Intelligent surface-assisted communications, localization, and sensing

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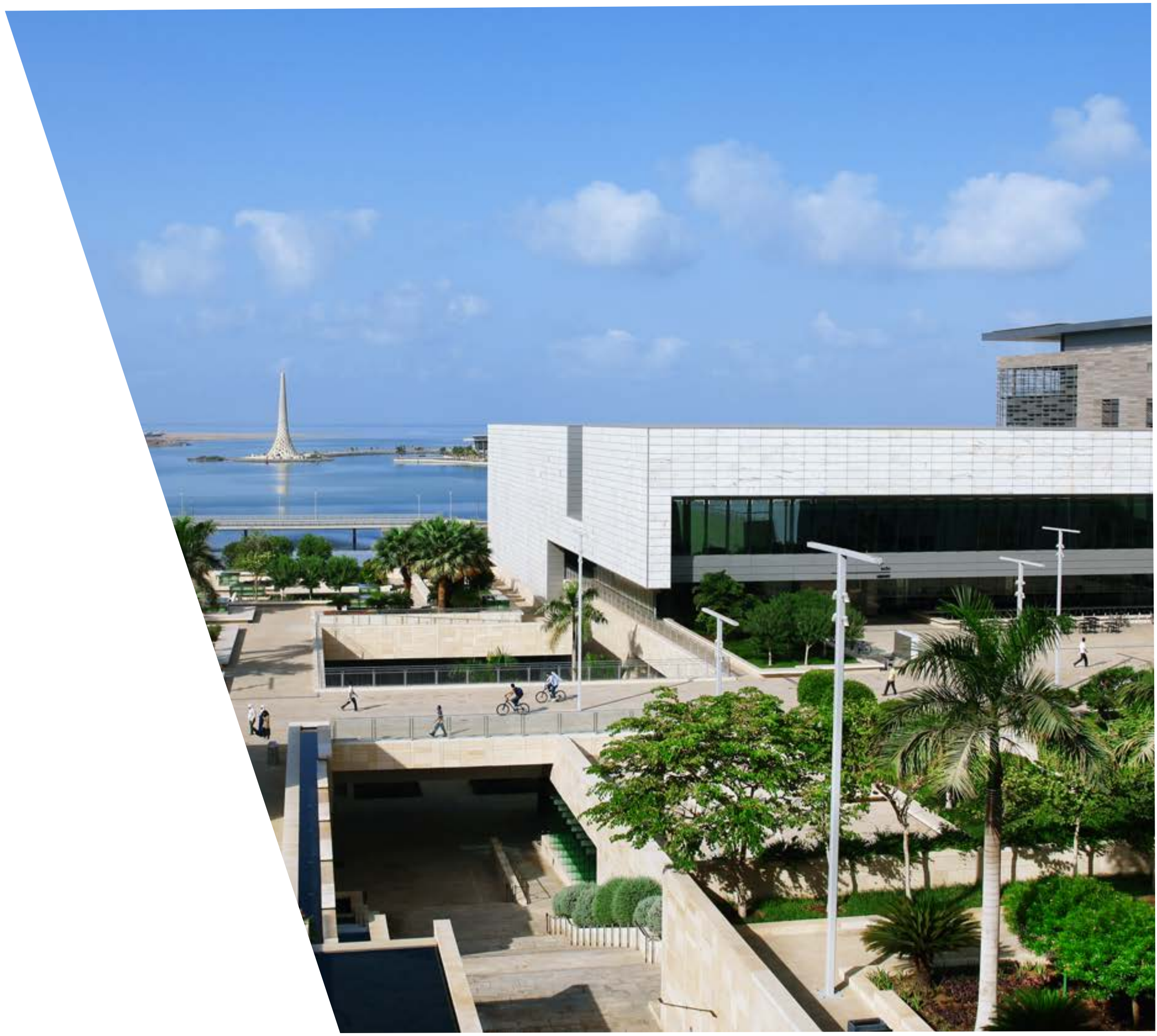
6G CHANNEL



