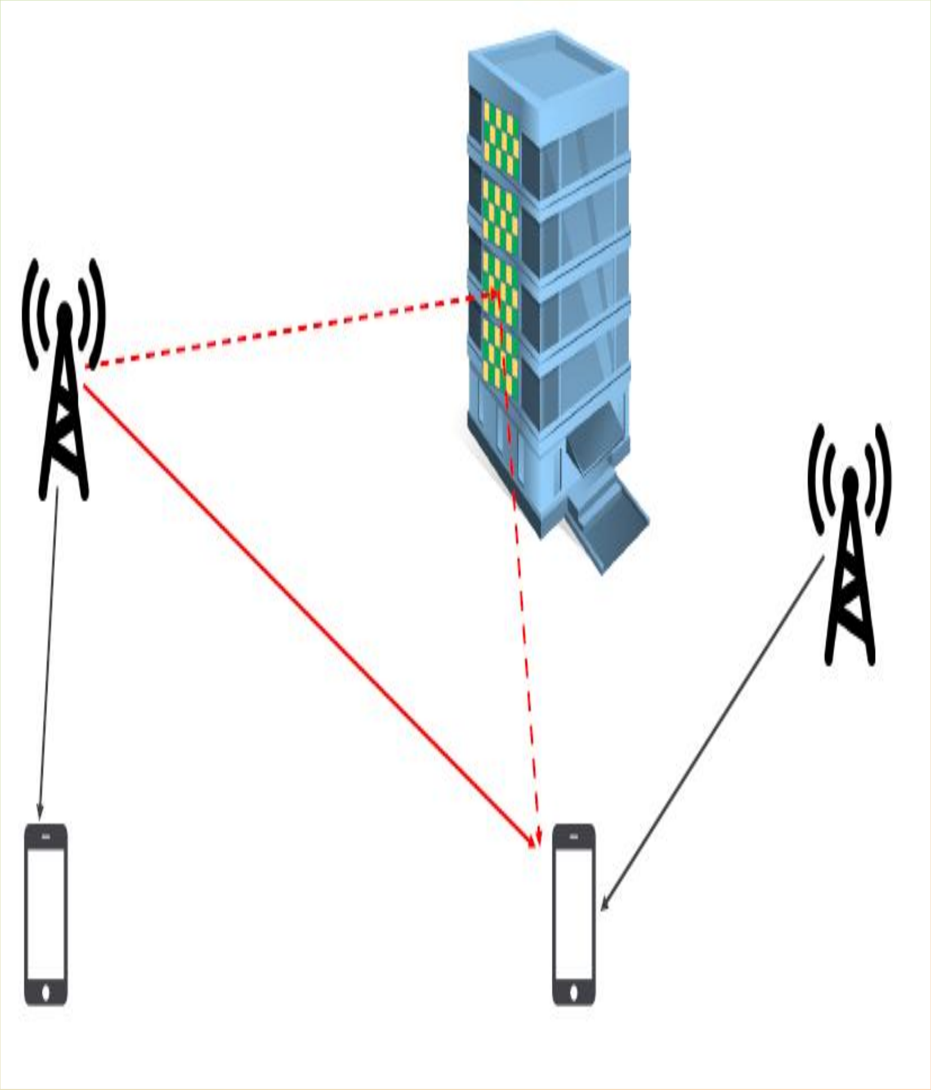
- Route selection
- Potential gain when RIS routing is used
- Optimal allocation of RISs' resources for routing multiple signals.

RIS Cooperative Communication



- Optimal RISs selection
- How many RISs should be allocated per user.
- Optimal Allocation of RISs' resources for serving multiple users

Interference Cancellation Using Destructive Combining



- **Resource allocation of RISs between signal enhancement and interference cancellation**
- **Selection criteria of RISs used for interference**

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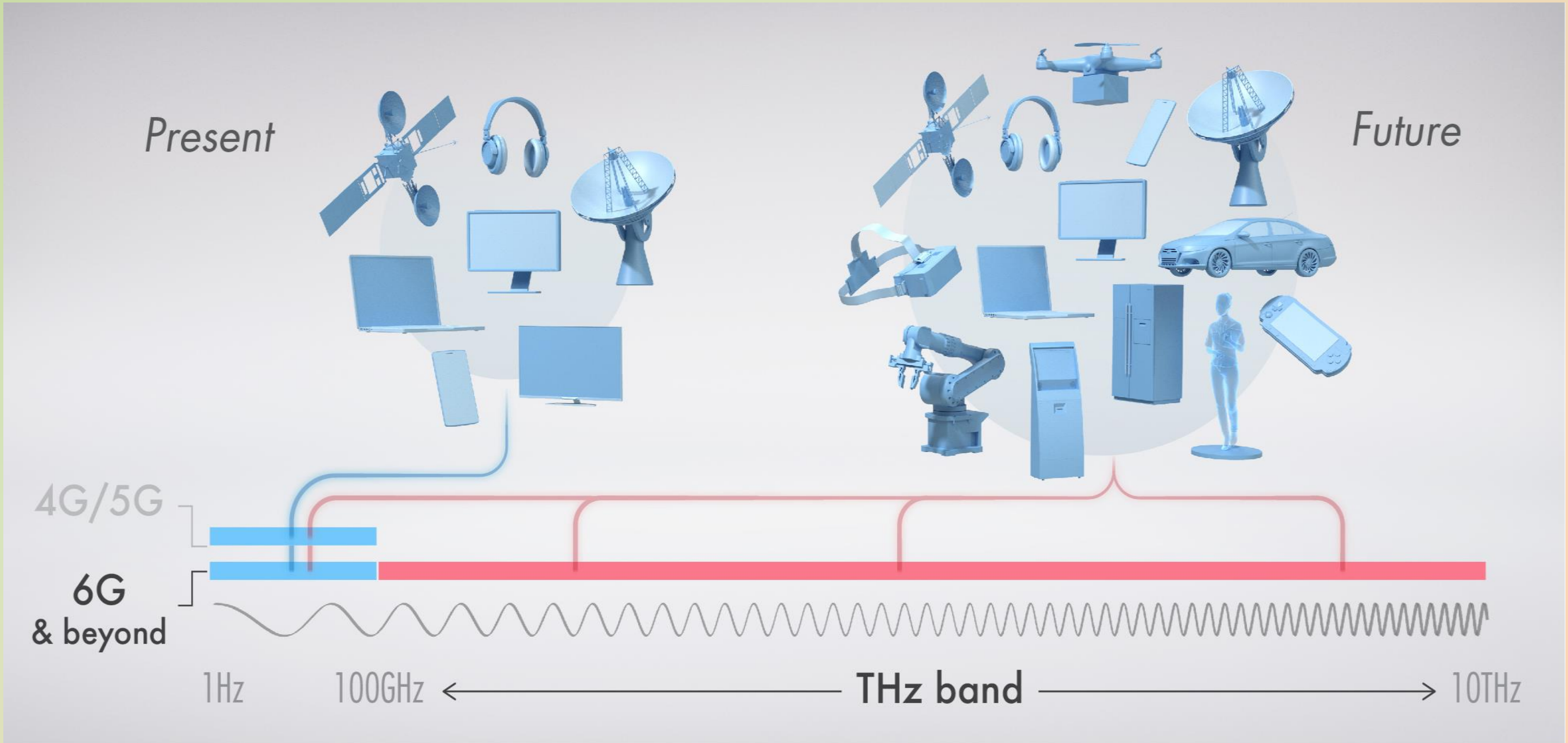
Extreme Bandwidth Communications



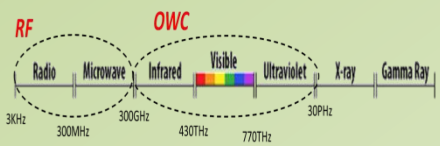
Terahertz Communications: A Rendezvous of Sensing, Imaging, and Localization



[1] H. Elayan, O. Amin, B. Shihada, R. M. Shubair, M. -S. Alouini, "Terahertz band: The last piece of RF spectrum puzzle for communication systems", IEEE Open Journal of the Communications Society, January 2020.

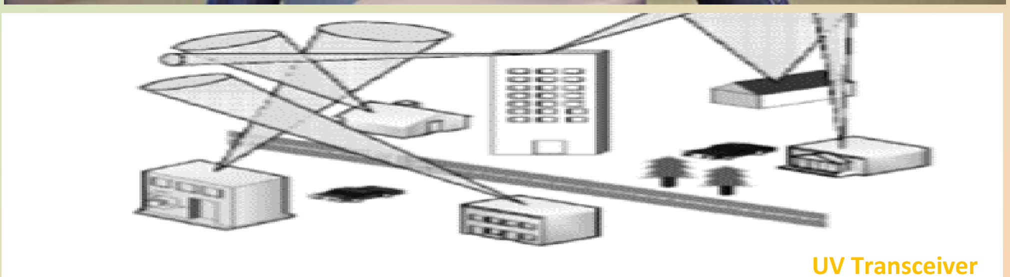
[2] H. Sarieddeen, M. -S. Alouini, T. Al-Naffouri, "Terahertz-band ultra-massive spatial modulation MIMO", IEEE Journal on Selected Areas in Communions, September 2019.

Optical Wireless Communications




FSO Transceiver

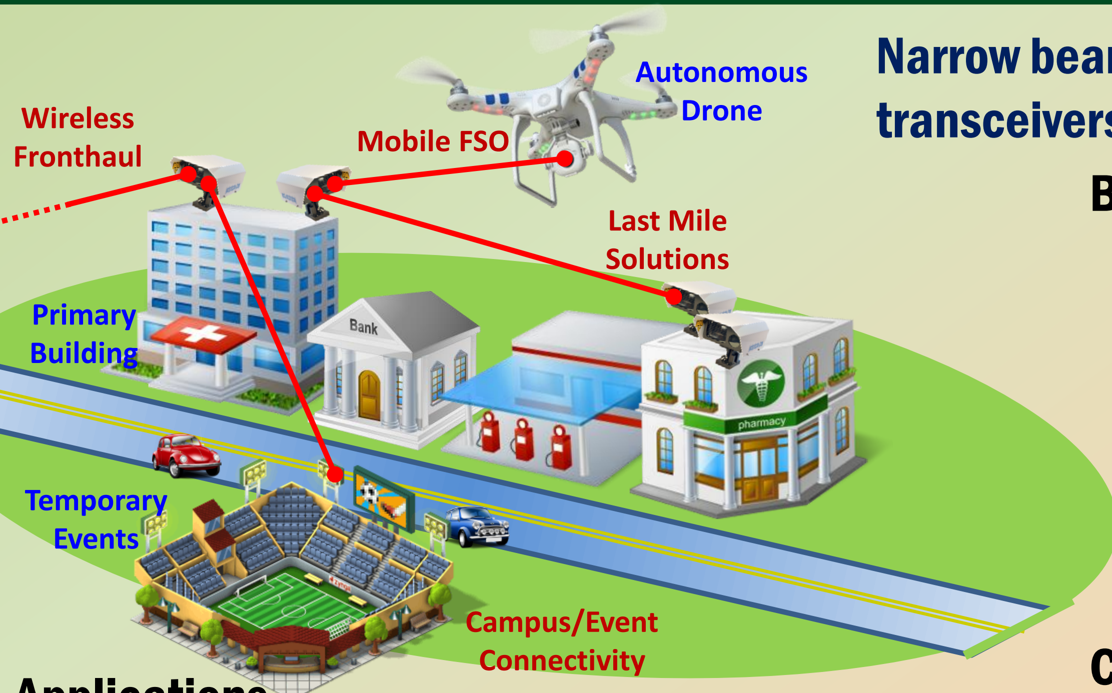
Indoor VLC


UV Transceiver

- Point-to-point **free space optical communications (FSO)** using lasers in the near IR band (750 nm to 1600 nm)
- **Visible light communications** (known also as **Li-Fi**) using LEDs in the 390 nm to 750 nm band.
- **NLOS UV communication** in the 200 nm to 280 nm band.

