Enabling 5G/6G Wireless Communications for Supporting Maritime Applications

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AFFORDABLE5G: High tech and affordable 5G network roll-out to every corner, October 2022

Outline of the presentation

- Personal introduction
- Maritime communication networks
- Research areas
- Conclusions
- Vision for future development

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- ☑ Personal introduction
- ☐ Maritime communication networks
- ☐ Research areas
- ☐ Conclusions
- ☐ Vision for future development

Background

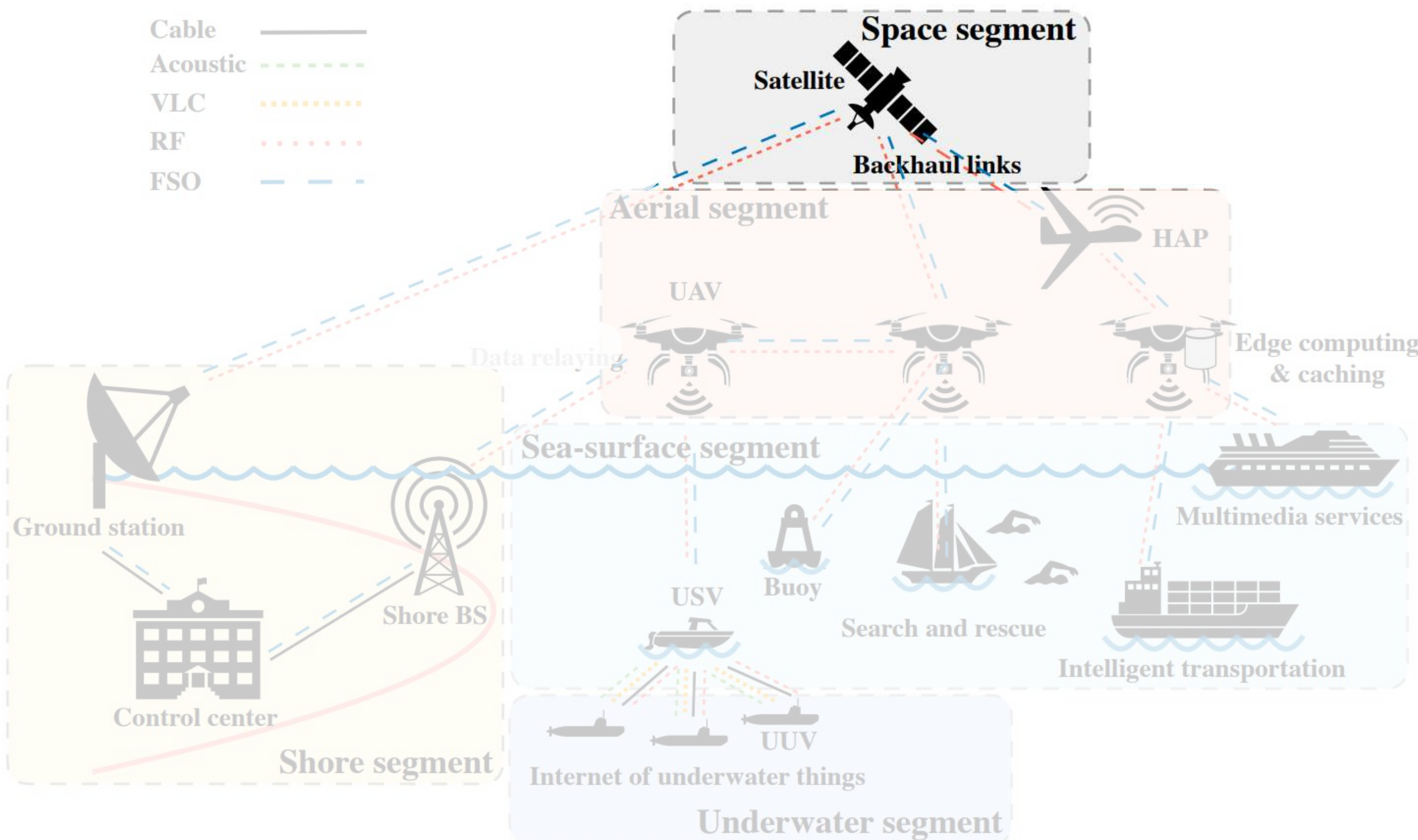
- Diploma “Electrical Engineering and Computer Technology,” University of Patras **2009**
- M.Sc. “Management and Technologies of Information and Communication Systems,” University of the Aegean **2011**
- Ph.D “Spectral Efficient Cooperative Relaying with Interference Mitigation in Heterogeneous Wireless Networks,” University of the Aegean **2014**
- Past positions
  - Post-doctoral researcher, Dept. of Information and Communication Systems Engineering, University of the Aegean **2014-2020**
  - Post-doctoral researcher, General Department, National and Kapodistrian University of Athens **2019**
  - Collaborative teaching personnel, Open University of Cyprus **2018-2022**
  - Post-doctoral researcher, IRIDA Research Centre for Communication Technologies, University of Cyprus **2021-2022**
- Currently:
  - Post-doctoral researcher, Department of Ports Management and Shipping, National and Kapodistrian University of Athens **2022…**

Outline of the presentation

- ❑ Personal introduction
- ☑ Maritime communication networks
  - Architecture
  - Communication technologies
  - Performance targets
- ❑ Research areas
- ❑ Conclusions
- ❑ Vision for future development

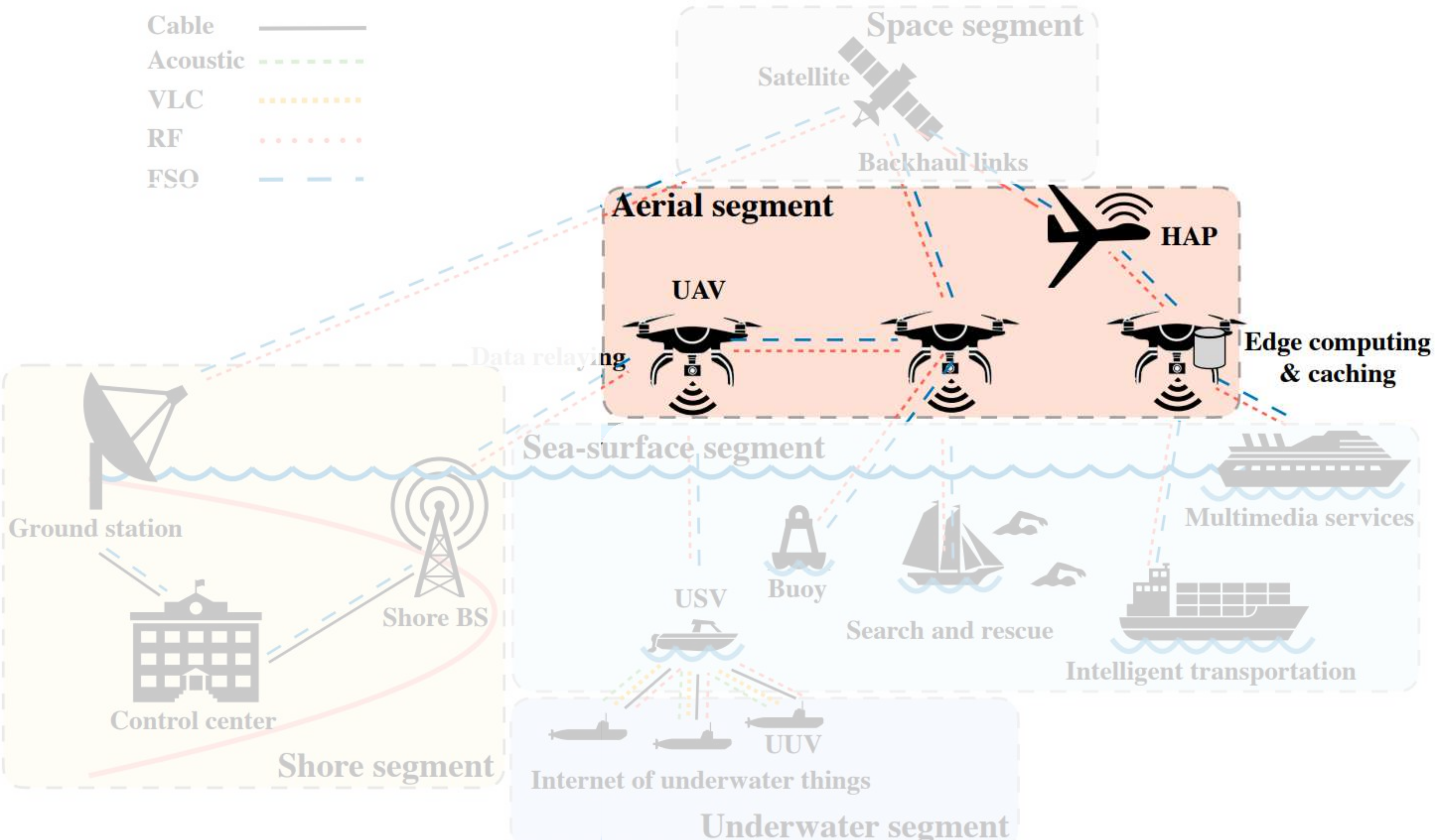
Maritime communication network architecture

Maritime communication network architecture



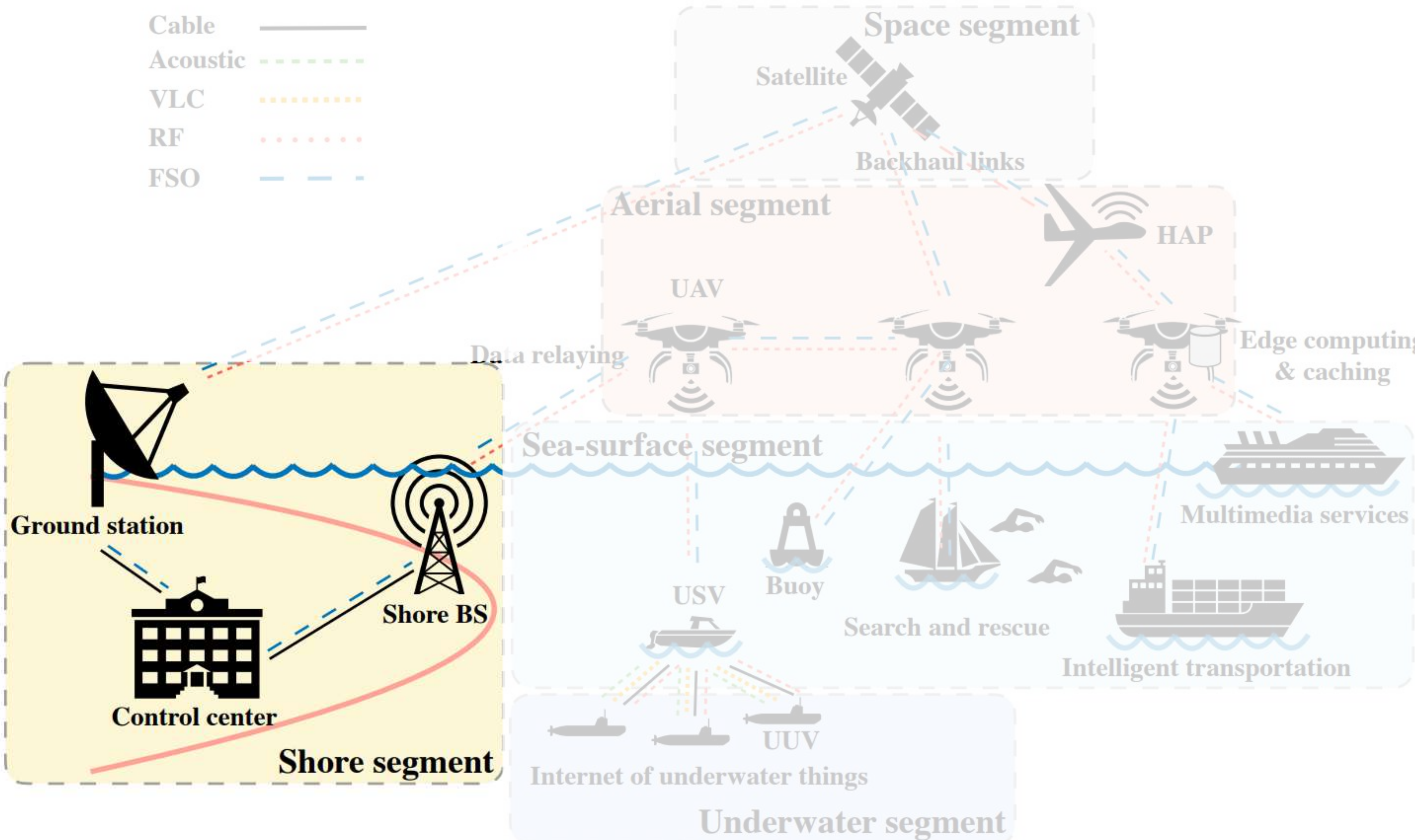
- Various satellite systems, e.g. geostationary earth orbit (GEO)-based INMARSAT and low-earth orbit (LEO) constellations, such as Starlink
- Back-up when shore BSs and aerial nodes fail to provide coverage to maritime nodes
- Backhauling/fronthauling to enable data availability across the maritime communication network (MCN)

Maritime communication network architecture



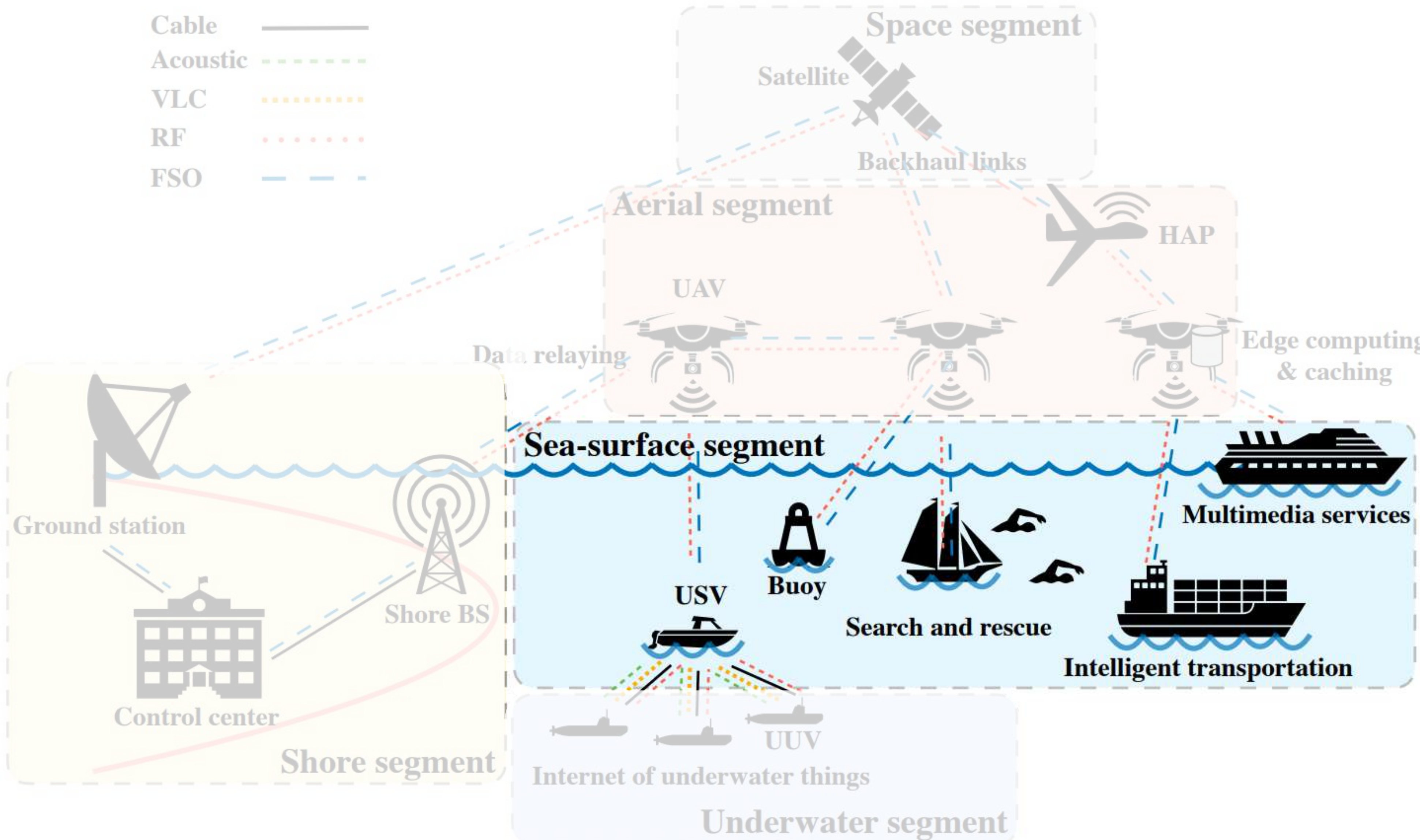
- Different aerial node types, including unmanned aerial vehicles (UAVs) and high-altitude platforms (HAPs)
- Dynamic provision of radio-resources to remote areas, low-latency compared to satellite links, reliable multi-hop transmissions and diverse wireless paths