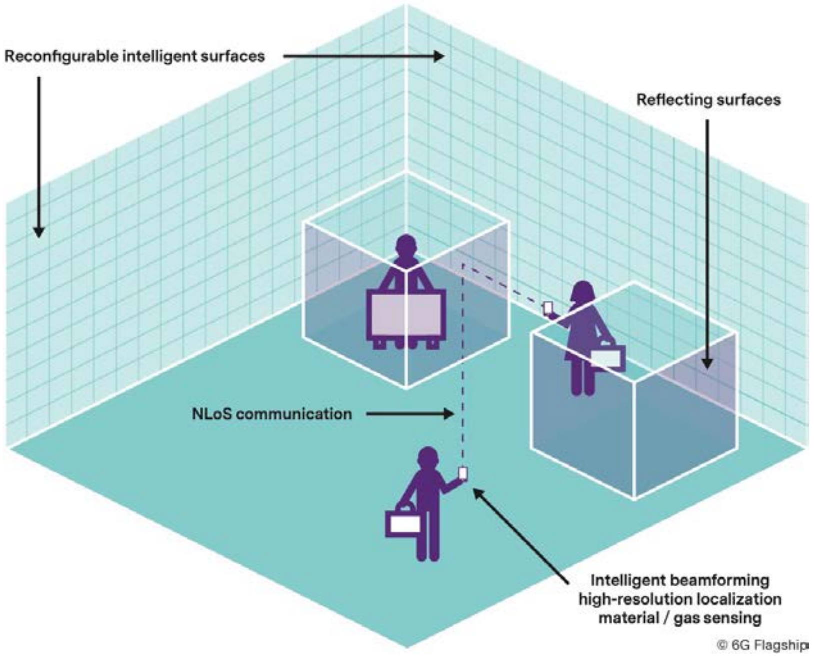
Intelligent reflecting surfaces (IRSs) are key infrastructure enablers for 6G

5G: Massive MIMO and mmWave

6G: Ultra massive MIMO, IRSs and THz

IRS-enabled solutions:

- Intelligently adapt network infrastructure to changes in environment
- Transform naturally passive wireless environments to active ones
- Tune IRS physical parameters in run time for propagation optimization
- Coverage extension and improved throughput
- Enhanced security and positioning
- Highly reduced power consumption and hardware footprints
- Cost-effective deployment on building facades and room walls/ceilings
- Increased reliability and massive connectivity
- Sense the environment for network optimization



[1]: Bourdoux, Andre, Andre Noll Barreto, Barend van Liempd, Carlos de Lima, Davide Dardari, Didier Belot, Elana-Simona Lohan et al. "6G White Paper on Localization and Sensing." arXiv preprint arXiv:2006.01779 (2020).

[2]: Rajatheva, Nandana, Italo Atzeni, Emil Bjornson, Andre Bourdoux, Stefano Buzzi, Jean-Baptiste Dore, Serhat Erkucuk et al. "White paper on broadband connectivity in 6G." arXiv preprint arXiv:2004.14247 (2020).

[3]: Di Renzo, Marco, Merouane Debbah, Dinh-Thuy Phan-Huy, Alessio Zappone, Mohamed-Slim Alouini, Chau Yuen, Vincenzo Sciancalepore et al. "Smart radio environments empowered by reconfigurable AI meta-surfaces: An idea whose time has come." EURASIP Journal on Wireless Communications and Networking 2019, no. 1 (2019): 1-20.

Booming research interest in the last two years

Reflectarrays: A discrete planar matrix of reflector antenna elements

Metasurfaces: Artificial materials with tunable physical properties: dense meta-atoms over a substrate (CMOS and MEMS switches)

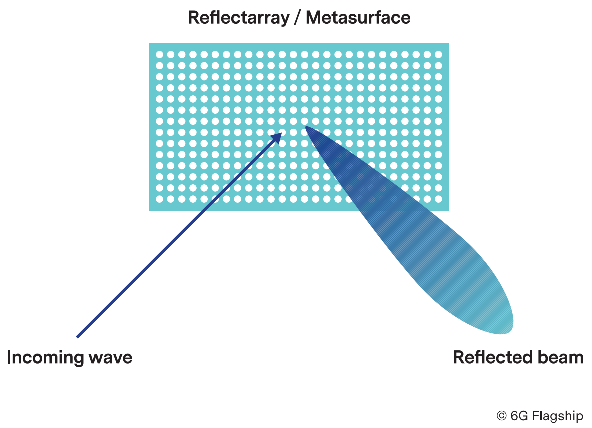
Active surfaces: Extensions to massive MIMO

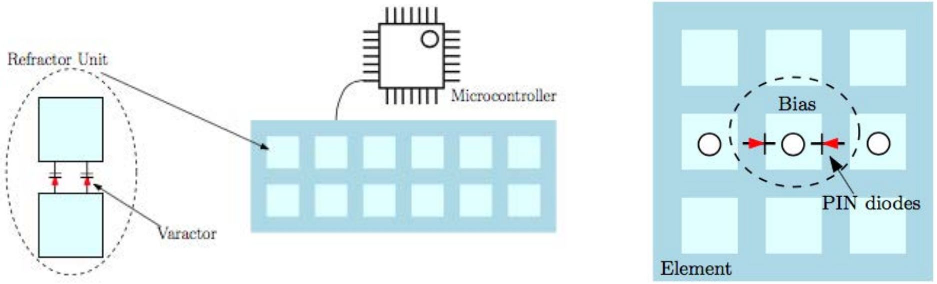
Passive surfaces: Low-cost circuitry – embedded sensors of passive elements

Contiguous: Virtually infinite number of elements

Discrete: Unit cells of software-tunable metamaterials

Modes of operation: Active transceivers, discrete IRSs for channel estimation, EM wave modulators (phase shift, steering, absorption, collimation, polarization modification)





[1]: Liaskos, Christos, Shuai Nie, Ageliki Tsioliaridou, Andreas Pitsillides, Sotiris Ioannidis, and Ian Akyildiz. "A new wireless communication paradigm through software-controlled metasurfaces." IEEE Communications Magazine 56, no. 9 (2018): 162-169.