[1] C.-X. Wang, F. Haider, X. Gao, X.-H. You, Y. Yang, D. Yuan, H. Aggoune, H. Haas, S. Fletcher, and E. Hepsaydir, "Cellular architecture and key technologies for 5G wireless communication networks," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 122-130, Feb. 2014.
[2] A. Chaaban, Z. Rezki, and M. -S. Alouini, "Fundamental limits of parallel optical wireless channels: Capacity results and outage formulation", IEEE Transactions on Communications, vol. 65, no. 1, pp. 296-311, January 2017.

Free Space Optical Communication



Narrow beam connects two optical wireless transceivers in LOS.

Benefits

- Unlicensed and unbounded spectrum
- Cost-effective
- Narrow beam-widths (Energy efficient, immune to interference and secure)
- Behind windows
- Fast turn-around time
- Suitable for brown-field

Challenges

- Additive noise and background radiation
- Atmospheric path loss
- Atmospheric Turbulences
- Alignment and tracking

Applications

- Initially used for secure military and in space
- Last mile solution
- Optical fiber back-up
- High data rate temporary links
- Wireless Fronthaul/Backhaul in celluar network

[1] M. Esmail, A. Raghed, H. Fathallah, and M. -S. Alouini, "Investigation and demonstration of high speed full-optical hybrid FSO/fiber communication system under light and storm condition", IEEE Photonics Journal, vol. 9, no. 2, February 2017.
[2] M. Esmail, A. Ragheb, H. Fathallah, and M. -S. Alouini, "Experimental demonstration of outdoor 2.2 Tbps super-channel FSO transmission system", in Proc. Optical Wireless Communications Workshop in conjunction with Proceedings IEEE International Conference on Communications (ICC'2016), Kuala Lumpur, Malaysia, May 2016.

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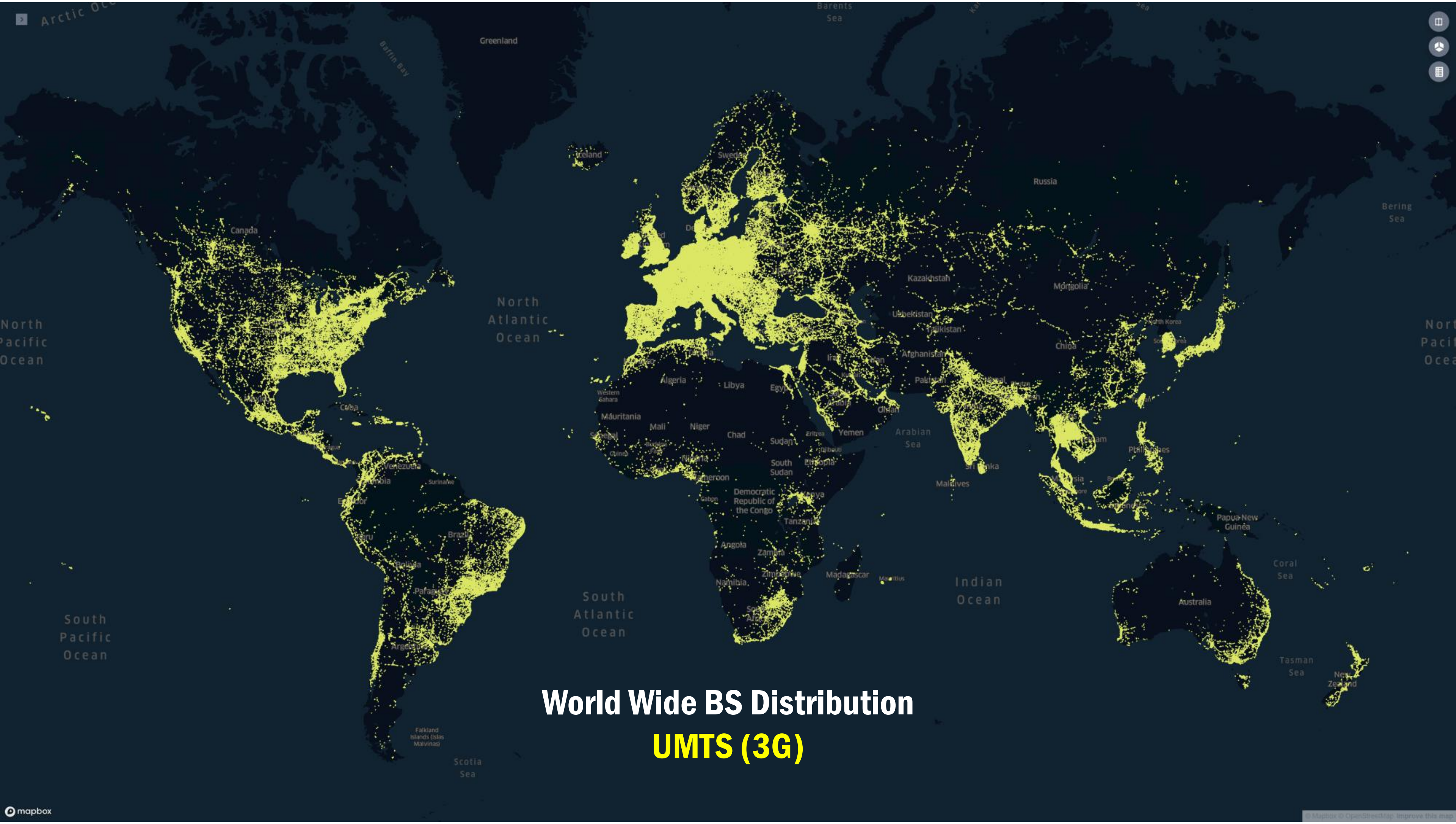
Connecting the Remaining 4 Billions

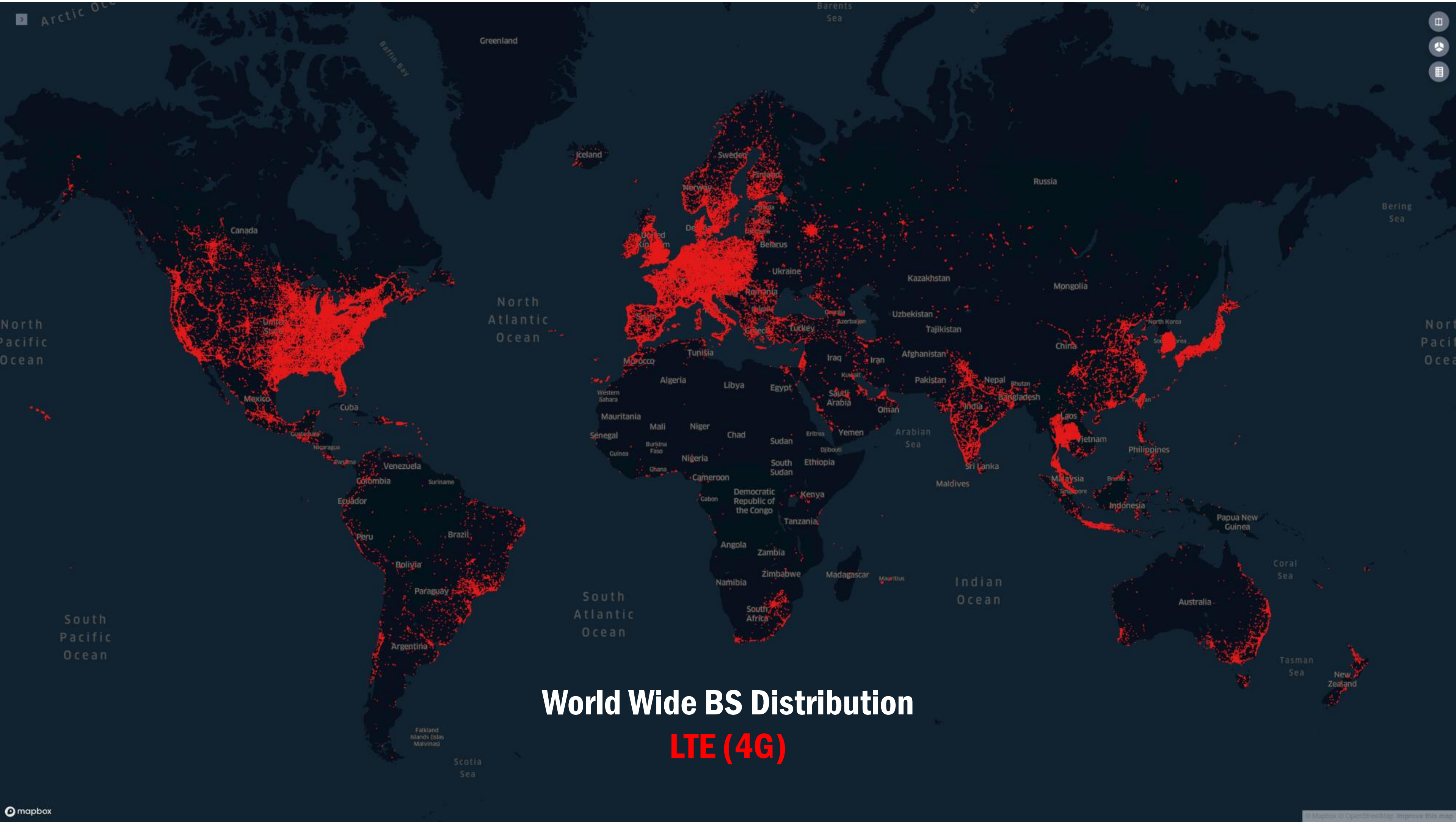
World Wide BS Distribution

GSM (2G)