Maritime communication network architecture



- Shore BSs provide coverage to nearby maritime nodes and UAVs, employing cellular standards
- Connectivity with the space segment allows data transmission within the broader MCN

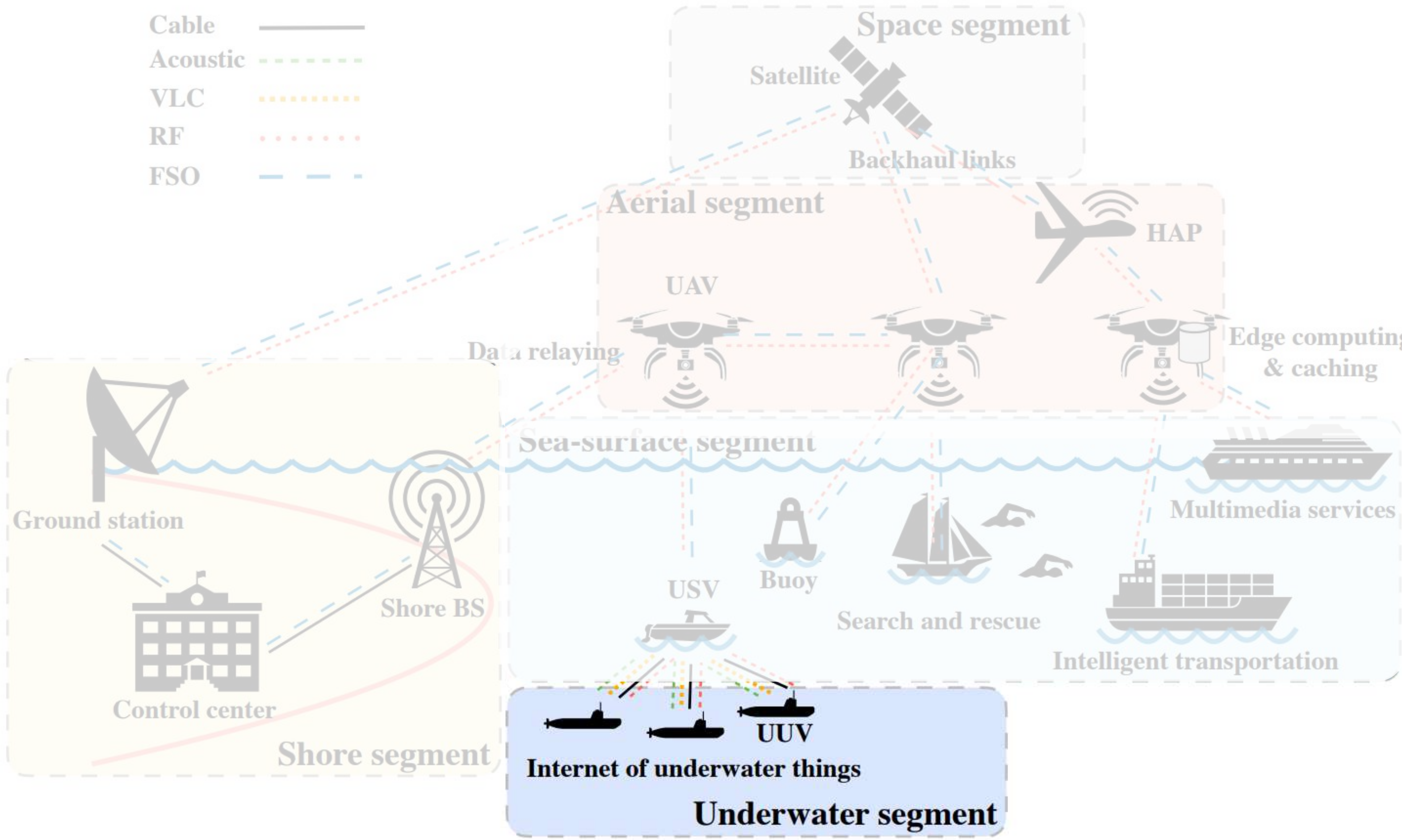
Maritime communication network architecture



- Unmanned surface vehicles (USVs), buoys and ships support intelligent transportation, environmental observation, underwater data relaying and search and rescue etc
- Novel paradigms include extended coverage giant cells, in the form of seaborne floating towers, being semisubmersible steel reinforced concrete platforms [Guan et al., 2021]

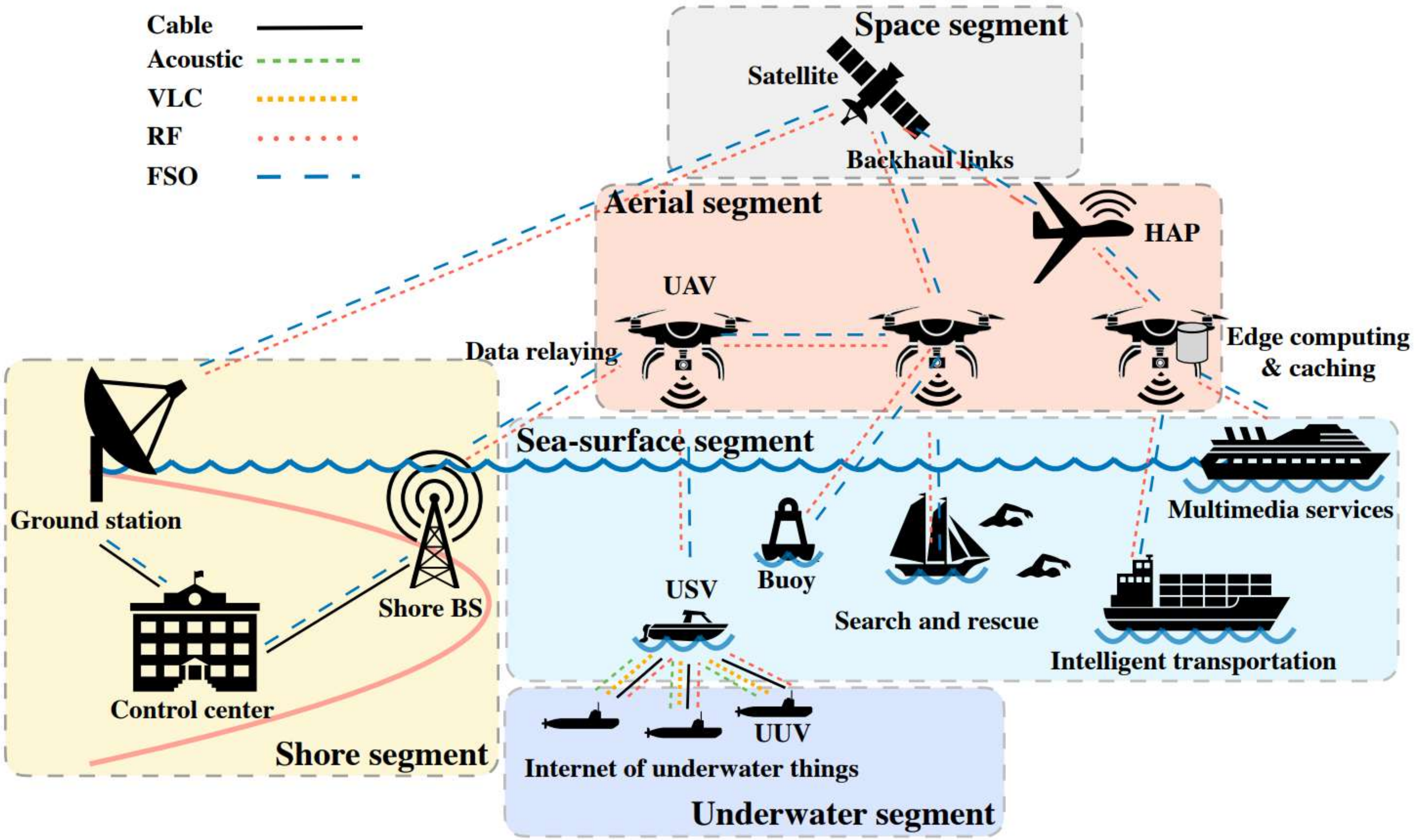
[Guan et al., 2021] S. Guan, J. Wang, C. Jiang, R. Duan, Y. Ren and T. Q. S. Quek, "MagicNet: The Maritime Giant Cellular Network," IEEE Commun. Mag., March 2021.

Maritime communication network architecture



- Sensors and unmanned underwater vehicles (UUVs) for marine data acquisition and transmission to UUVs, ships or UAVs
- Electromagnetic waves experience high attenuation in seawater and long-distance transmission relies on acoustic signals

Communication technologies



- Radio frequency (RF) communications (VHF, cellular, Wi-Fi standards)
- Free space optical (FSO) for large bandwidth and high data rate under line-of-sight (LoS)
- Visible-light communications (VLC) using light-emitting diodes (LEDs) to facilitate underwater communications
- Acoustic communications offer long-range underwater transmission but are characterized by small channel capacity and high propagation delay

Performance targets

- Energy efficiency/network lifetime maximization
- Low-latency communication
- Spectral efficiency
- Satellite/aerial-aided coverage improvement
- Low-complexity and distributed network operation

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- ☑ Research areas
  - Motivation
  - Power minimization
  - Delay minimization
  - Capacity improvement
  - Coverage improvement
  - Complexity reduction
- ☐ Conclusions
- ☐ Vision for future development

Motivation

6G-aided MCNs

Energy- constrained IoT devices and unmanned vehicles need low-power operation

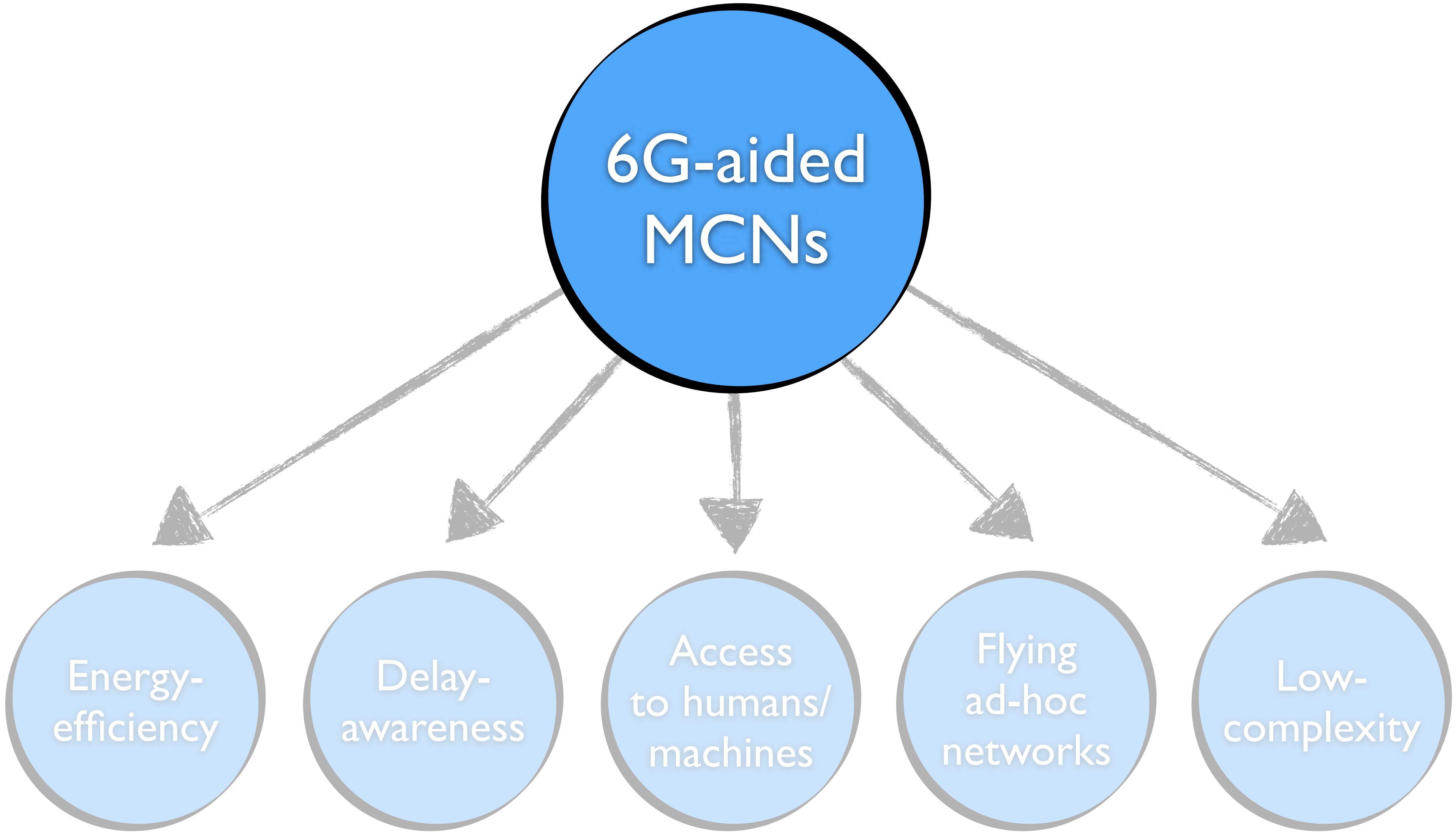
Low-latency maritime applications (UAVs/USVs/UUVs coordination, intelligent transportation etc.)