[2]: Alghamdi, Rawan, Reem Alhadrami, Dalia Alhothali, Heba Almorad, Alice Faisal, Sara Helal, Rahaf Shalabi et al. "Intelligent Surfaces for 6G Wireless Networks: A Survey of Optimization and Performance Analysis Techniques." arXiv preprint arXiv:2006.06541 (2020).

[3]: Basar, Ertugrul, Marco Di Renzo, Julien De Rosny, Merouane Debbah, Mohamed-Slim Alouini, and Rui Zhang. "Wireless communications through reconfigurable intelligent surfaces." IEEE Access 7 (2019): 116753-116773.a

IRS-assisted localization is an emerging paradigm

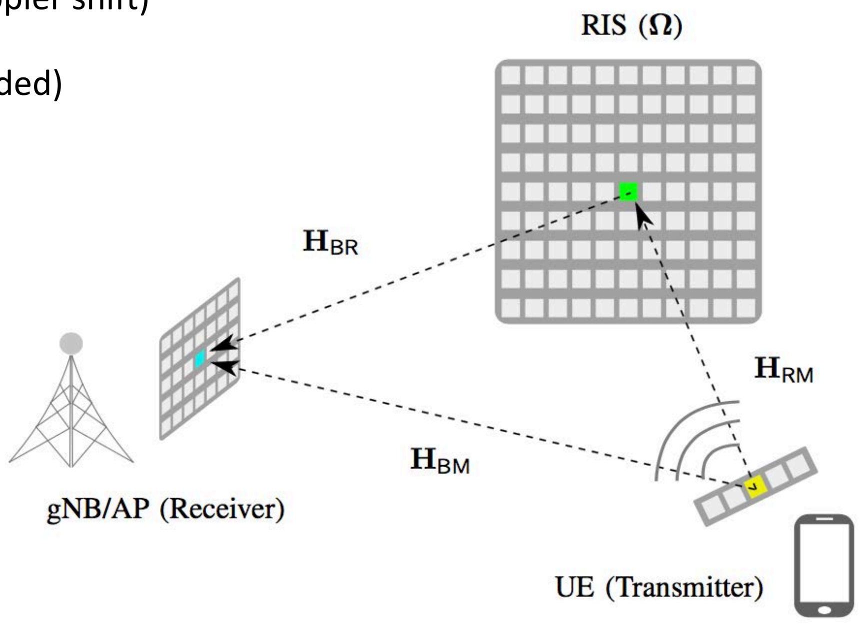
IRSs were initially proposed for satellite and radar communication systems

A variation of measurements techniques (ToA, PoA, AoD, AoA, and the Doppler shift)

IRSs support high RSS values and coverage probability (no line-of-sight needed)

Challenges:

- IRS and channel modeling
- Near-field propagation
- Channel estimation
- System architecture and signaling
- IRS control
- Waveform design
- Simultaneous localization and mapping (SLAM)



Localization is also a prerequisite for IRS operation

[1]: Wymeersch, Henk, Jiguang He, Benoît Denis, Antonio Clemente, and Markku Juntti. "Radio localization and mapping with reconfigurable intelligent surfaces." arXiv preprint arXiv:1912.09401 (2019).
[2]: Elzanaty, Ahmed, Anna Guerra, Francesco Guidi, and Mohamed-Slim Alouini. "Reconfigurable Intelligent Surfaces for Localization: Position and Orientation Error Bounds." arXiv preprint arXiv:2009.02818 (2020).