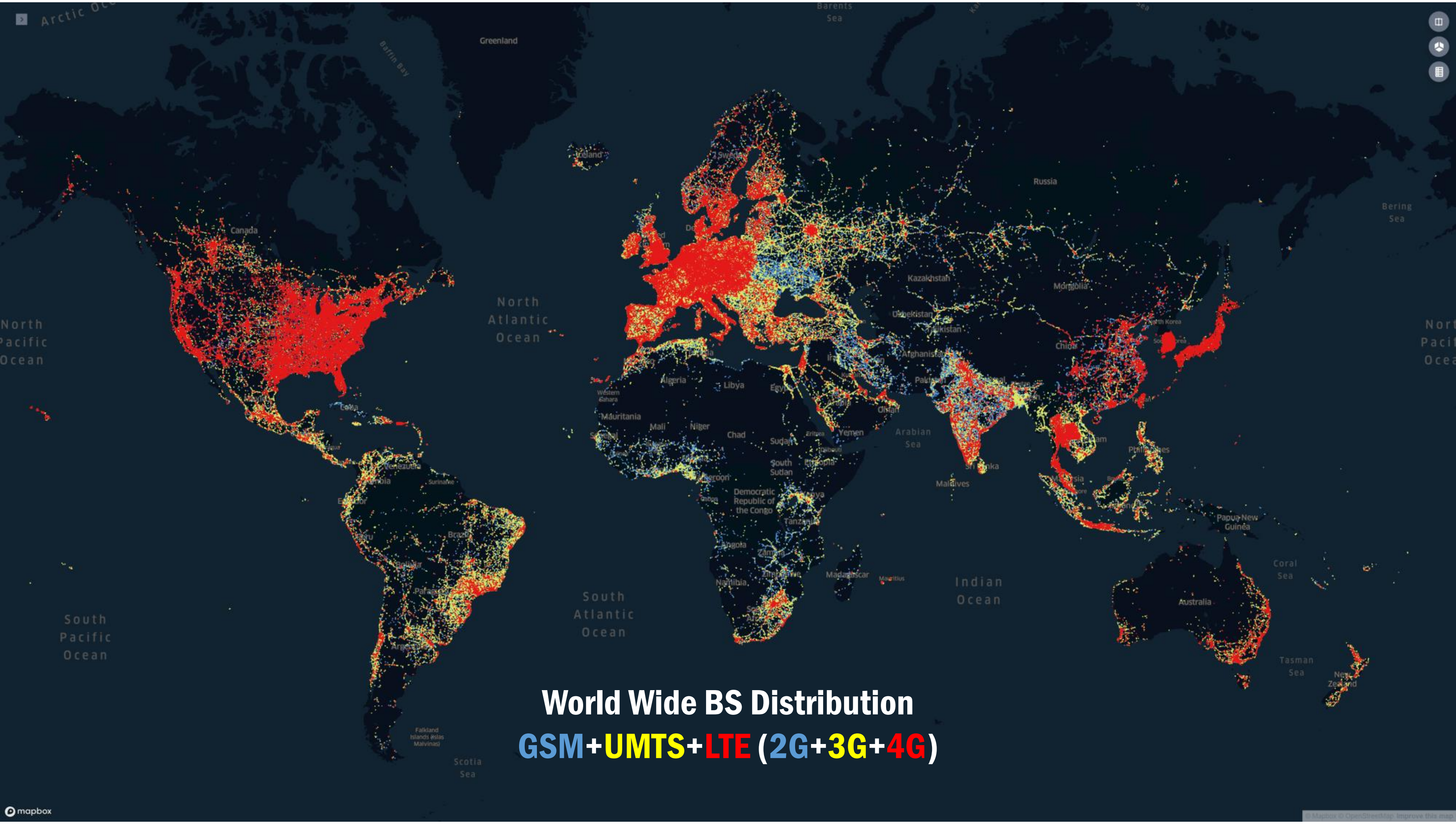
World Wide BS Distribution

UMTS (3G)



World Wide BS Distribution

LTE (4G)

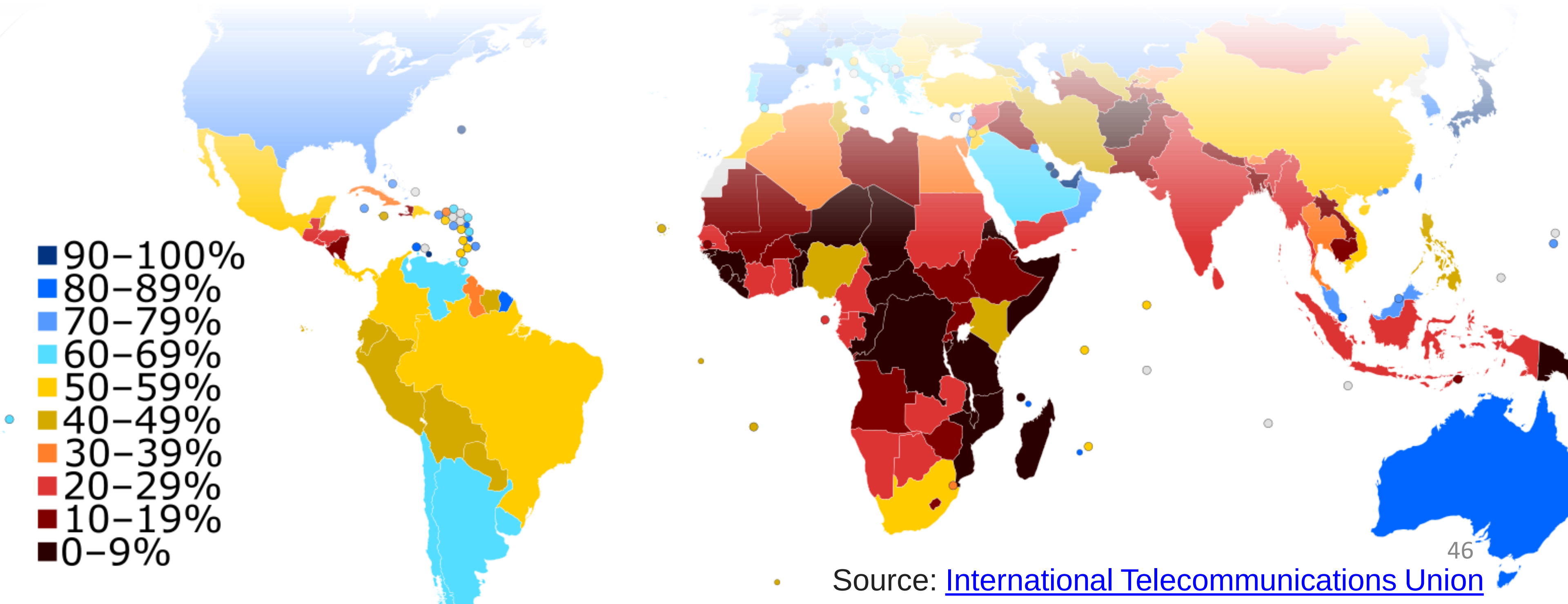


World Wide BS Distribution

GSM+UMTS+LTE (2G+3G+4G)

Global Connectivity

- **Billions of people around the world are still without internet access.**
  - **Understanding the reasons behind the "Digital Divide"**
  - **High-quality connectivity enables richer/denser communities to share knowledge and strengthen the economies of less fortunate/dense communities.**



Source: [International Telecommunications Union]

Urban Connectivity

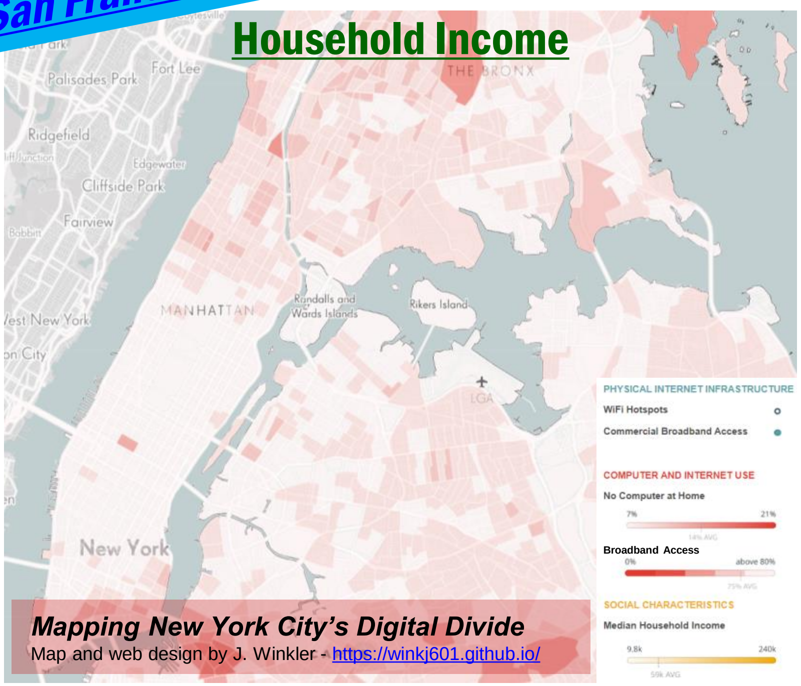
Digital Divide Is Wider Than We Think. The New York Times

The Former Homeless Man Bringing Web Access to the Bronx. BBC

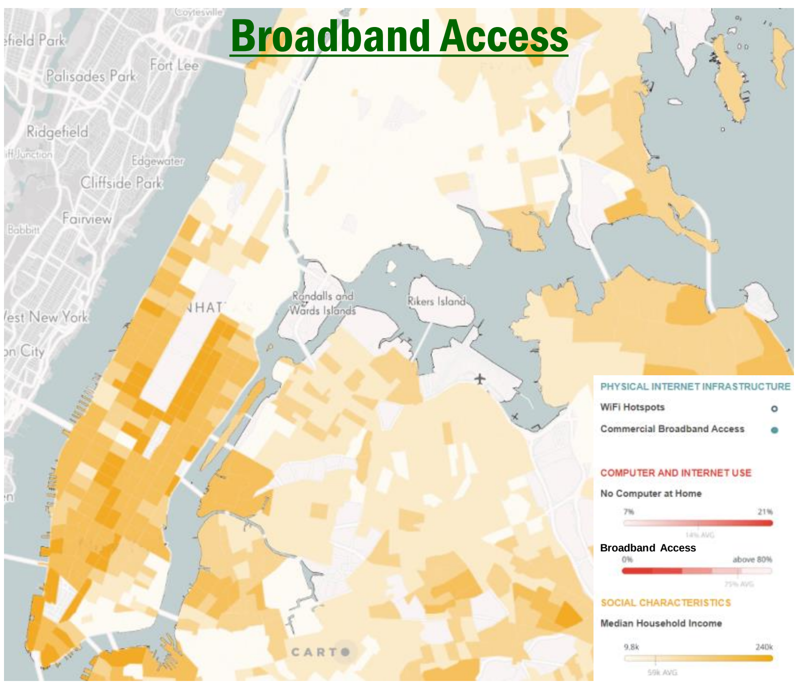
Can San Francisco Finally Close its Digital Divide? SFWEEKLY

- In communities with low income, the digital disparity is much more profound.
- People who have high-quality internet service are more likely to benefit from health care, self-education and social/governmental services.
- It needs collaboration and agreement among various stakeholders, i.e., government, policy makers, service provider, manufacturer and community members.