Mass connectivity must be guaranteed to coexisting users and IoT devices

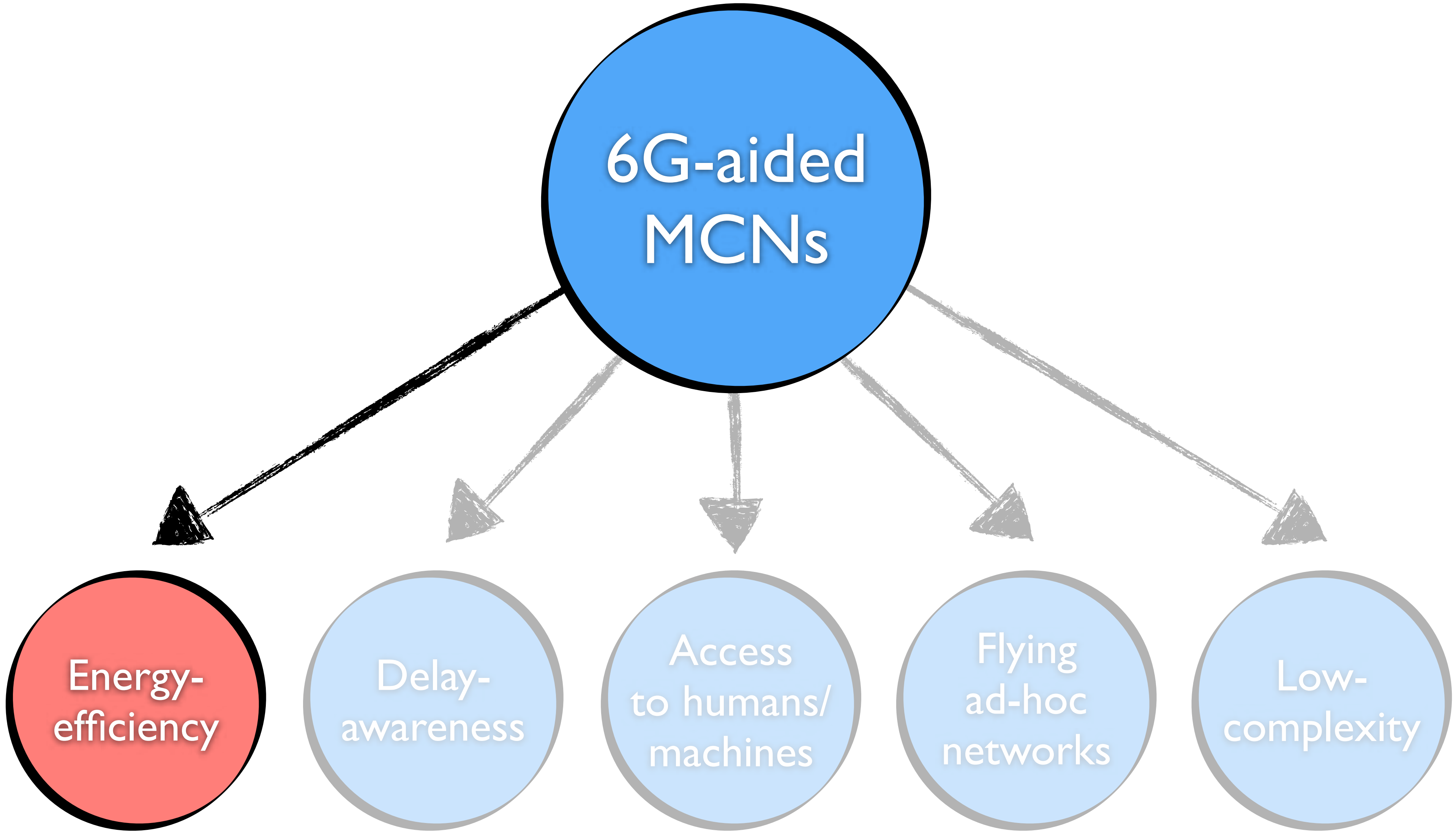
Deployment of aerial nodes is vital for improved coverage and access

Low-complexity network coordination is needed due to the massive number of users and IoT devices

Research areas



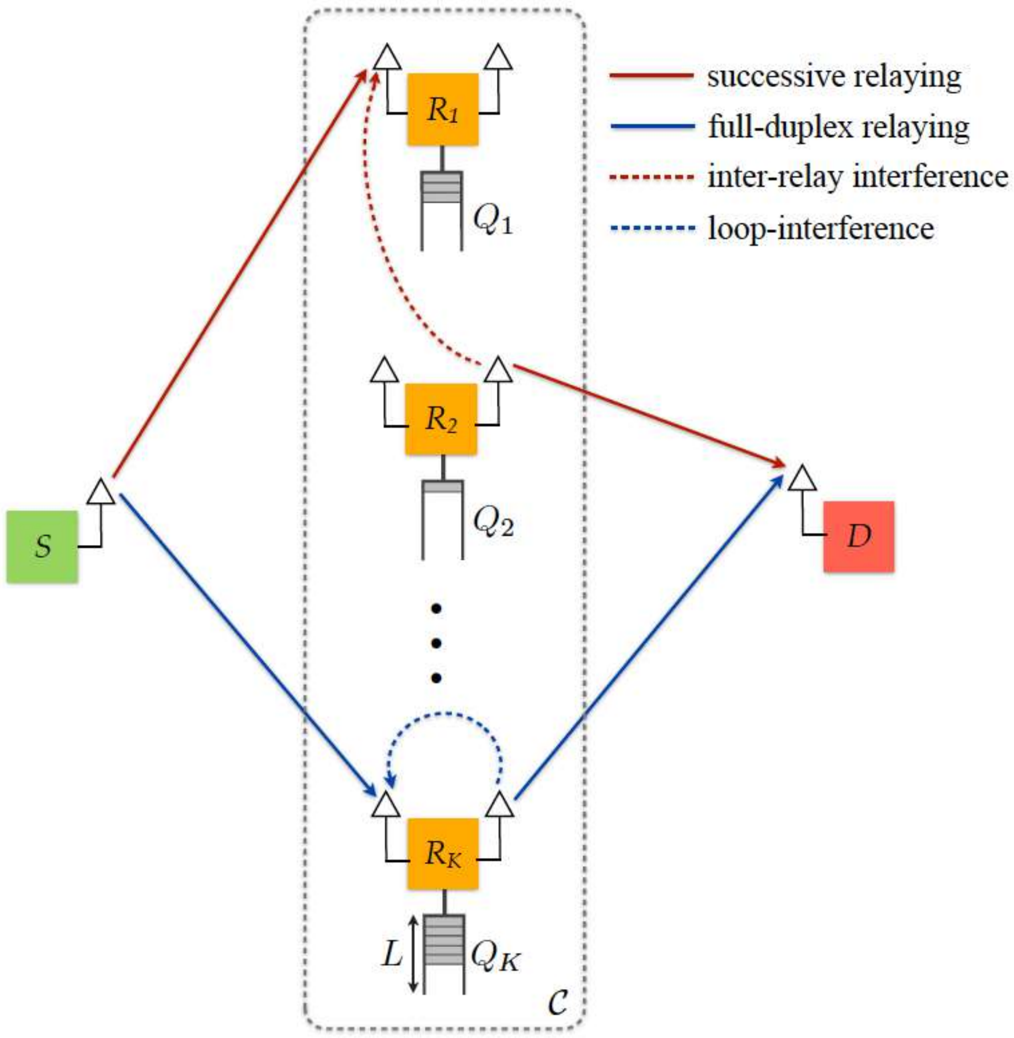
Research areas



CSI exploitation for power adaptation

Power minimization (1/2)

- Problem: When CSI is available and fixed rate is required, fixed transmit power is inefficient
- Solution: Hybrid algorithms integrating HD/ successive/FD modes with power adaptation
  - Selection of the relay/relay-pair requiring the minimum power for a pre-defined rate [Nomikos et al., 2015]
  - With multi-antenna relays, FD transmissions with power adaptation for LI mitigation are possible [Nomikos et al., 2016]
  - When statistical CSI is available, power adaptation is performed for the duration of a frame [Nomikos et al. 2018]



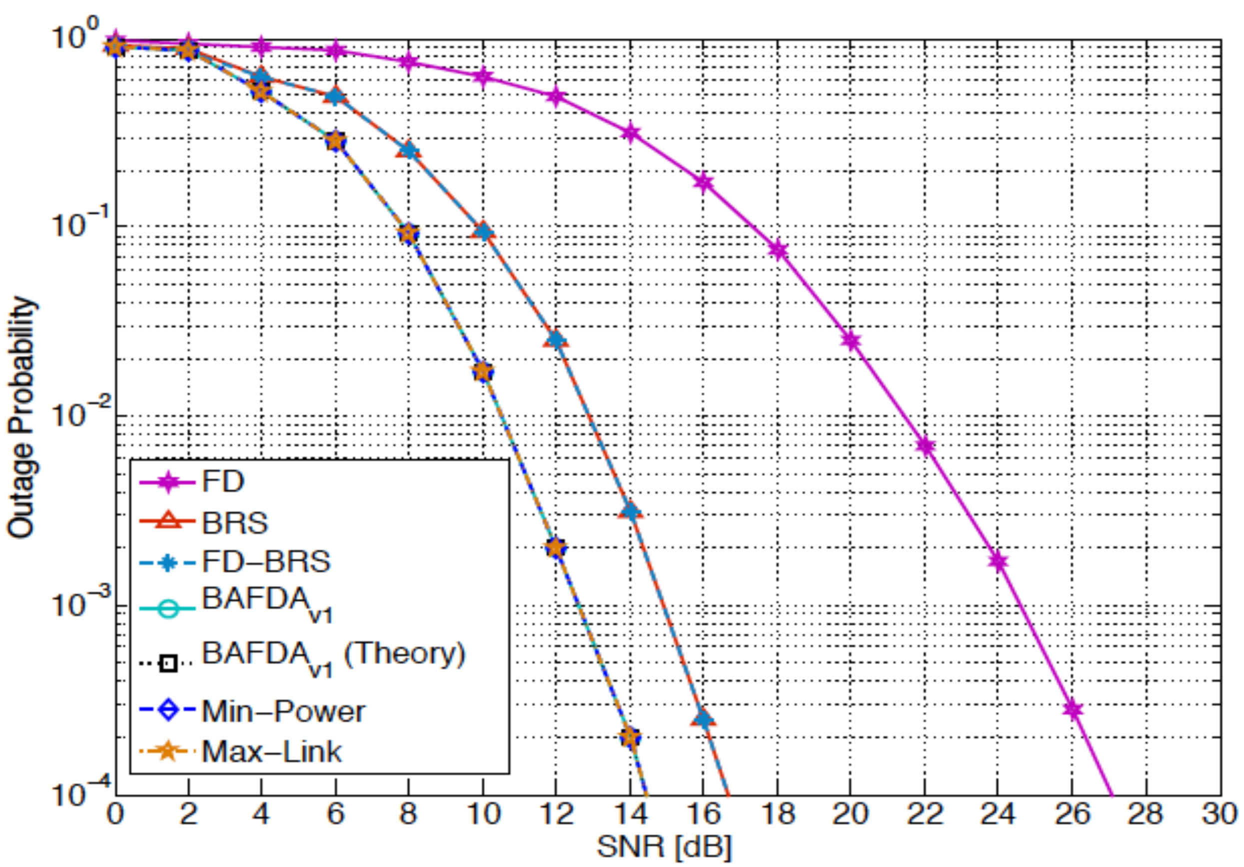
[Nomikos et al., 2015] N. Nomikos, T. Charalambous, I. Krikidis, D. N. Skoutas, D. Vouyioukas and M. Johansson, "A buffer-aided successive opportunistic relay selection scheme with power adaptation and inter-relay interference cancellation for cooperative diversity systems," IEEE Trans. on Commun., May 2015.

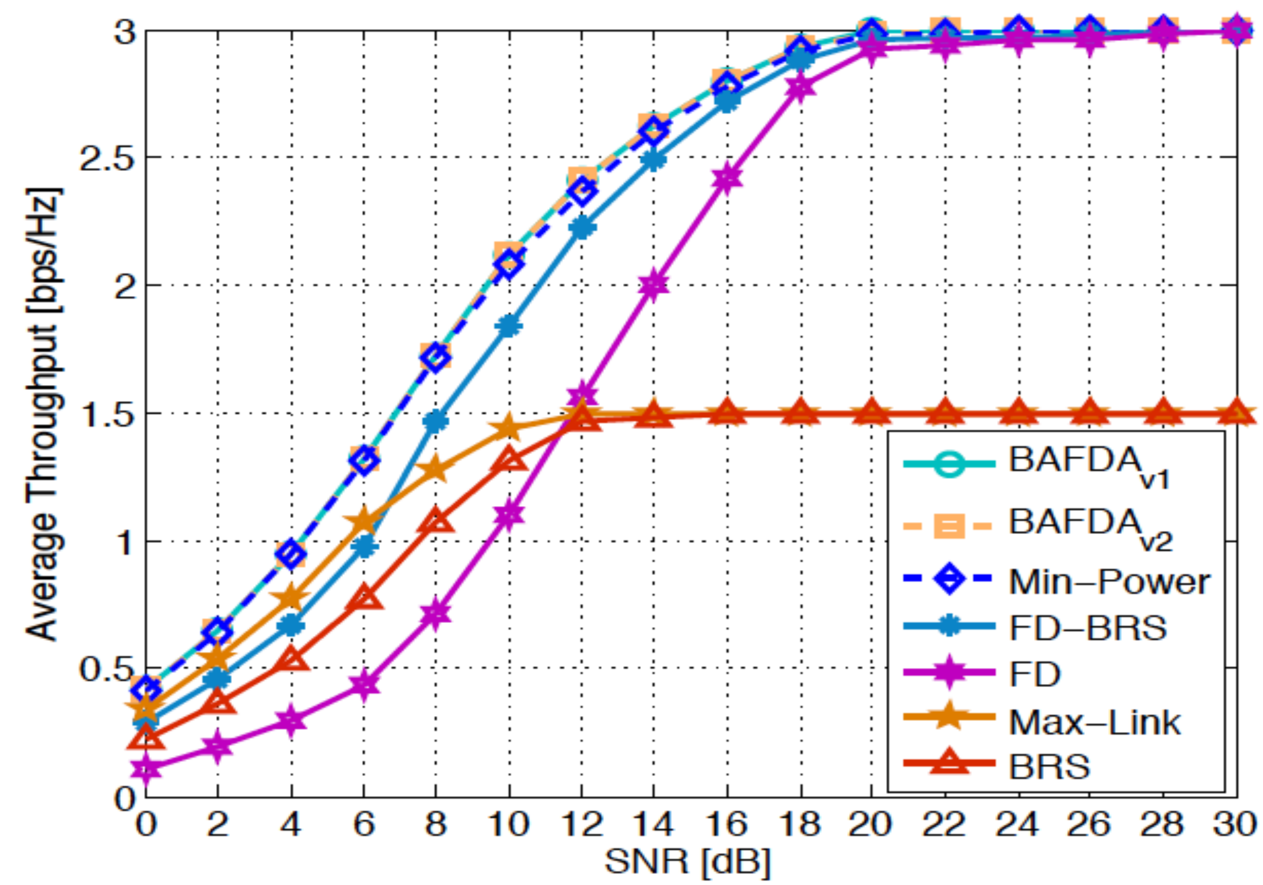
[Nomikos et al., 2016] N. Nomikos, T. Charalambous, I. Krikidis, D. N. Skoutas, D. Vouyioukas, M. Johansson and C. Skianis, "A survey on buffer-aided relay selection," IEEE Commun. Surv. & Tut., Secondquarter 2016.

[Nomikos et al., 2018] N. Nomikos, T. Charalambous, D. Vouyioukas, R. Wichman and G. K. Karagiannidis, "Power adaptation in buffer-aided full-duplex relay networks with statistical CSI," IEEE Trans. on Veh. Tech., Aug. 2018.