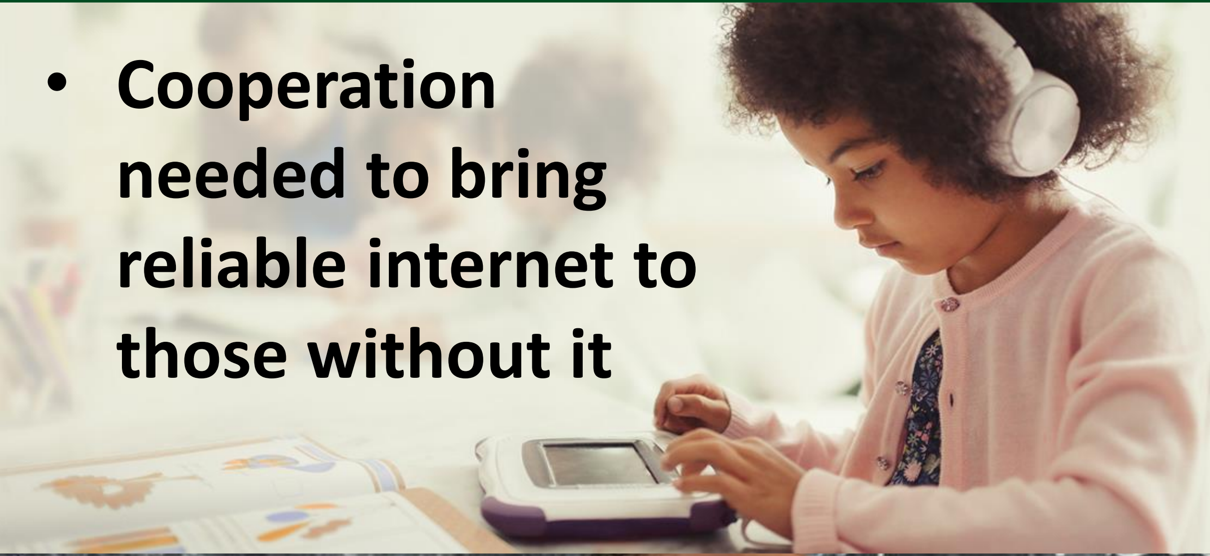
Household Income VS Broadband Access



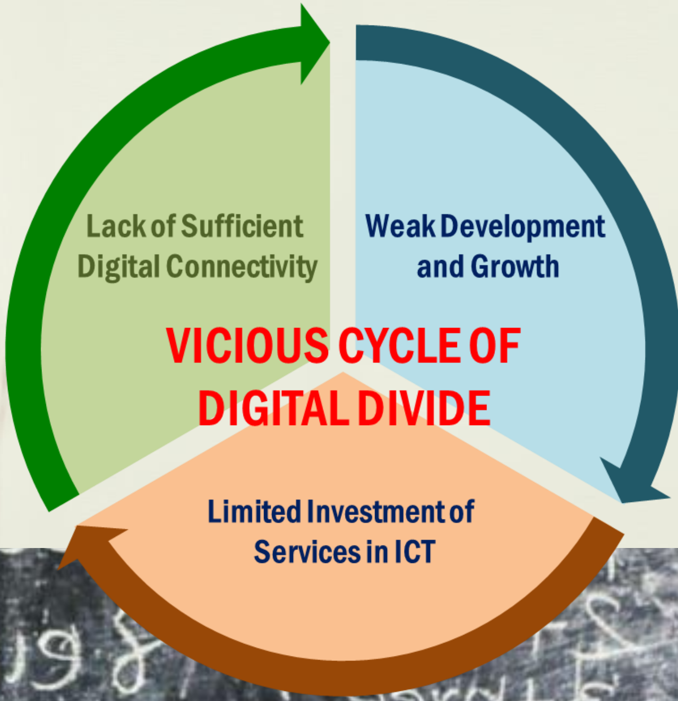
Mapping New York City's Digital Divide
Map and web design by J. Winkler - https://winkj601.github.io/



Bridging Digital Divide



- Cooperation needed to bring reliable internet to those without it



Social Barriers

- Poor infrastructure
- Low quality of education for schooling
- Shortage of healthcare

[1] E. Yaacoub and M.-S. Alouini, “A Key 6G Challenge and Opportunity - Connecting the Remaining 4 Billions: A Survey on Rural Connectivity,” Submitted for Publication. Available at https://arxiv.org/abs/1906.11541

Smart Cities to Smart Living

Smart Grid
Smart Transportation
Environmental Protection
Water Distribution
Smart Healthcare

SMART CITY
BUILDING TOMORROW'S CITIES

SMART EVERYWHERE
Equal and Eco-Friendly
Quality of Life

Smart Village
Smart Home
Virtual Education
Remote Healthcare
Nature Friendly

SMART LIVING

High Data Rate

URLLC

High Speed
Backhaul

[1] E. Yaacoub and M.-S. Alouini, "From smart cities to smart living: Providing backhaul connectivity for IoT in rural areas," Submitted for Publication

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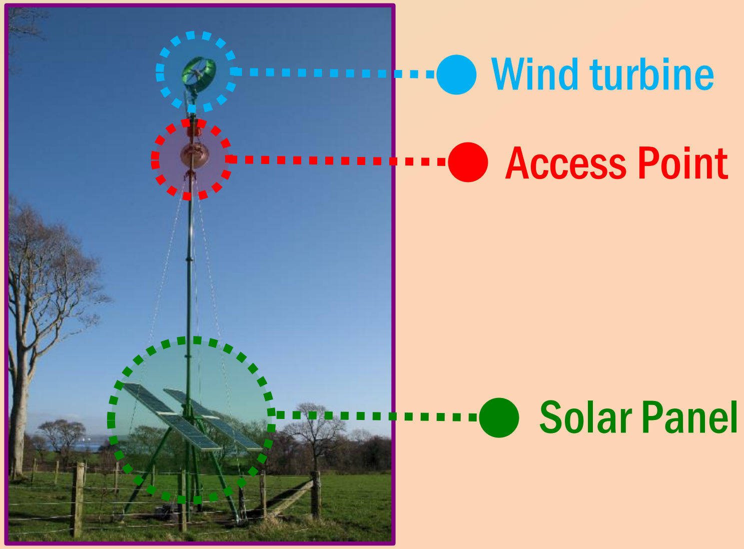
Technology Insights for Rural Connectivity

Renewable-Powered Access Points

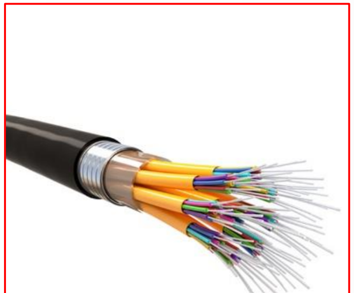
[Solar powered kiosks are charging phones in Rwanda.]

- Mobile phones are popular but keeping them powered isn't necessarily easy in developing countries.
- The renewable energy sources such as photo-voltaic cells and wind turbine can help people having access to electricity.



Prototype “WindFi” Base Station

Rural Backhaul Connectivity


OPTIC FIBER

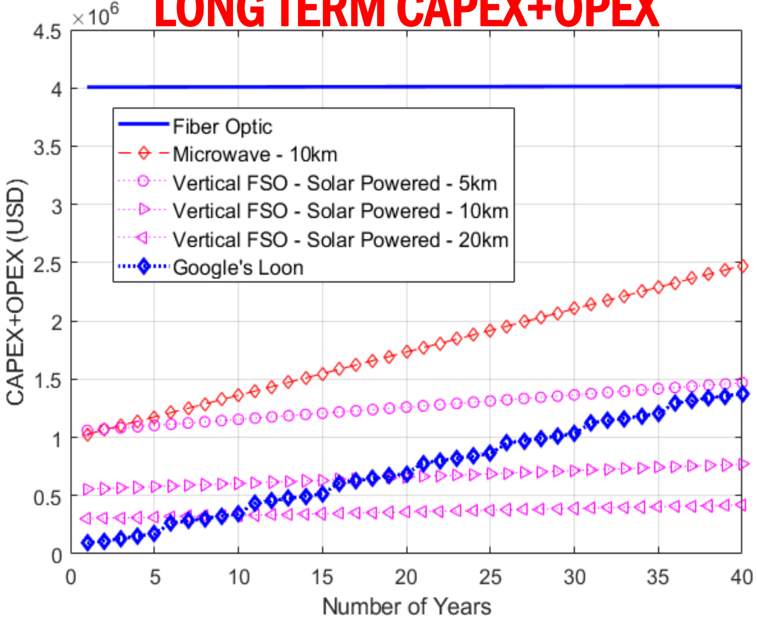

FSO


MICROWAVE


HAP


SATELLITE

LONG TERM CAPEX+OPEX



Rural Backhaul Solutions

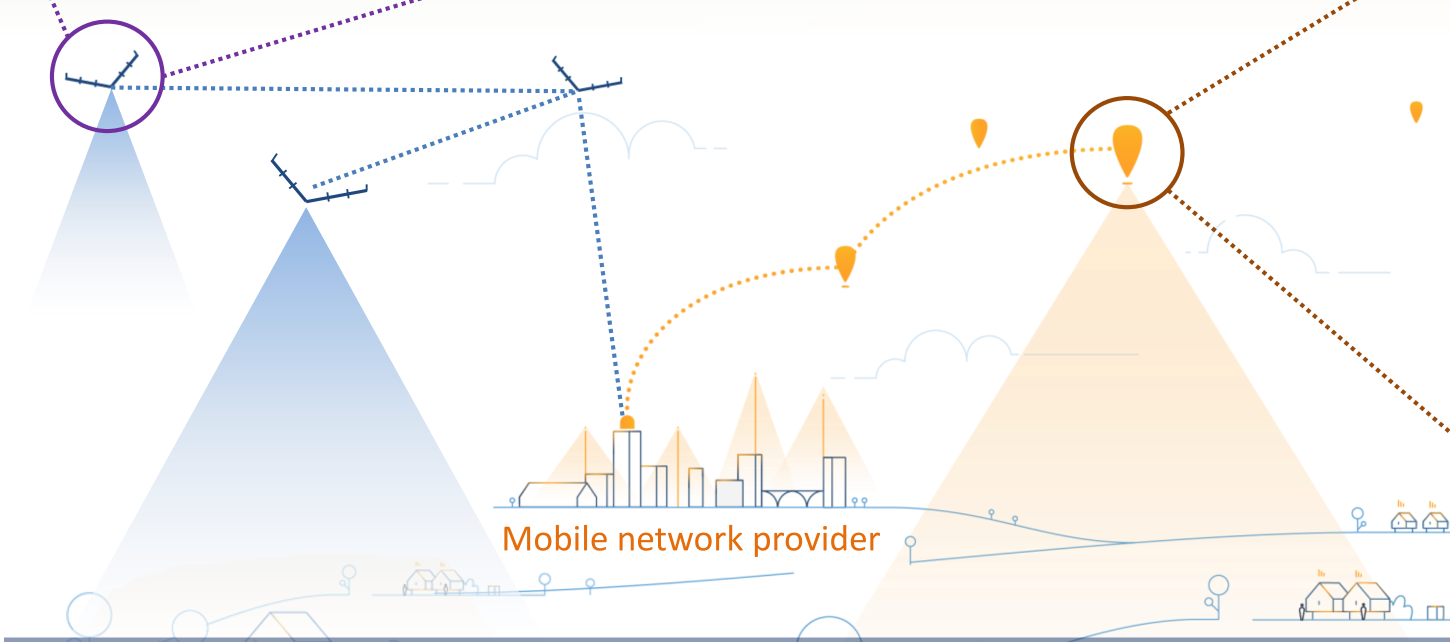
High Speed Backhaul

[1] E. Yaacoub and M.-S. Alouini, "From smart cities to smart living: Providing backhaul connectivity for IoT in rural areas," Submitted for Publication

High Altitude Platform (HAP) Backhaul

"Tower-in-the-air"

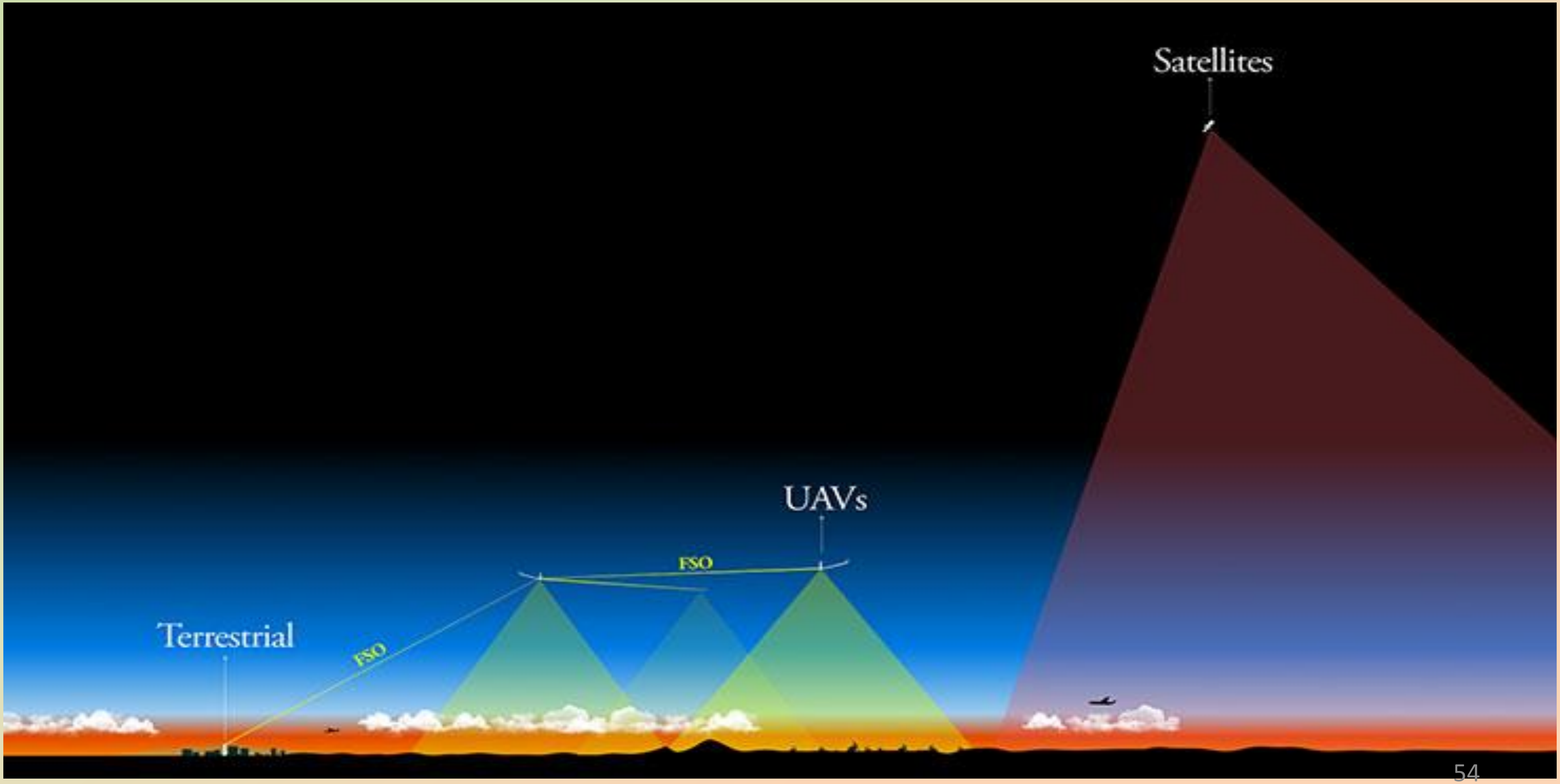
- Solar-powered swarm of HAPs in the backbone network at a height of 18-28 km



J.-H. Lee, K.-H. Park, M.-S. Alouini, and Y.-C. Ko, "Free space optical communication using UAV: optimization for flight-time and energy-efficiency" IEEE ICC'2019, May 2019 and journal version accepted in IEEE Trans. Wireless Comm.

FSO for UAV Communication

Facebook Aquila Project



Satellite Constellations Backhaul

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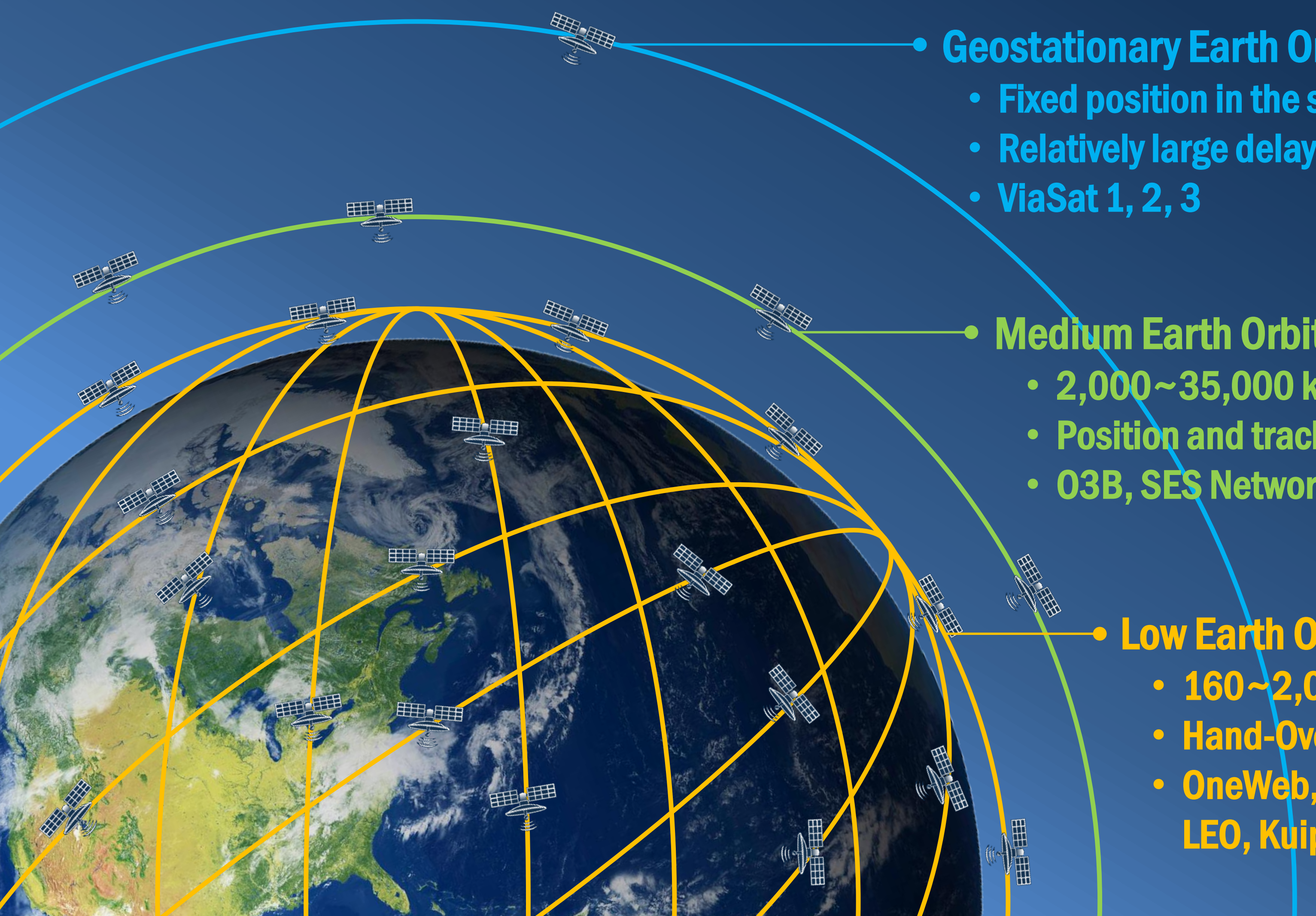
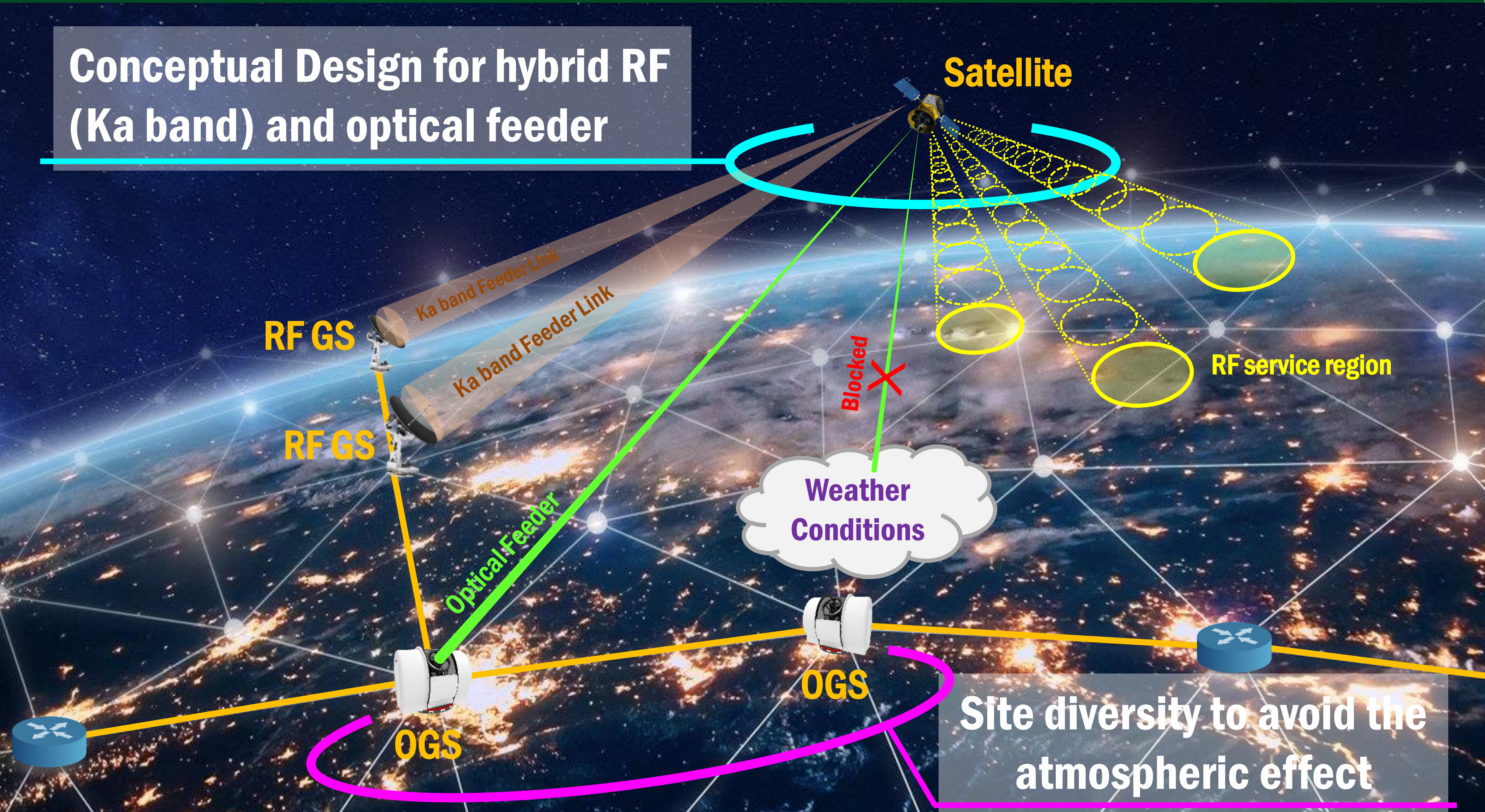
Manufacturing Cost Down => Mass Production