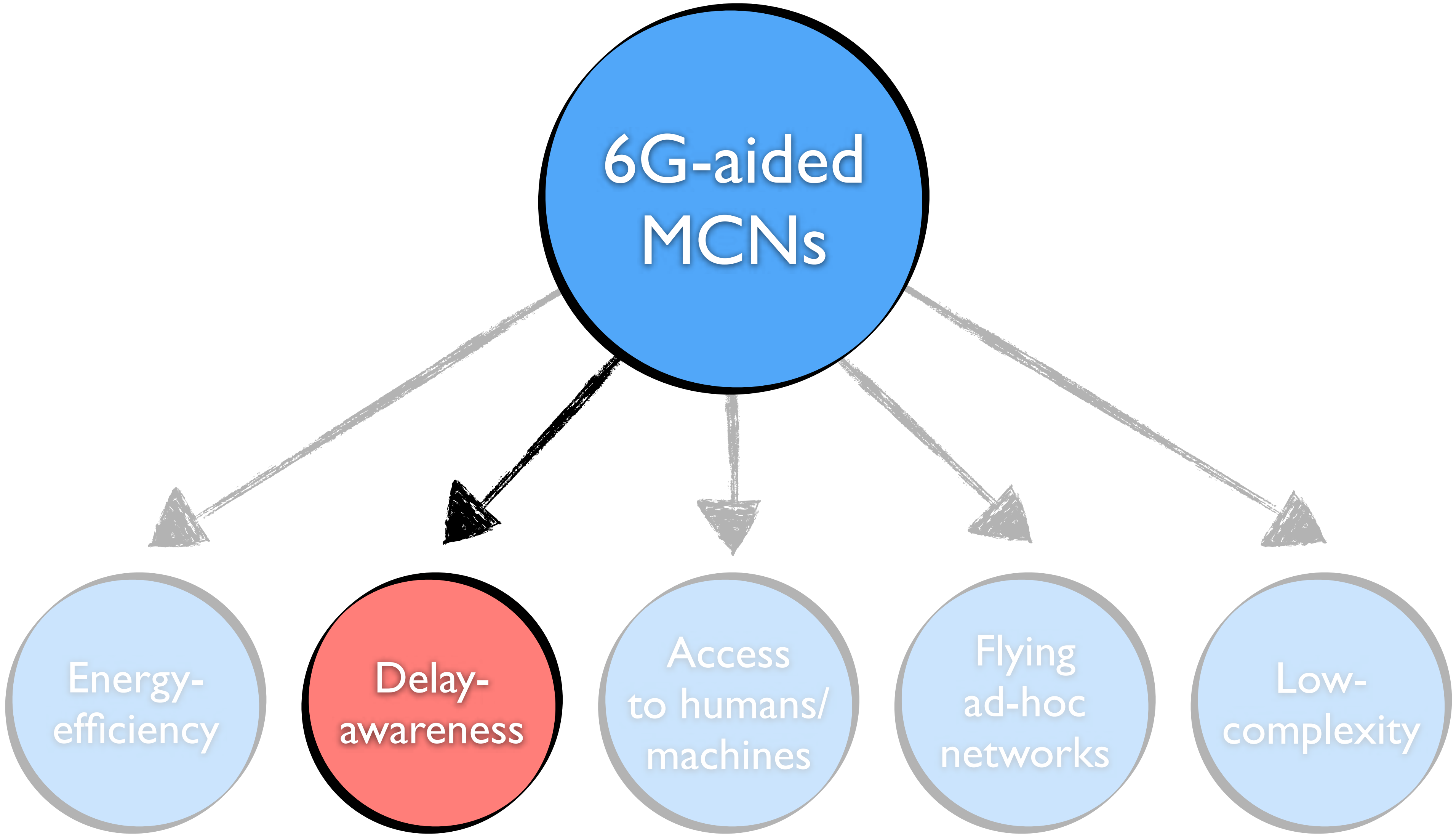
Power minimization (2/2)

- Using instantaneous CSI, the proposed algorithms (min-pow, BAFDA) provide:
  - Reduced outages, by relying on the robust max-link
  - Improved throughput, due to FD and successive transmissions





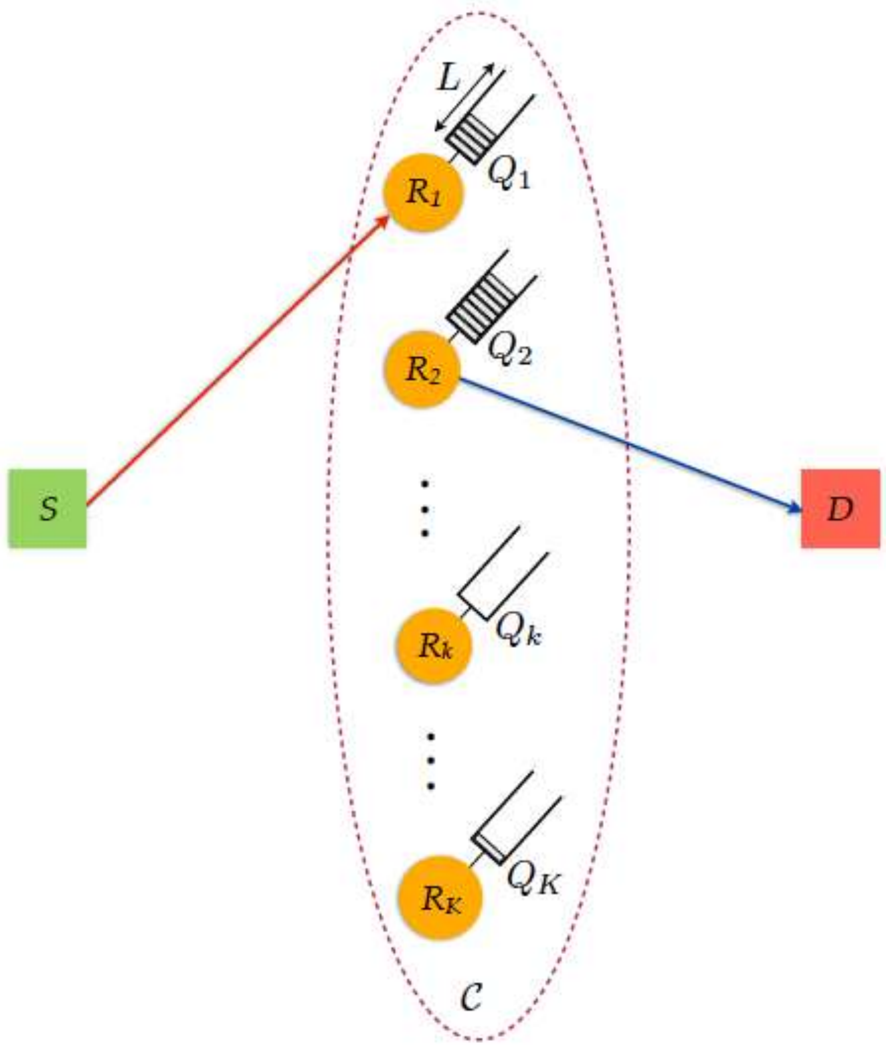
Research areas



Prioritize relay-destination links and exploit buffer status to avoid buffer starvation

Delay minimization (1/2)

- Problem: Buffers provide increased degrees of freedom for relay selection but may introduce delay
- Solution: Modified versions of hybrid relay selection (HRS) and max-link [Poulimeneas et al., 2016, Nomikos et al., 2018]
    - Selection chooses among the feasible source-relay (relay-destination) links the ones with the smallest (largest) data queue
    - The relay-destination link is prioritized and buffers are kept non-empty

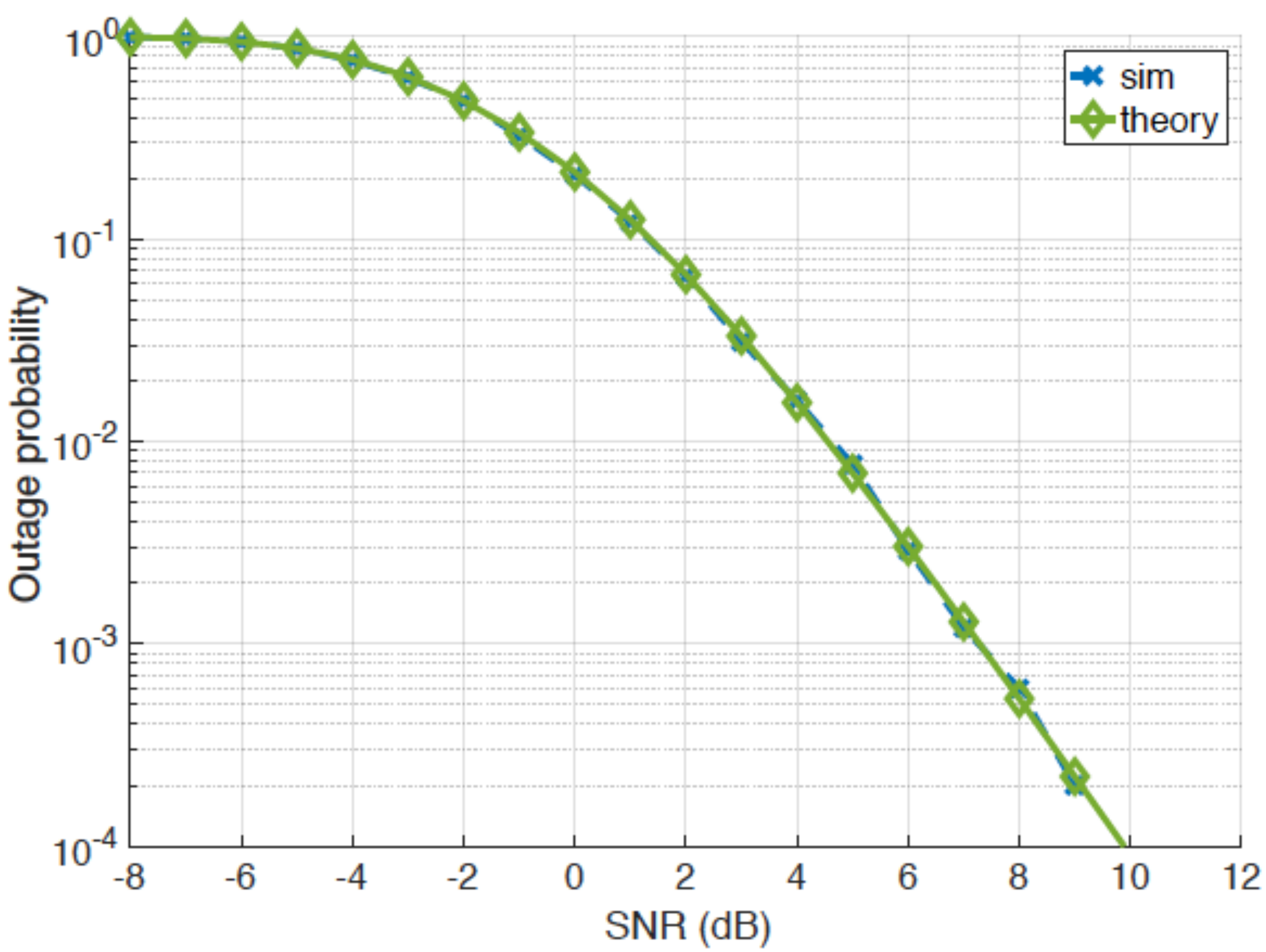


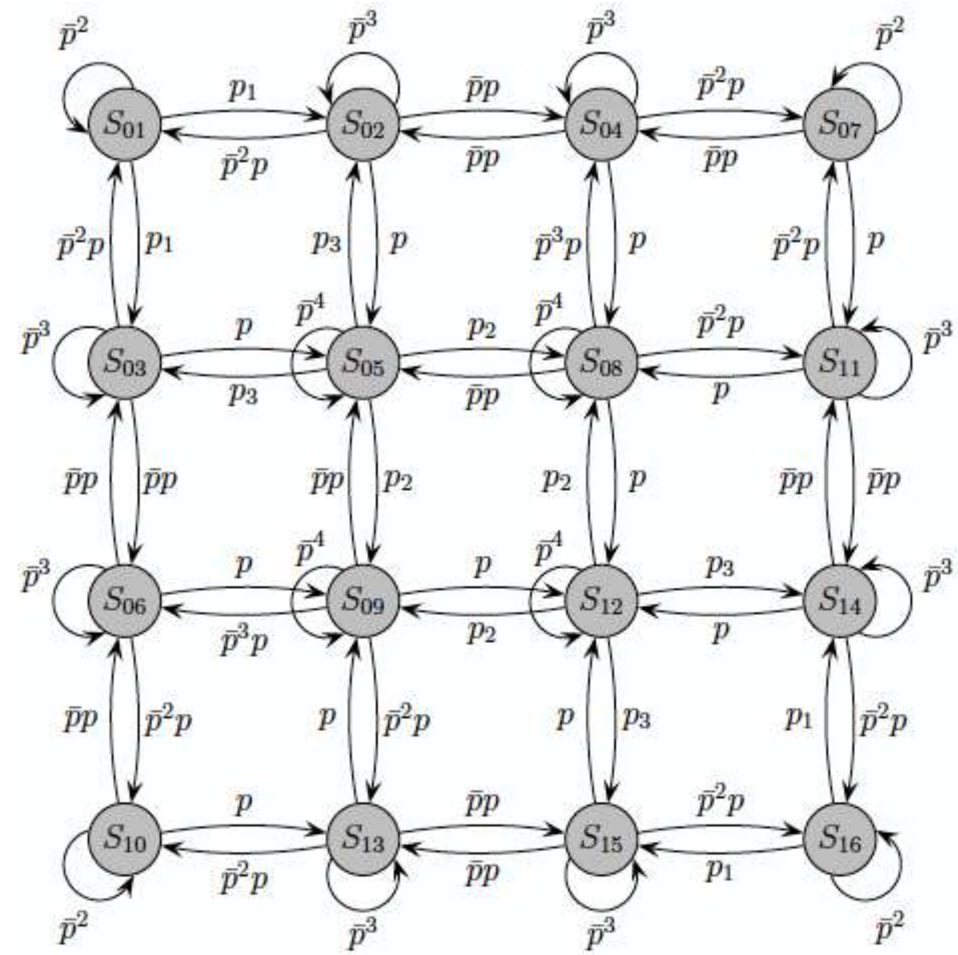
[Poulimeneas et al., 2016 (1)] D. Poulimeneas, T. Charalambous, N. Nomikos, I. Krikidis, D. Vouyioukas and M. Johansson, "A delay-aware hybrid relay selection policy," Int. Conf. on Telecommun. (ICT), Thessaloniki, Greece, May 2016 (Best-paper finalist).

[Nomikos et al., 2018] N. Nomikos, D. Poulimeneas, T. Charalambous, I. Krikidis, D. Vouyioukas and M. Johansson, "Delay- and diversity-aware buffer-aided relay selection policies in cooperative networks," IEEE Access, vol. 6, pp. 73531-73547, Nov. 2018.