- **Geostationary Earth Orbit (GEO) Satellite**
  - Fixed position in the sky at ~35,000 km
  - Relatively large delay
  - ViaSat 1, 2, 3
- **Medium Earth Orbit (MEO) Satellite**
  - 2,000~35,000 km
  - Position and tracking
  - O3B, SES Networks
- **Low Earth Orbit (LEO) Satellite**
  - 160~2,000 km
  - Hand-Over
  - OneWeb, Starlink, TeleSat LEO, Kuiper

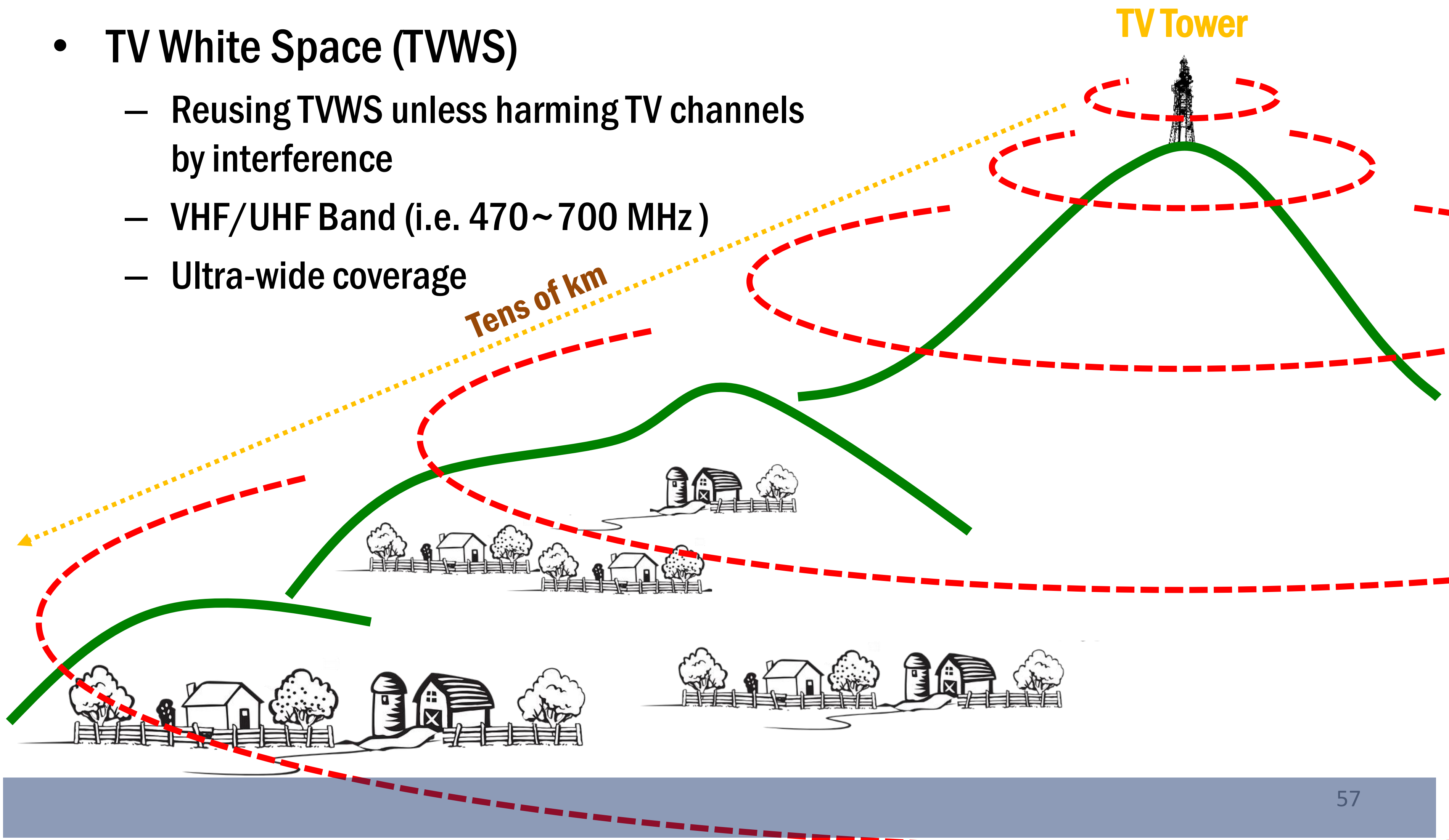
Hybrid VHT Satellite with Site Diversity



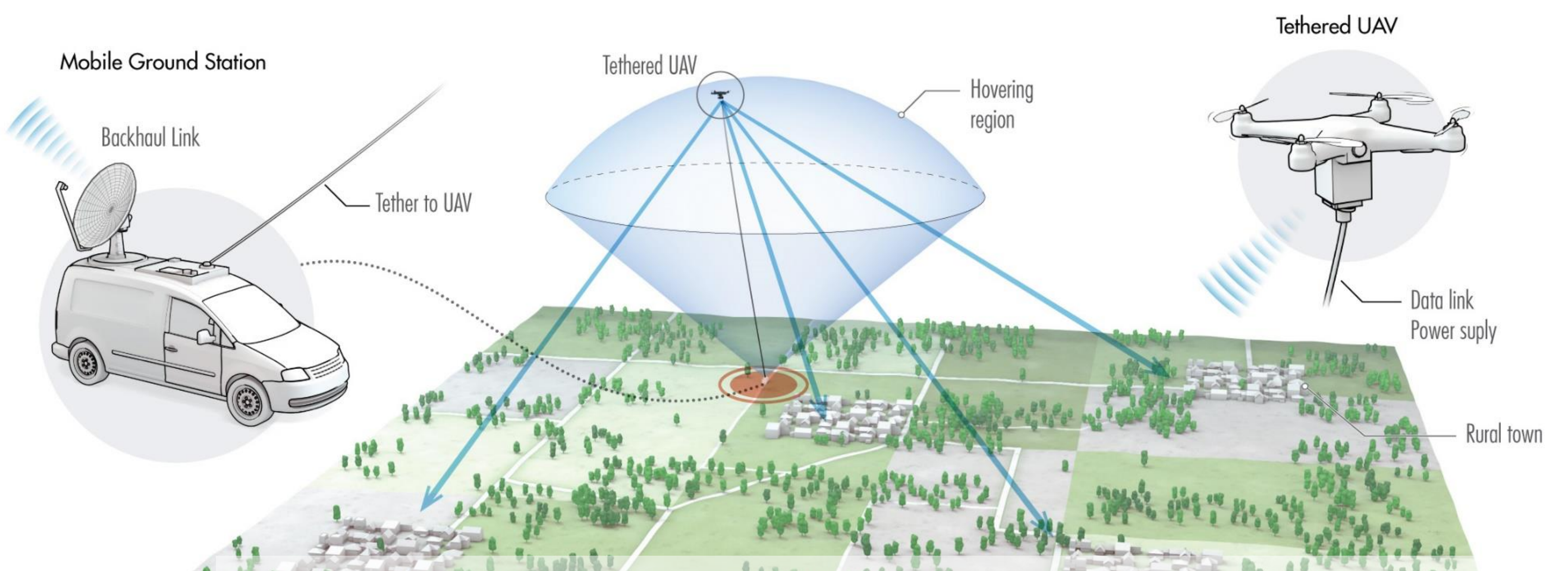
[1] E. Zedini, A. Kammoun, and M. –S. Alouini, "Performance of multibeam very high throughput satellite systems based on FSO feeder links with HPA nonlinearity, Submitted for publication

Existing TV Infrastructure

- TV White Space (TVWS)
  - Reusing TVWS unless harming TV channels by interference
  - VHF/UHF Band (i.e. 470~700 MHz)
  - Ultra-wide coverage



Tethered UAV/Balloon

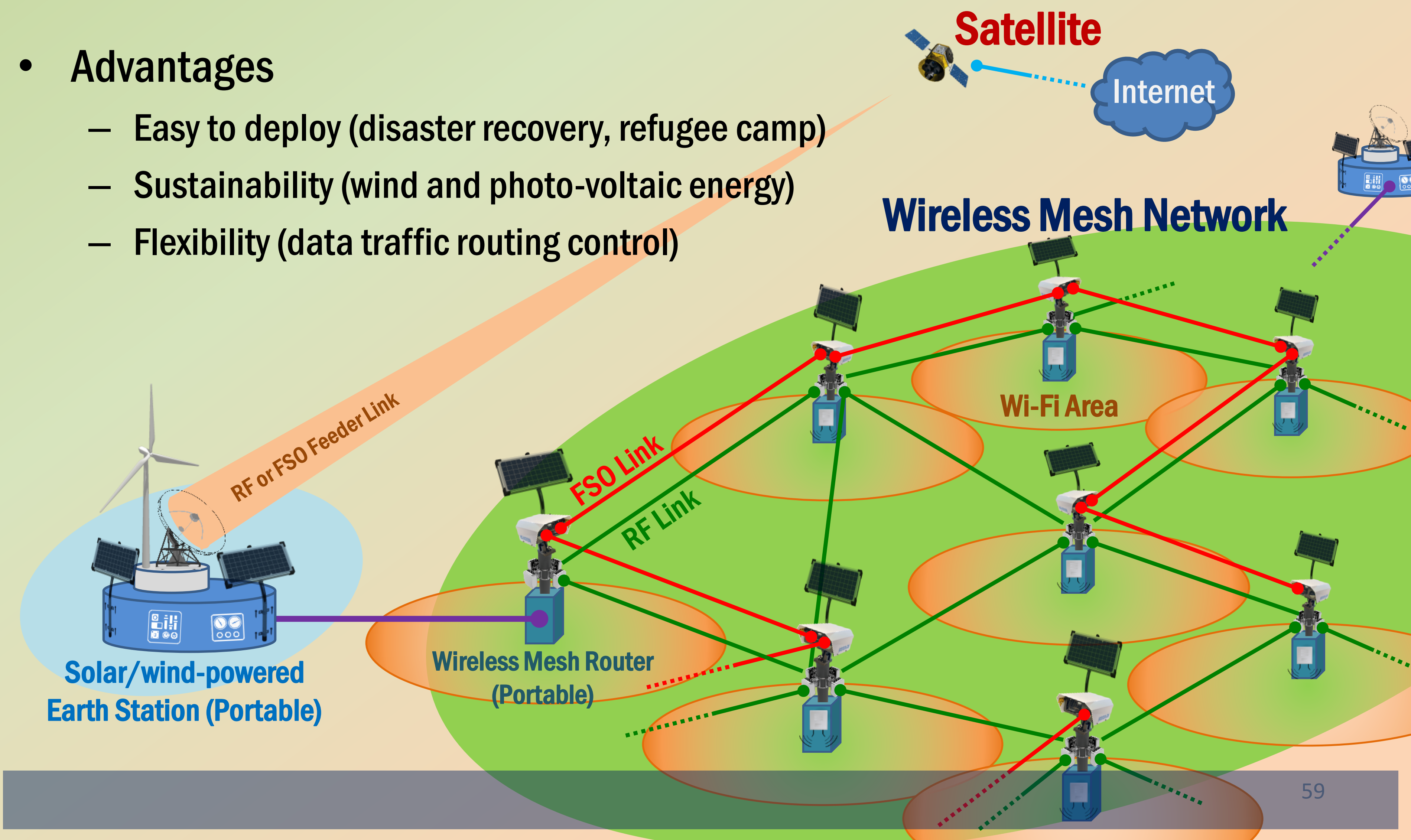


Advantages

- Unlimited flight time
- Supports heavier payload
- Wired/reliable backhaul link
- Mobility and relocation flexibility: Track the time-varying traffic demand spatial distribution
- Line-of-sight with ground users: Probability increases with altitude

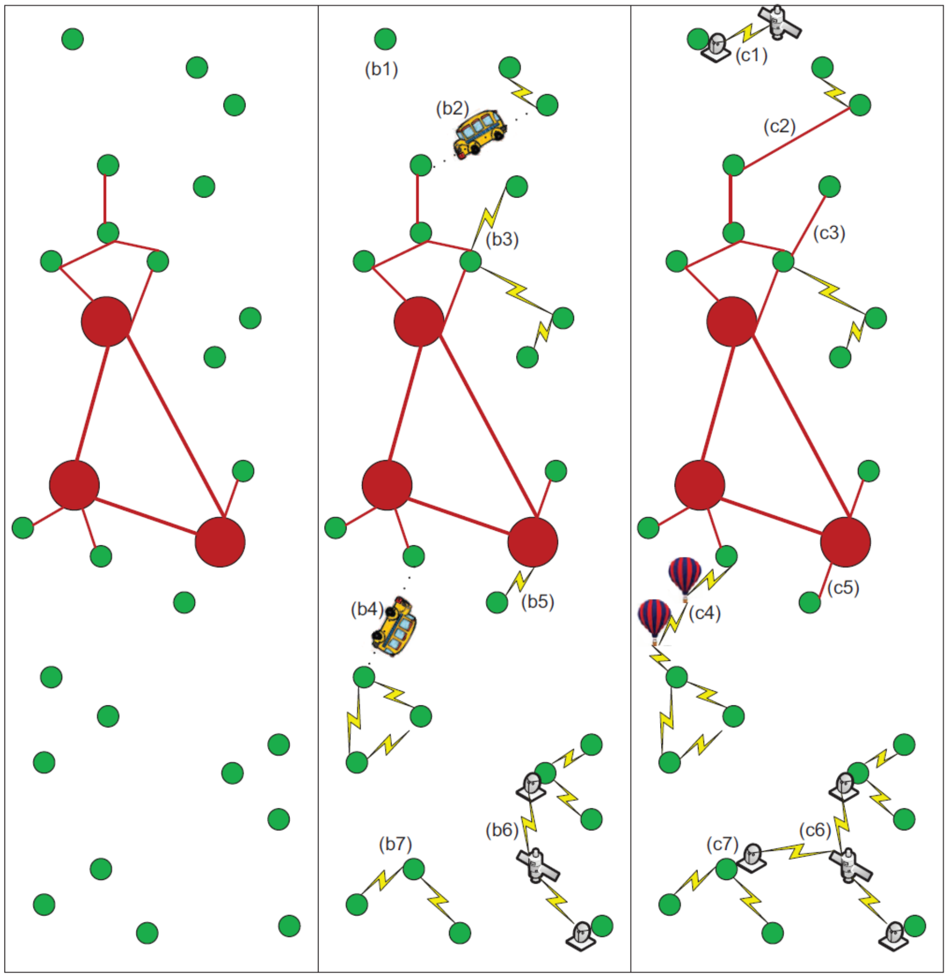
Wireless Mesh Networks

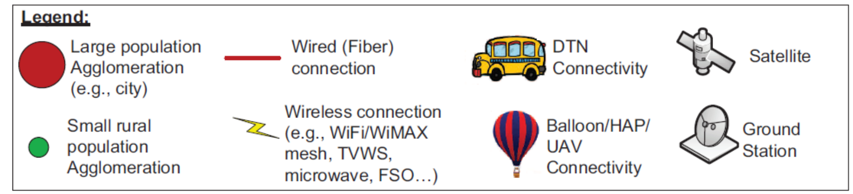
- Advantages
  - Easy to deploy (disaster recovery, refugee camp)
  - Sustainability (wind and photo-voltaic energy)
  - Flexibility (data traffic routing control)