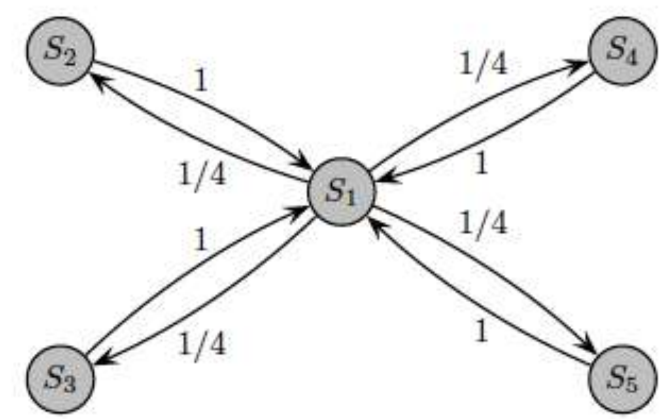
Delay minimization (2/2)

- Theoretical analysis showed that diversity can be maintained
- Asymptotic delay performance depends only on the number of relays
- The outage performance is improved, as buffer starvation is avoided



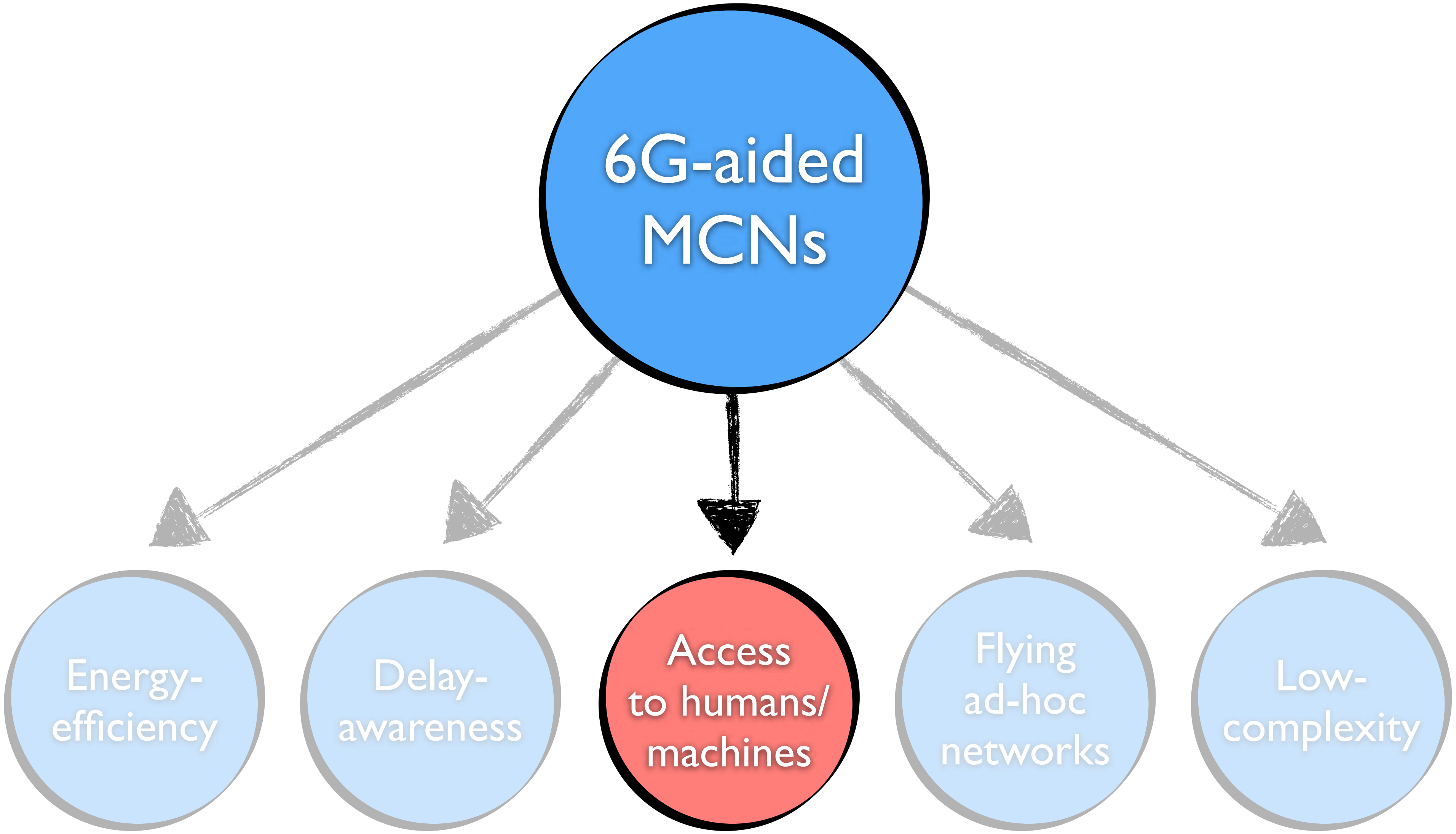


State	S_r
S_{01}	00
S_{02}	10
S_{03}	01
S_{04}	20
S_{05}	11
S_{06}	02
S_{07}	30
S_{08}	21
S_{09}	12
S_{10}	03
S_{11}	31
S_{12}	22
S_{13}	13
S_{14}	32
S_{15}	23
S_{16}	33



State	S_r
S_1	2222
S_2	1222
S_3	2122
S_4	2212
S_5	2221

Research areas



Non-orthogonal multiple access (NOMA), considering the CSI and rate requirements of users and IoT devices

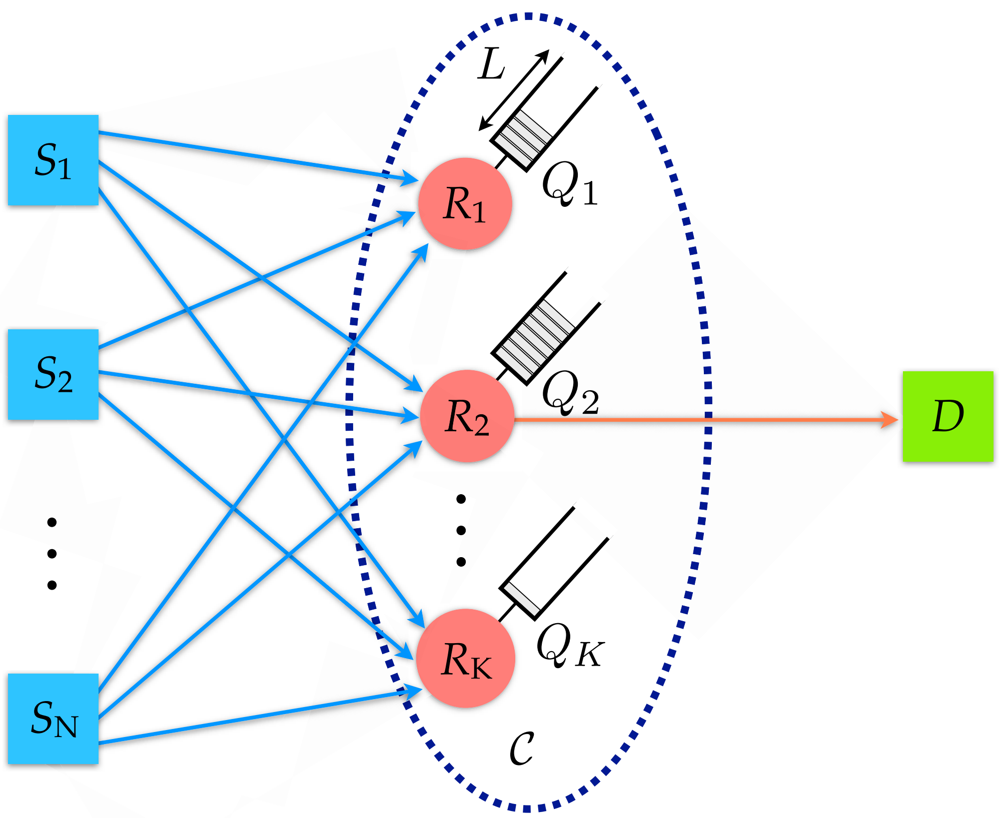
Capacity improvement (1/4)

- Problem: In the uplink, orthogonal access cannot satisfy mass connectivity and CSI acquisition by IoT devices results in high energy and complexity costs

- Solution: Dynamic decoding ordering at the relays allows the simultaneous reception of signals from users and IoT devices through successive interference cancellation (SIC) [Nomikos et al., 2019(1), Nomikos et al., 2019 (2)]

  - Flex-NOMA exploits CSI at the receiver and selects the relay with the largest buffer size

  - Users and machines do not need CSI, as they broadcast to the relays with fixed power

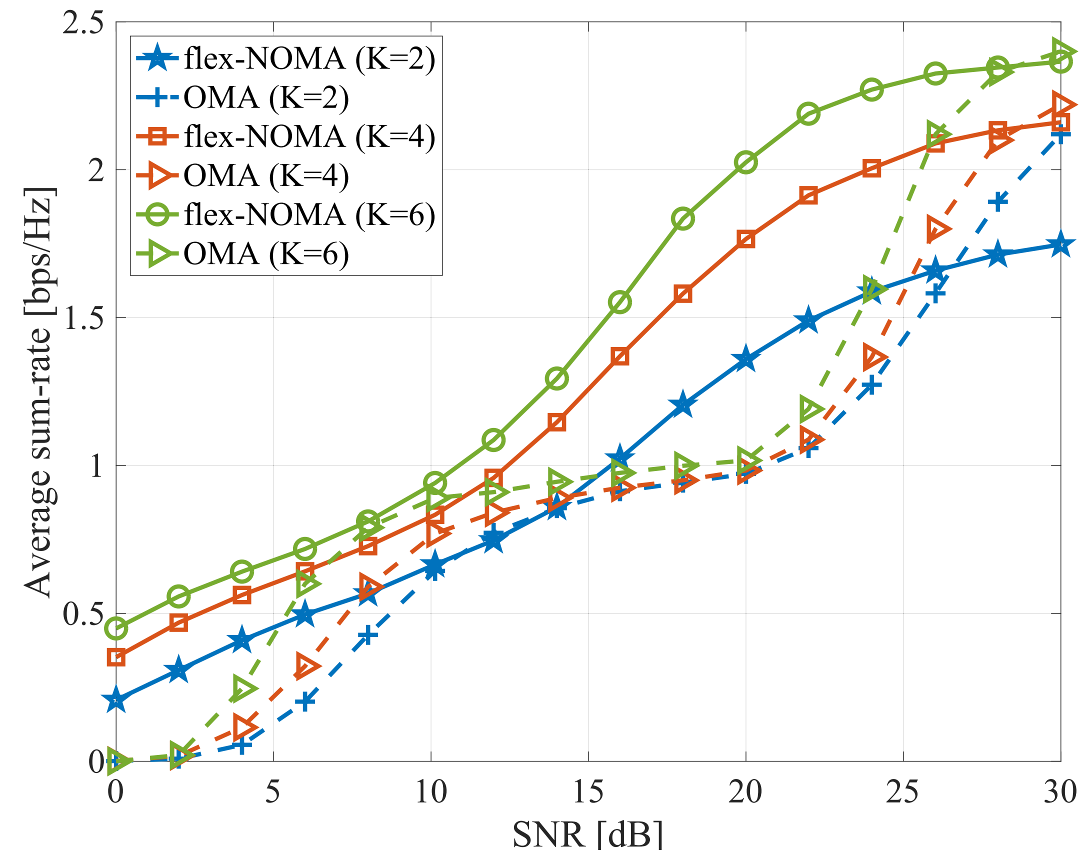


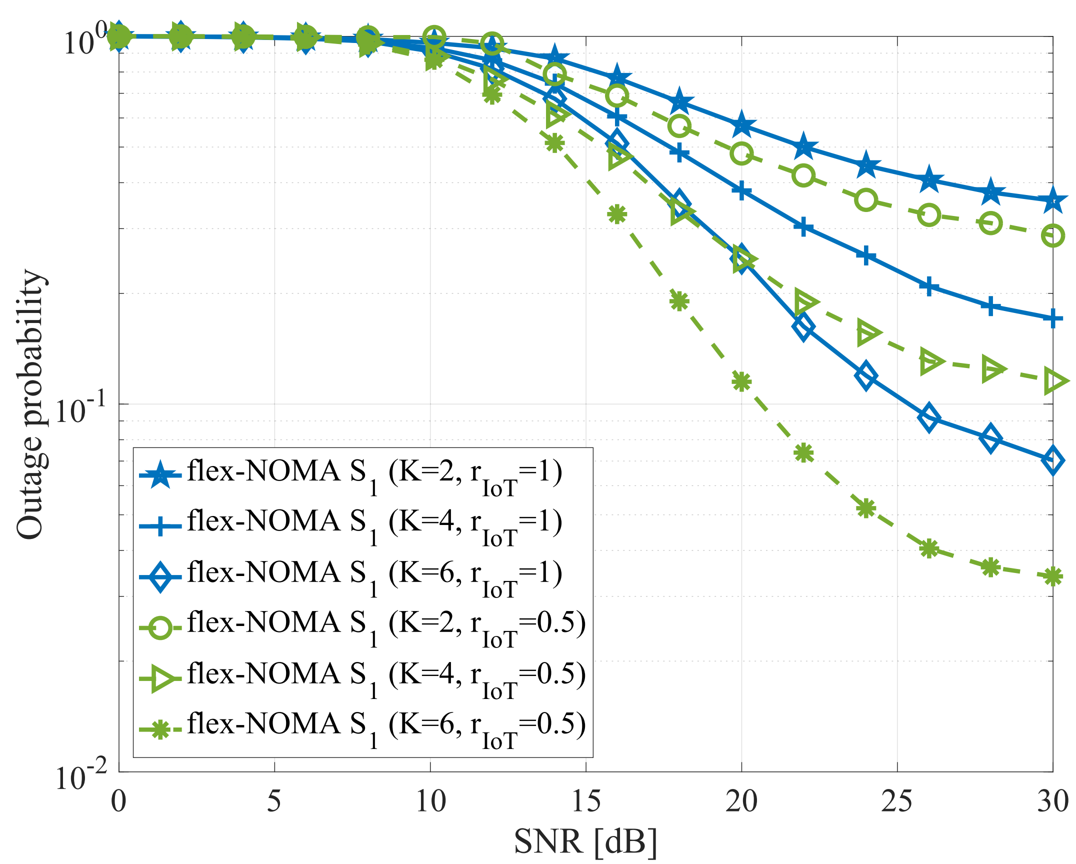
[Nomikos et al., 2019] N. Nomikos, T. Charalambous, D. Vouyioukas, G. K. Karagiannidis and R. Wichman, "Hybrid NOMA/OMA with buffer-aided relay selection in cooperative networks," IEEE Journal of Sel. Topics in Signal Proc., Jan. 2019.

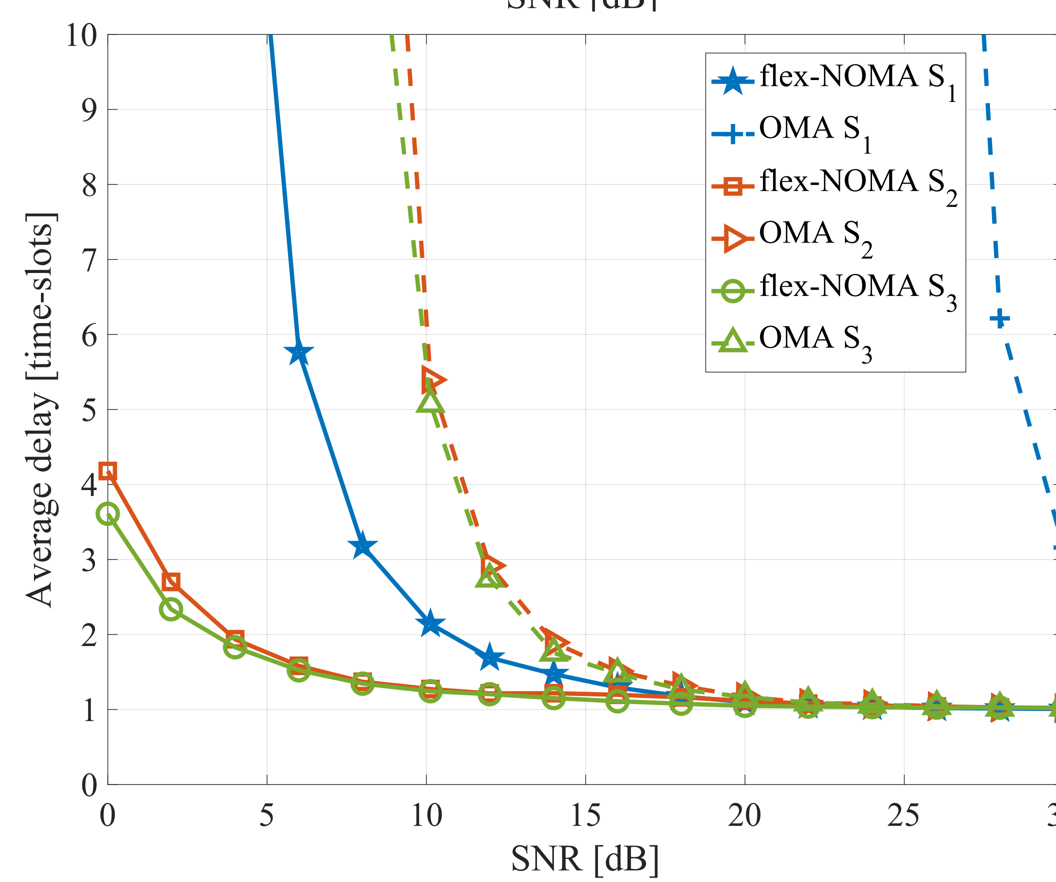
[Nomikos et al., 2019] N. Nomikos, E. T. Michailidis, P. Trakadas, D. Vouyioukas, T. Zahariadis, and I. Krikidis, "Flex-NOMA: Exploiting buffer-aided relay selection for massive connectivity in the 5G uplink," IEEE Access, July 2019.

Capacity improvement (2/4)

- Scenarios where a user coexists with two IoT devices and different rate requirements (r_{H2H} = 3 bps/Hz, r_{IoT} = 1 or 0.5 bps/Hz)
- Flex-NOMA offers improved outage performance to H2H communications, compared to OMA
- Higher average sum-rate is provided for varying SNR
- Lower delay is achieved by avoiding orthogonal resource allocation







Capacity improvement (3/4)

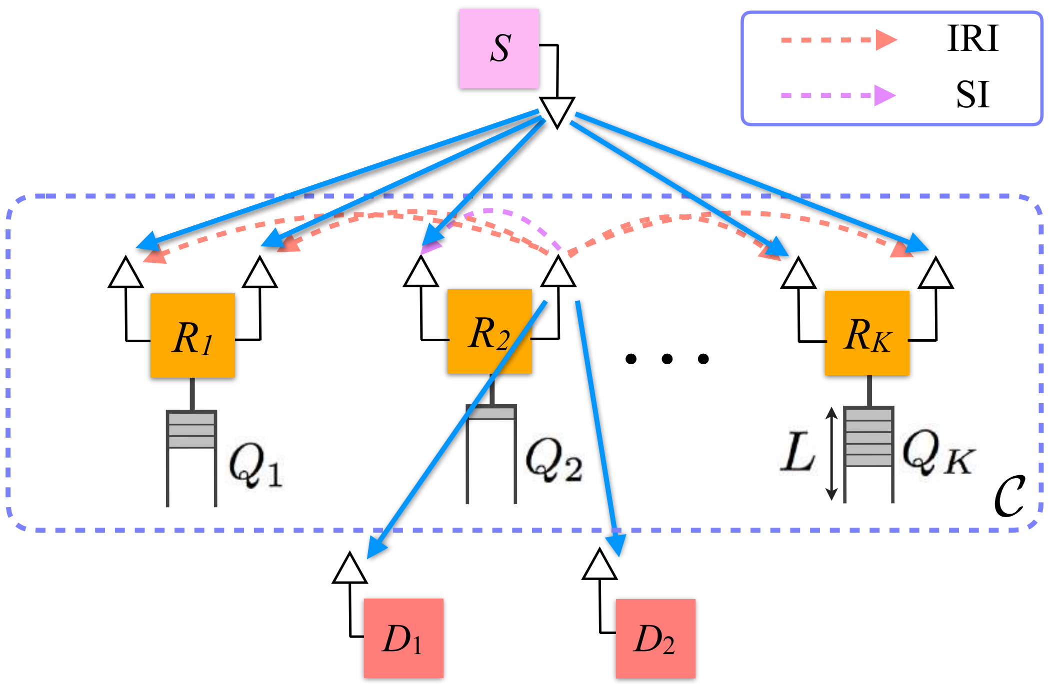
- Problem: The mass connectivity potential of NOMA decreases when HD relays are employed

- Solution: Integrating NOMA with buffer-aided FD relays for hybrid FD/successive/HD operation [Nomikos et al., 2019, Nomikos et al., 2020, Nomikos et al., 2021]

  - BA hybrid NOMA (BAHyNOMA) algorithm uses broadcasting in the first hop, avoiding CSI acquisition at the transmitter

  - Relays store packets, seamlessly switching among FD/HD operation when FD transmission is not possible

  - NOMA transmissions are performed in the second hop, considering the CSI and rate requirements of users and machines



[Nomikos et al., 2019] N. Nomikos, P. Trakadas, A. Hatziefremidis, and S. Voliotis, "Full-Duplex NOMA Transmission with Single-Antenna Buffer-Aided Relays," Electronics, Dec. 2019.

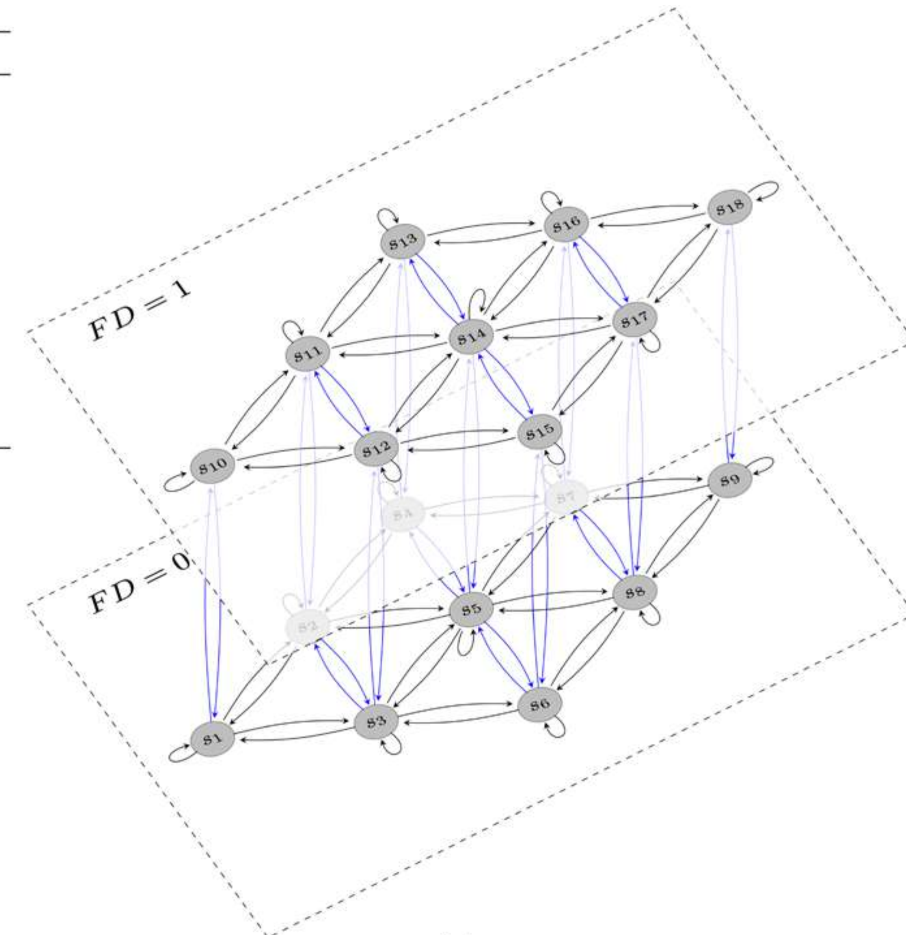
[Nomikos et al., 2020] N. Nomikos, T. Charalambous, D. Vouyioukas, R. Wichman and G. K. Karagiannidis, "Integrating broadcasting and NOMA in full-duplex buffer-aided opportunistic relay networks," IEEE Trans. on Veh. Tech., Aug. 2020.

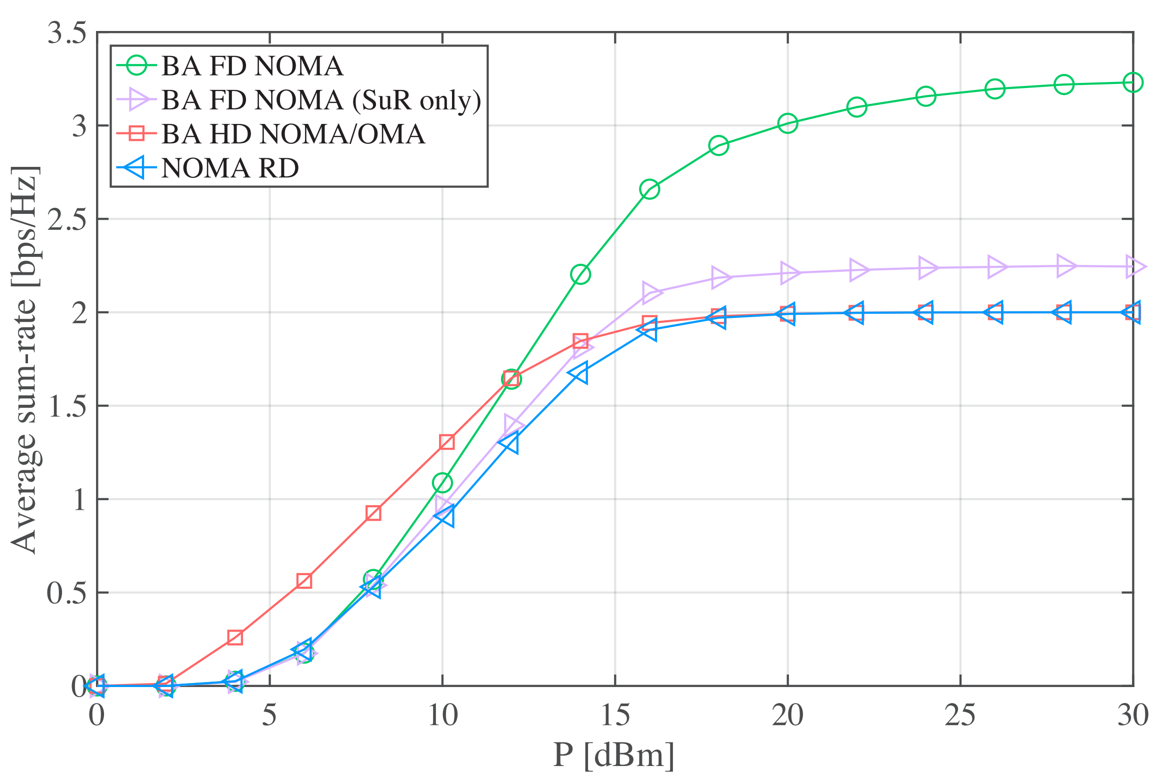
[Nomikos et al., 2021] N. Nomikos, T. Charalambous, D. Vouyioukas and G. K. Karagiannidis, "When buffer-aided relaying meets full duplex and NOMA," IEEE Wireless Commun., Feb 2021.

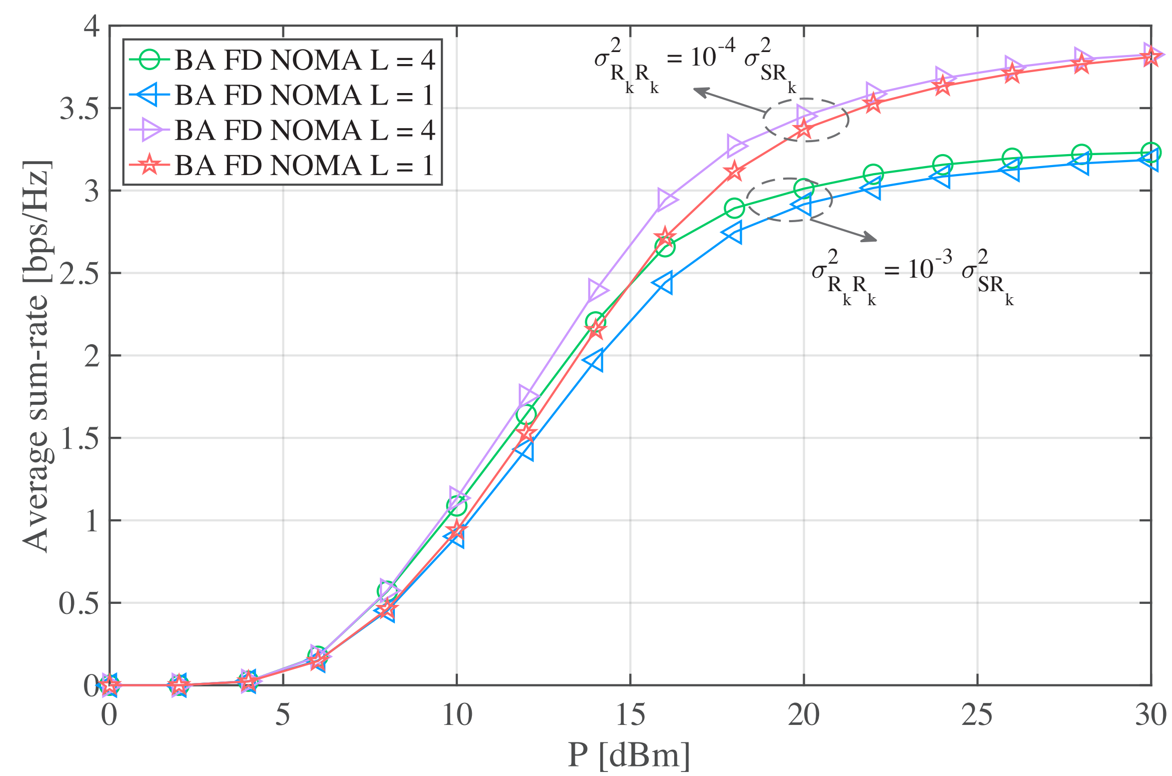
Capacity improvement (4/4)

- A two-user scenario where the first user is closer to the relays and the other at the network edge is investigated
- Sum-rate performance surpasses that of HD NOMA/OMA and OMA due to FD transmissions
- In cases with reduced LI, the FD performance gain increases