Broadband Connectivity

From Urban to Rural Areas





Phase B

(b2), (b4) : Delay Tolerant Network

(b6) : Satellite Backhaul Network

(b7) : Isolated Local Network

Phase C

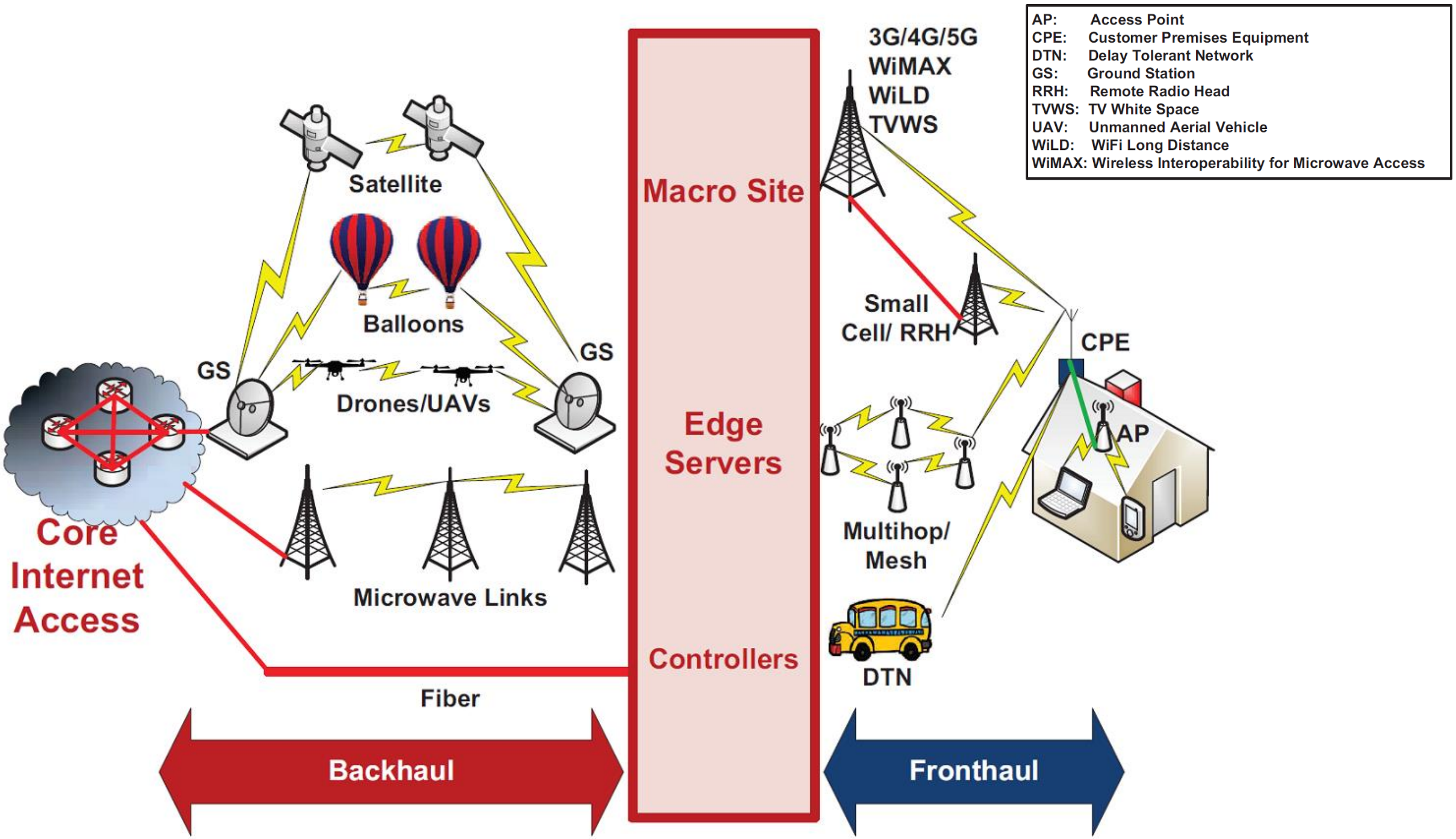
(c2), (c3), (c5) : Permanent Connection

(c4) : HAP Backhaul Network

(c7) : Satellite Backhaul Network

Gradual Expansion of Broadband Connectivity

Fronthaul and Backhaul Solutions



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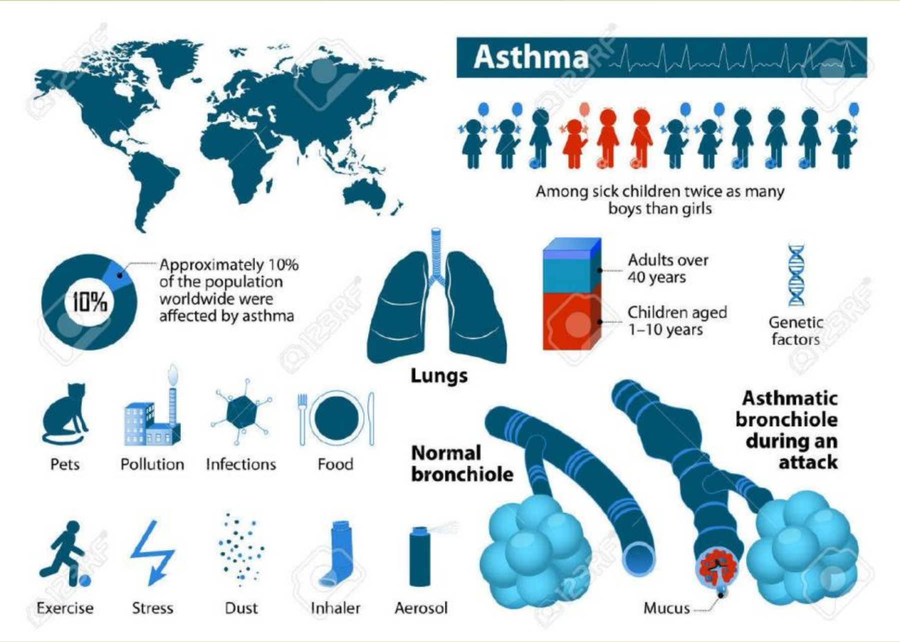
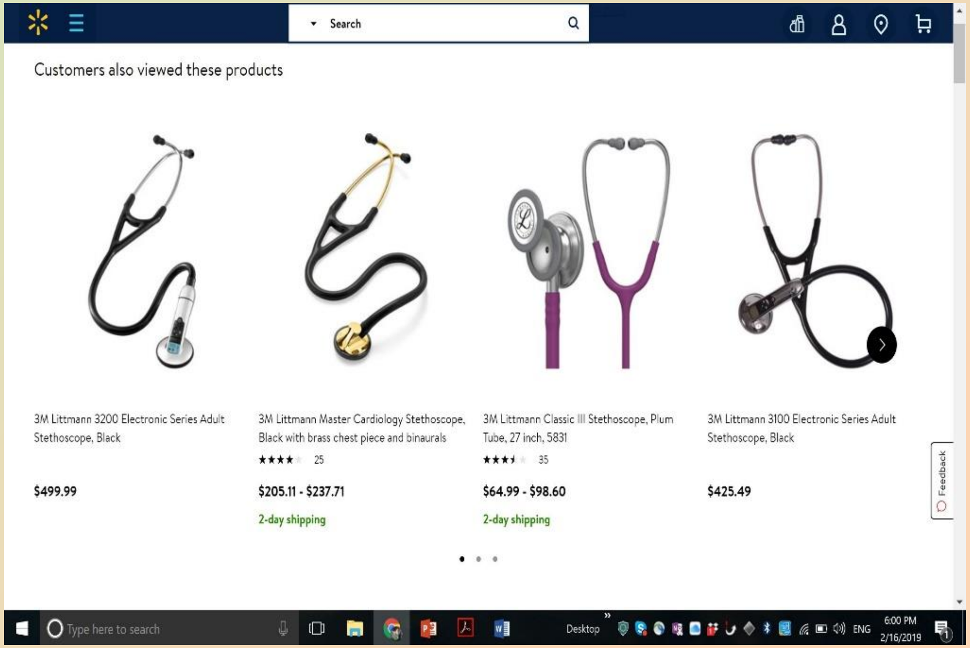
Potential Applications



Chronic Low-Cost Monitoring of Asthma





- Chronic monitoring of respiratory issues can be life saving
- With the advances in electronic technology it is possible

DIY Integration Strategy with Papers

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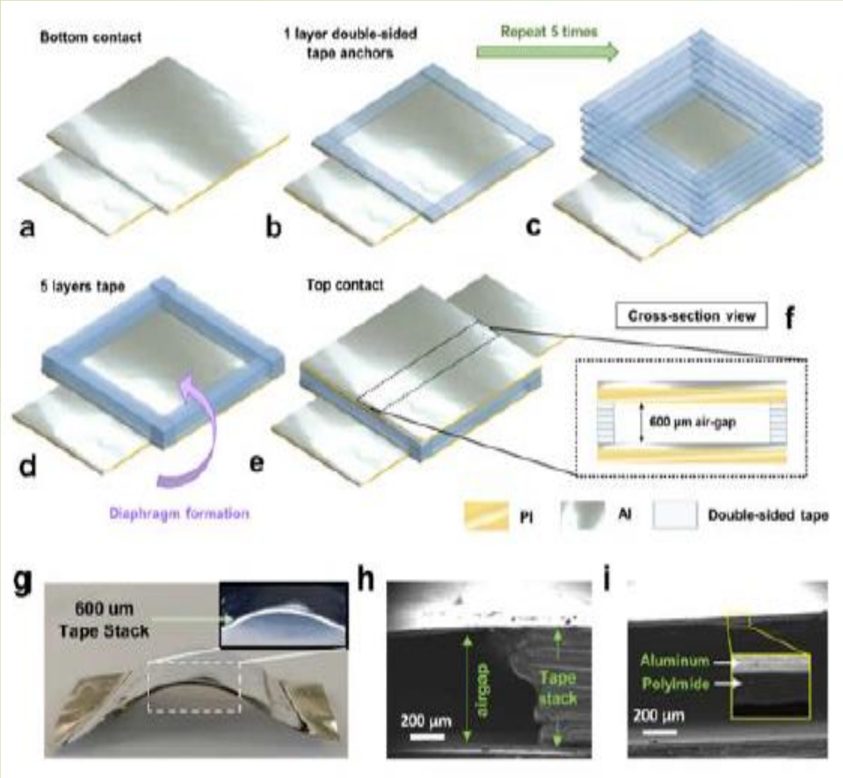


- **DIY Fabrication:**
  - **Simplified fabrication**
  - **Use sustainable materials: paper and tape**
- **Wearable soft acoustic sensor**

[1] S. M. Khan and M. M. Hussain, "Low-cost foil based wearable sensory system for respiratory sound analysis to monitor wheezing", IEEE Intl. Conf. Wearable and Implantable Body Sensor Networks (BSN 2019), May 2019, Chicago, IL, USA.
[2] S. Ahmed and M. -S. Alouini, " Rotational operator of the fractional Fourier transform enhances the detection of R peaks in arrhythmic ECG signals ", Under review.

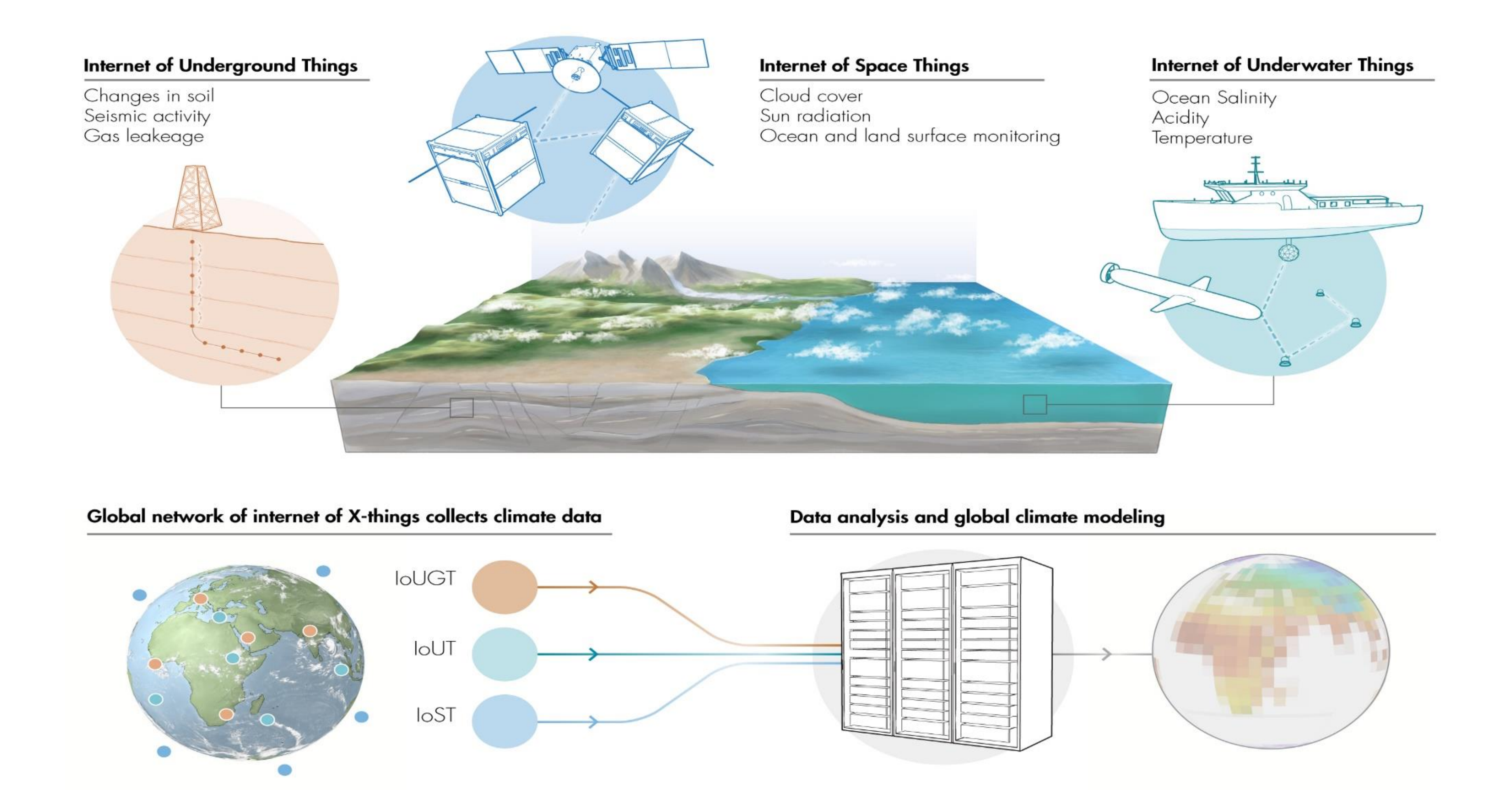
Self-Organizing Pop-up Networks

Emergency Connectivity

After Hurricane in Puerto Rico in 2017, Project Loon supported emergency connectivity while mobile networks were being recovered.

Challenges of Pop-up Networks

Climate Monitoring Using Internet of X-Things



[1] N. Saeed, A. Celik, T. Al-Naffouri, and M. -S. Alouini, "Underwater optical wireless communications, networking, and localization: A survey", Elsevier Adhoc Networks, 2019.
[2] N. Saeed, T. Al-Naffouri, and M. -S. Alouini, "Towards the Internet of underground things: A systematic survey", IEEE Communications Surveys and Tutorials, 2019.
[3] N. Saeed, A. Elzanaty, H. Almorad, H. Dahrouj, T. Y. Al-Naffouri, M -S. Alouini, "CubeSat communications: Recent advances and future challenges", Under Review.

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Thank You

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