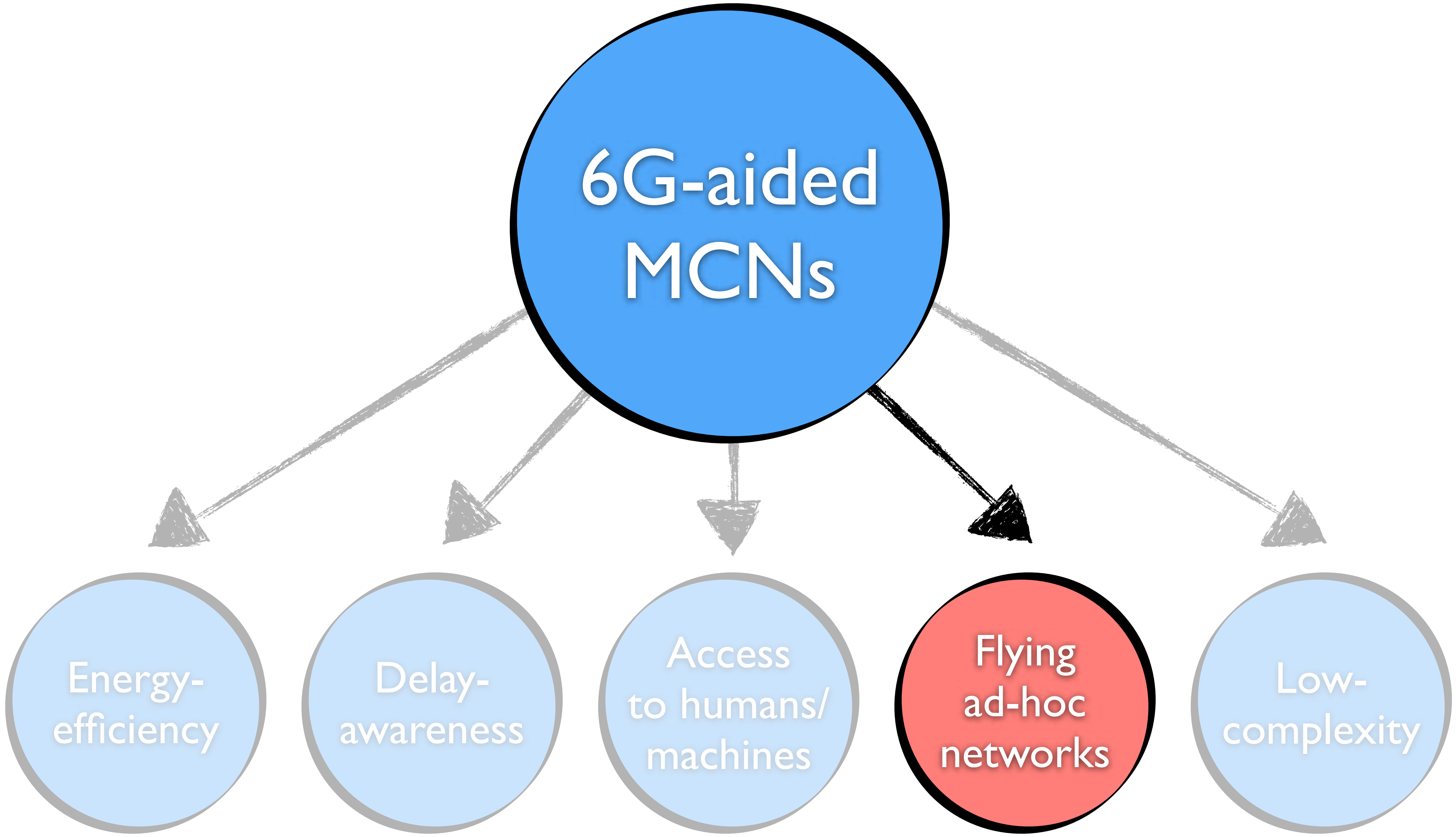
States		S_r
S_1	S_{10}	00
S_2	S_{11}	10
S_3	S_{12}	01
S_4	S_{13}	20
S_5	S_{14}	11
S_6	S_{15}	02
S_7	S_{16}	21
S_8	S_{17}	12
S_9	S_{18}	22







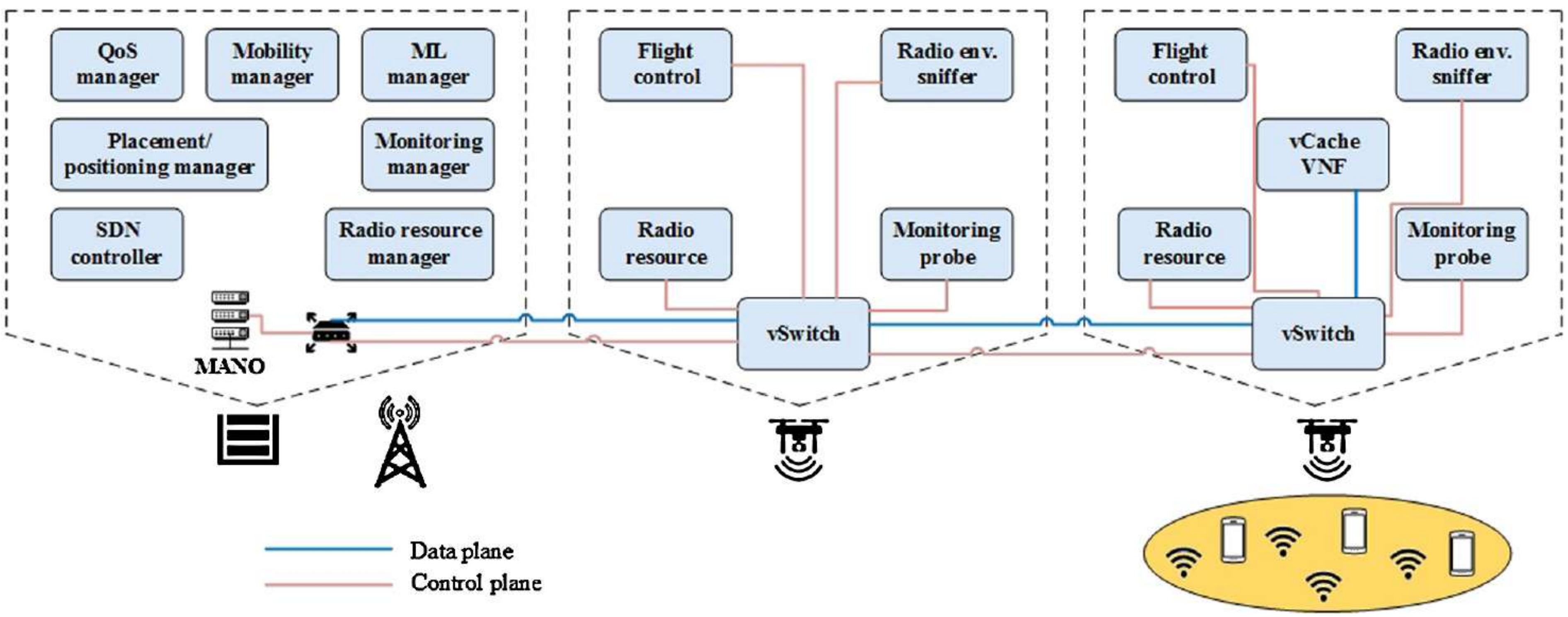
Research areas



Optimization of aerial nodes' position for improved coverage of users and IoT devices

Coverage improvement (1/2)

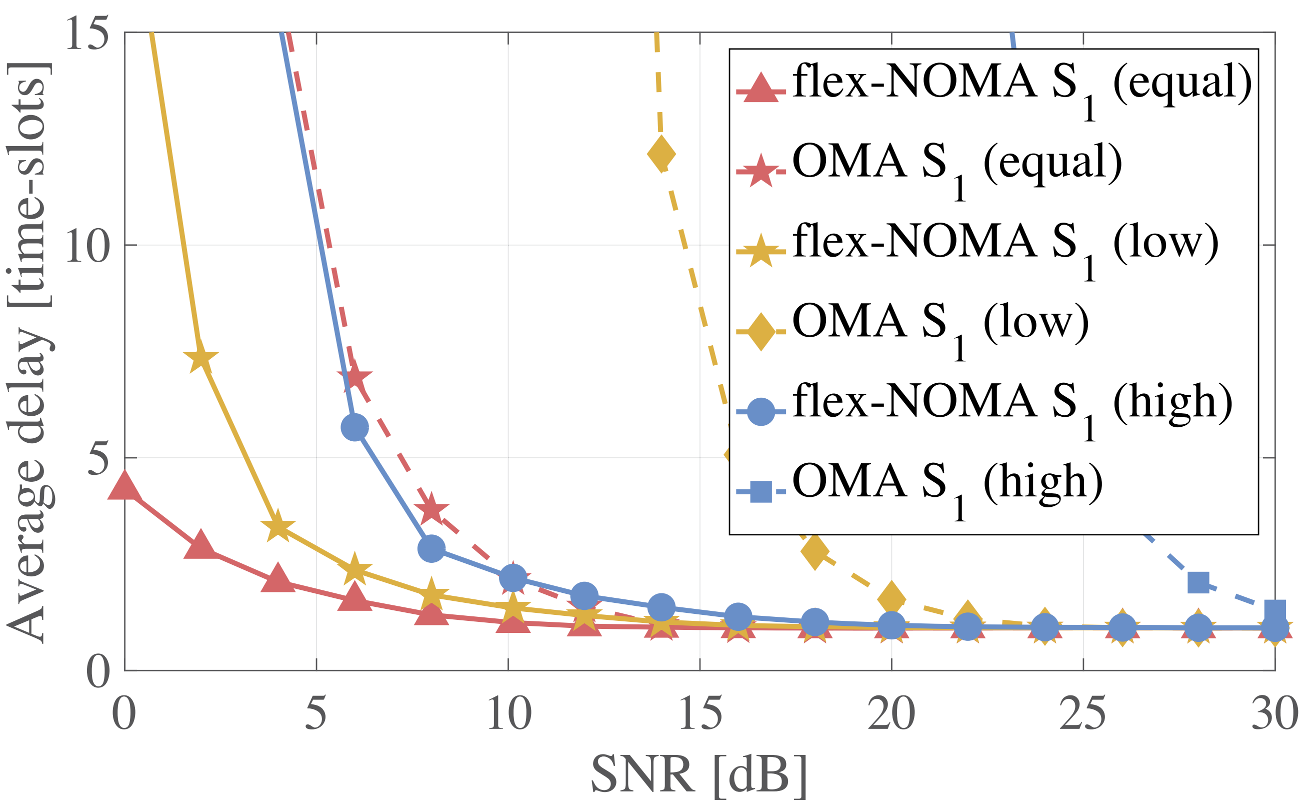
- Problem: Low channel asymmetry reduces the performance of NOMA when connecting coexisting users and IoT devices
- Solution: A flexible moving radio access network (RAN), consisting of aerial nodes which can increase channel asymmetry by repositioning [Nomikos et al., 2020]
  - The proposed RAN includes network softwarization and orchestration characteristics to dynamically deploy aerial nodes and resources
  - Radio access uses NOMA, exploiting channel / rate asymmetry of users and IoT devices

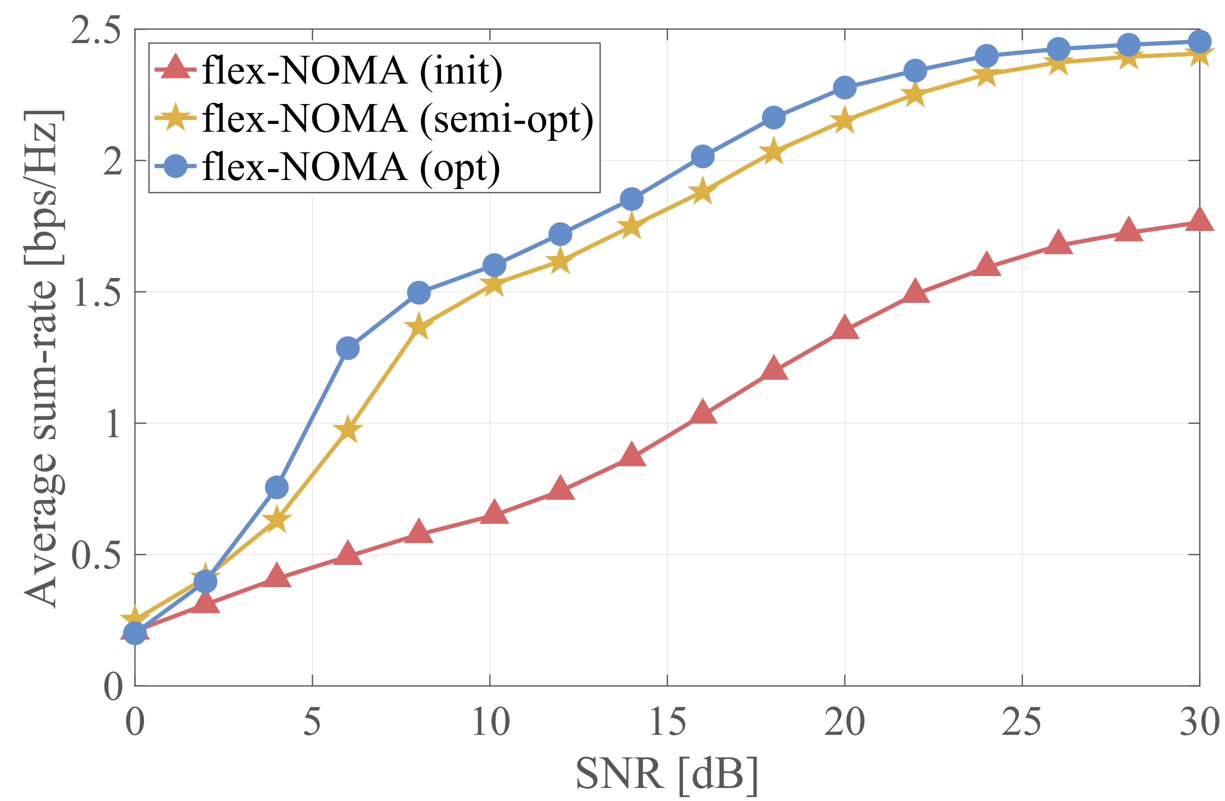


[Nomikos et al., 2020] N. Nomikos, E. T. Michailidis, P. Trakadas, D. Vouyioukas, H. Karl, J. Martrat, T. Zahariadis, K. Papadopoulos, S. Voliotis, " UAV-based moving 5G RAN for massive connectivity of mobile users and IoT devices," Vehicular Commun., Oct. 2020.

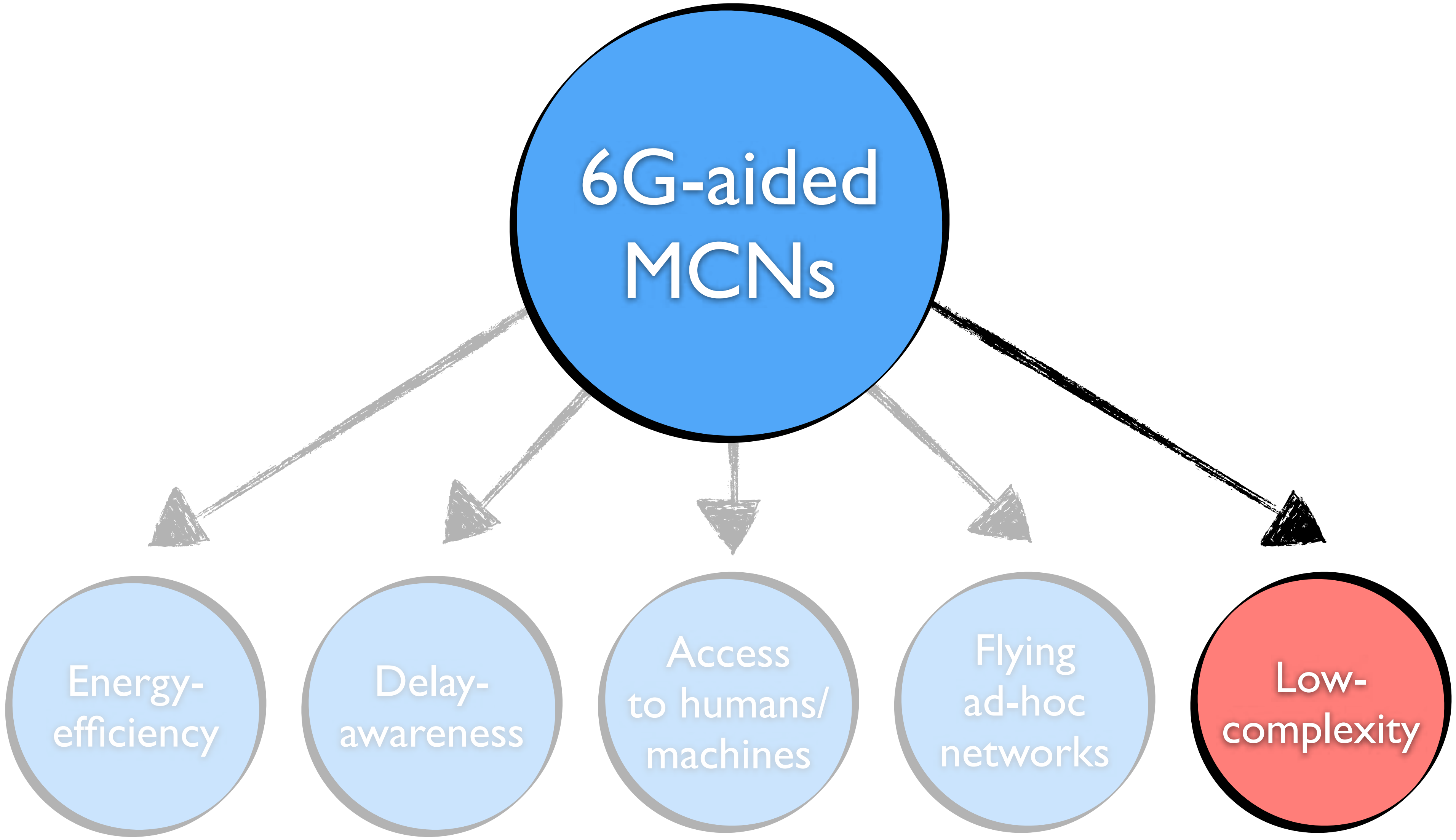
Coverage improvement (2/2)

- Scenarios where a user coexists with two IoT devices with different rate requirements
  - NOMA reduces the delay over OMA independently of the rate asymmetry
- Different cases of optimized flying RA nodes positioning for increased channel asymmetry and improved NOMA (*K = 2*)
  - When aerial nodes reposition for higher channel asymmetry sum-rate increases





Research areas

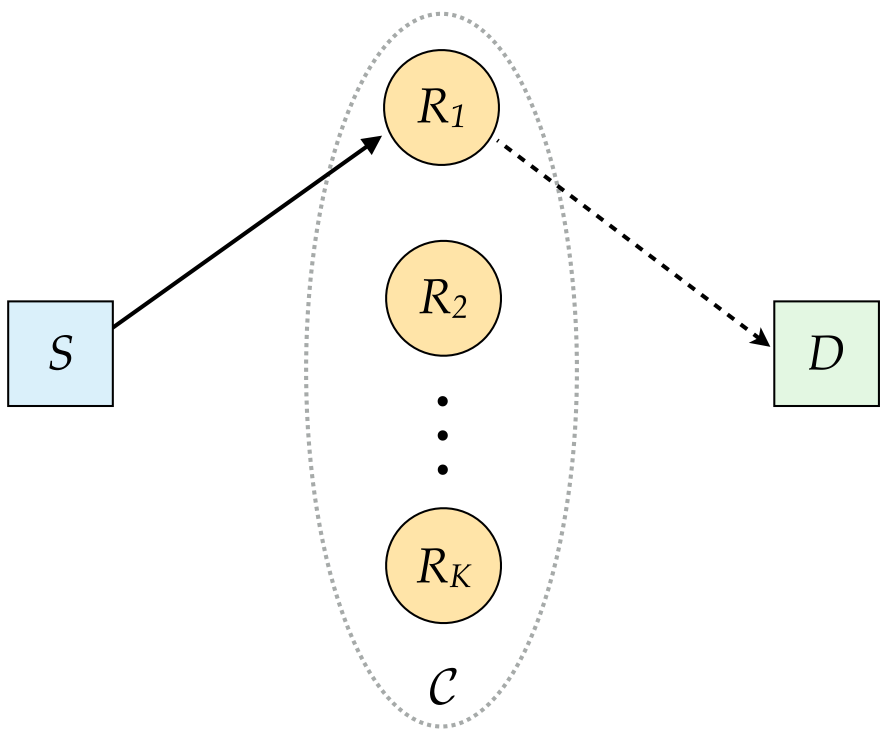


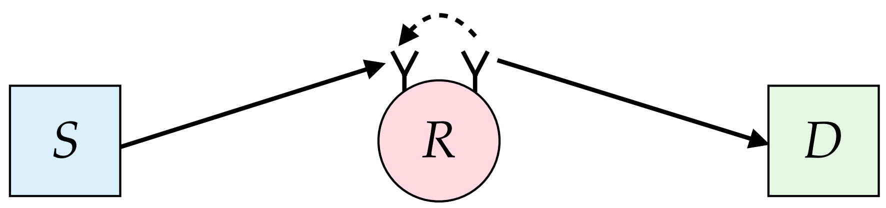
Avoid excessive network coordination overheads to support the massive number of users and IoT devices

Complexity reduction (1/2)

- Problem: Relay selection and power control mechanisms incur increased network coordination overheads

- Solution: The adoption of reinforcement learning through multi-armed bandits (MAB) eliminates the need for CSI, using one-bit ACK/NACK feedback [Nomikos et al., 2020, Nomikos et al., 2021]
  - The use of upper confidence bound (UCB) algorithms guarantees that average regret grows logarithmically over the time horizon
  - Distributed network operation is achieved by integrating synchronized timers at the relays into the MAB framework





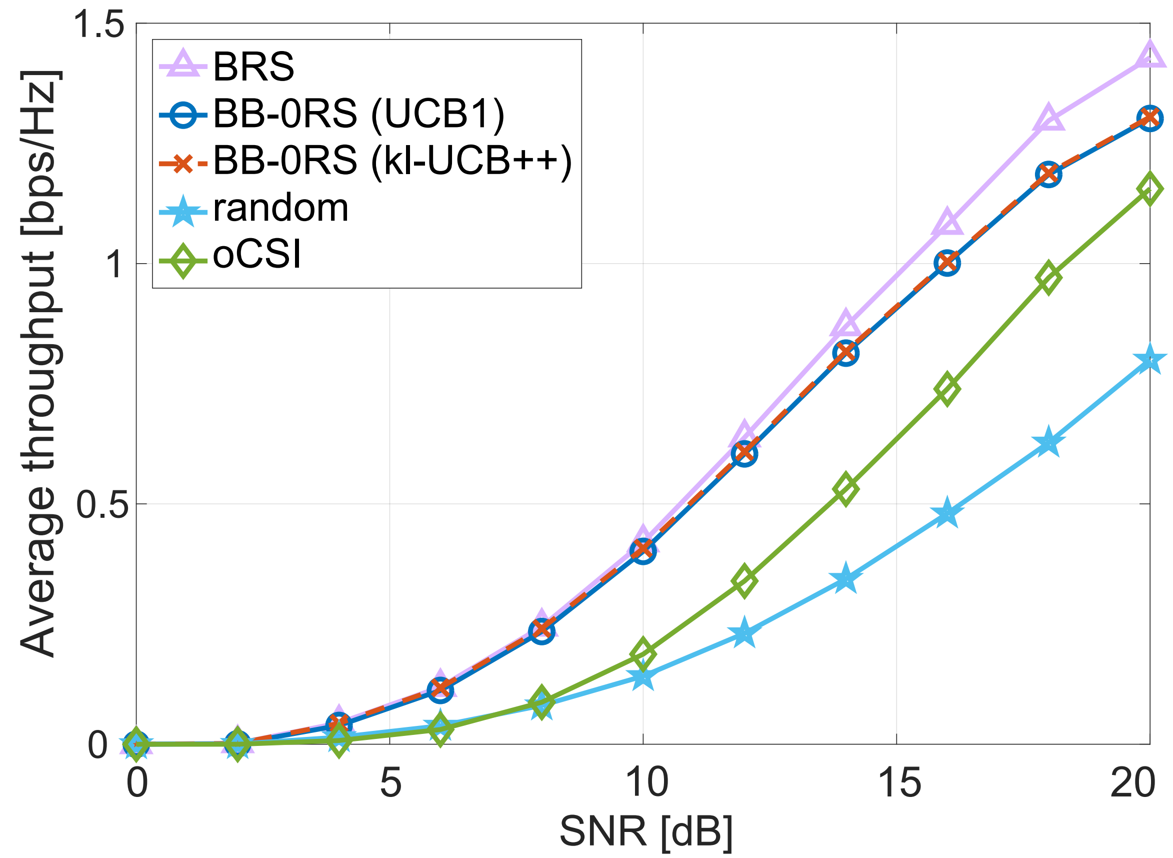
[Nomikos et al., 2020] N. Nomikos, S. Talebi, R. Wichman, and T. Charalambous, “Bandit-based relay selection in cooperative networks over unknown stationary channels,” IEEE International Workshop on Machine Learning for Signal Proc. (MLSP), Espoo, Finland, Oct. 2020.

[Nomikos et al., 2022] N. Nomikos, M. S. Talebi, T. Charalambous and R. Wichman, "Bandit-Based Power Control in Full-Duplex Cooperative Relay Networks With Strict-Sense Stationary and Non-Stationary Wireless Communication Channels," IEEE Open Journal of the Communications Society, February 2022.

Complexity reduction (2/2)

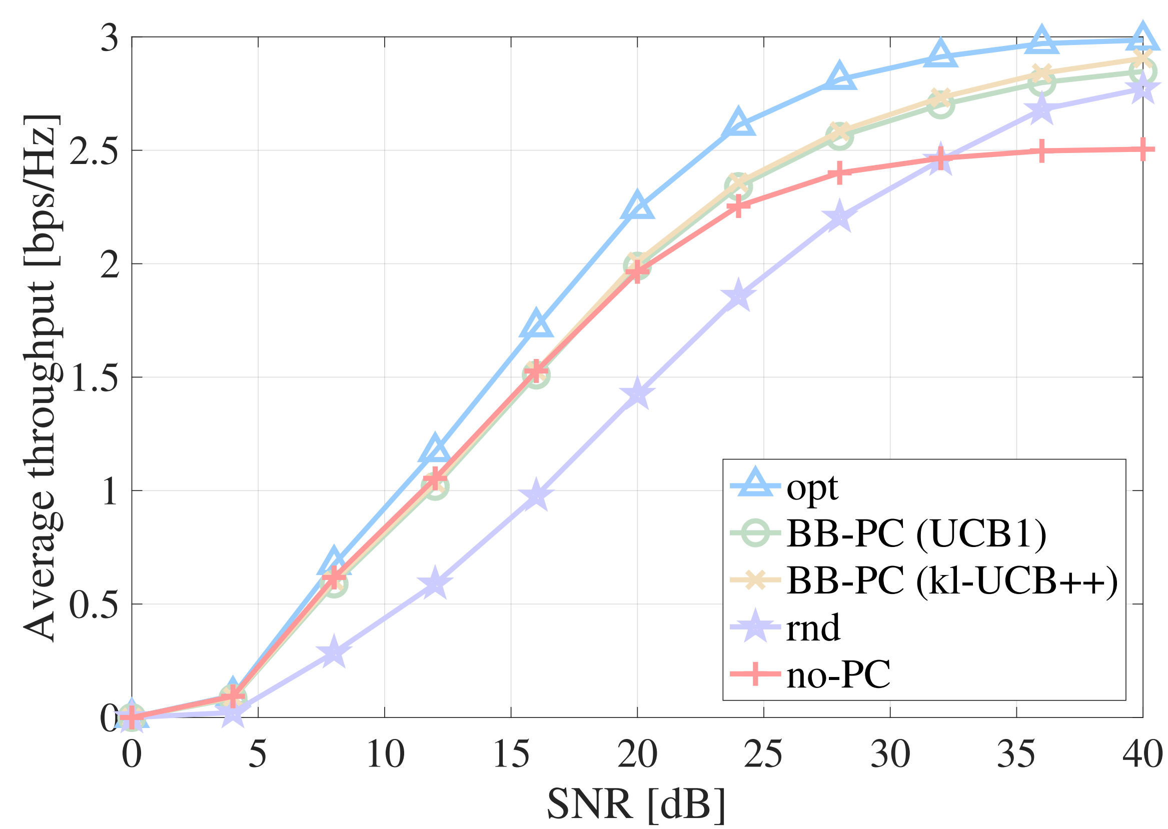
- Bandit-based opportunistic relay selection (BB-ORS) has a small performance gap compared to optimal relay selection with full CSI knowledge

- BB-ORS offers significantly higher average throughput over random relay selection and relay selection with outdated CSI (oCSI)



- A small performance gap is observed compared to optimal power control with full CSI knowledge

- In FD relay networks, bandit-based power control (BB-PC) outperforms the cases without power control (no-PC) and random power level selection



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Conclusions

- Distributed and low-complexity opportunistic relaying algorithms were proposed, for hardware- and energy-constrained maritime IoT devices and vessels
- Hybrid HD/FD/successive relaying reduces outages, power expenditure and delays and increases throughput
- NOMA showed tremendous mass connectivity potential for users and IoT devices
- Various CSI cases were examined for users and IoT devices with different capabilities
- Reinforcement learning was integrated in multi-hop networks with promising results

…but still many 6G techniques and maritime topologies to take into consideration!

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Vision for future development

- Coexisting users and IoT devices stresses backhaul/fronthaul of ground and maritime networks, needing radical offloading paradigms, e.g. reinforcement learning-aided caching [Nomikos et al., 2022 (1)]
- There is increased potential for integrating machine learning algorithms in maritime communication networks, e.g. multi-armed bandits for trajectory design
- Maritime networks and the Internet of Underwater Things, comprising vessels, platforms, users and machines require novel grant-free non-orthogonal multiple access and the use of intelligent reflecting surfaces to maximize the capacity
- Aerial networks will coexist with shore base stations and satellites, necessitating dynamic backhauling/fronthauling in maritime settings [Nomikos et al., 2022 (2)]

[Nomikos et al., 2022 (1)] N. Nomikos, S. Zoupanos, T. Charalambous, and I. Krikidis "A survey on reinforcement learning-aided caching in mobile edge network," IEEE Access, January 2022.

[Nomikos et al., 2022 (2)] N. Nomikos, P. K. Gkonis, P. S. Bithas, and P. Trakadas "A survey on UAV-aided maritime communications: Deployment considerations, applications, and future challenges," arXiv, September 2022.

Thank you!

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Questions?