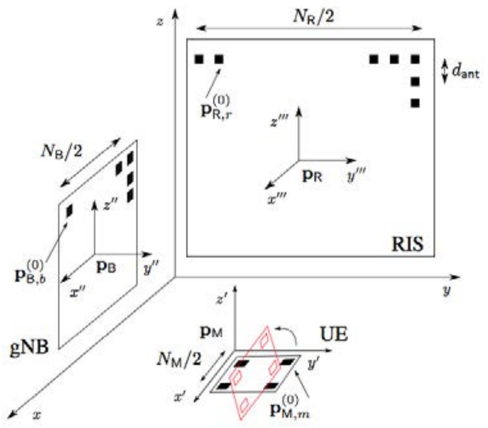
IRS localization position and orientation error bounds

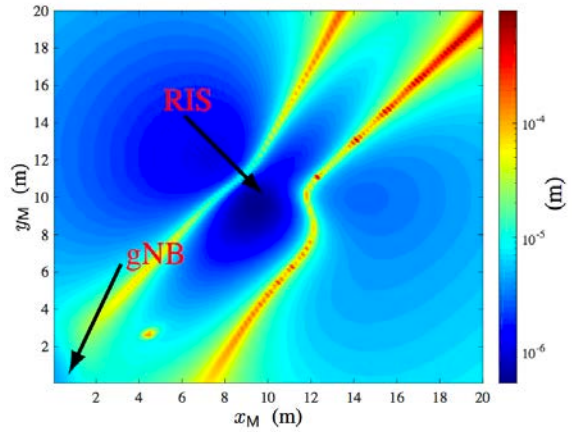
Cramér–Rao Lower Bounds (CRLB) for IRS position and orientation errors [1]:

- Signal model valid for both near-field and far-field propagation conditions
- Near-optimal closed-form IRS phase profile for joint communication and localization

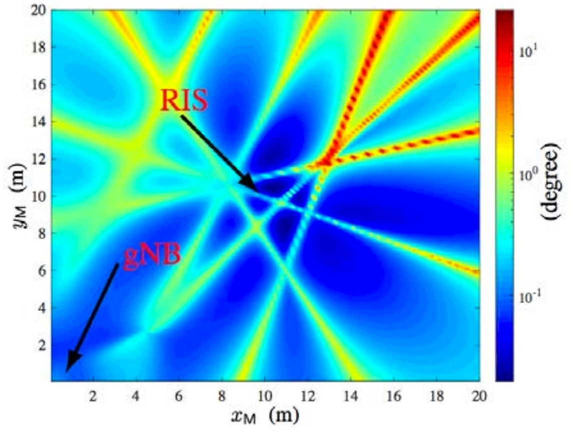
Error bounds on mmWave IRS systems [2]:

- Better positioning performance and smaller orientation error bounds even for 40 elements
- Can be virtually regarded as a two-line-of-sight aided positioning system





position error bound



orientation error bound

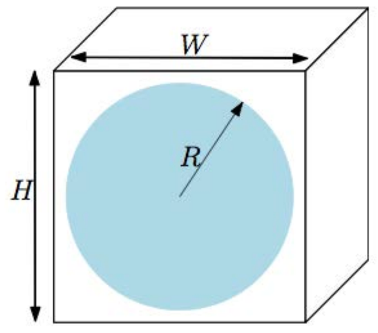
[1]: Elzanaty, Ahmed, Anna Guerra, Francesco Guidi, and Mohamed-Slim Alouini. "Reconfigurable Intelligent Surfaces for Localization: Position and Orientation Error Bounds." arXiv preprint arXiv:2009.02818 (2020).

[2]: He, Jiguang, Henk Wymeersch, Long Kong, Olli Silvén, and Markku Juntti. "Large intelligent surface for positioning in millimeter wave MIMO systems." In 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), pp. 1-5. IEEE, 2020.

Localization using active large intelligent surfaces (LISs)

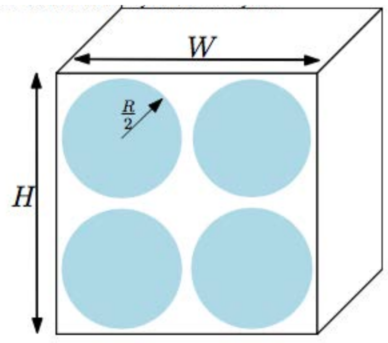
Distributed vs Centralized LIS systems [1,2]:

- CRLB decreases linearly with surface area
- Increased robustness by subdividing a given surface area into smaller units
- Higher probability of coverage results in improved positioning
- Increased complexity and feedback overheads
- Specialized hardware for phase calibration and cooperation between sub-units



Spherical LIS systems [3]:

- Can act as both reflecting surfaces and relaying surfaces
- Better RSS gains for mobile users
- Lower CRLB compared to planar LIS
- Same information-theoretic properties with rotation



[1]: Hu, Sha, Fredrik Rusek, and Ove Edfors. "Beyond massive MIMO: The potential of data transmission with large intelligent surfaces." IEEE Transactions on Signal Processing 66, no. 10 (2018): 2746-2758.

[2]: Alghamdi, Rawan, Reem Alhadrami, Dalia Alhothali, Heba Almorad, Alice Faisal, Sara Helal, Rahaf Shalabi et al. "Intelligent Surfaces for 6G Wireless Networks: A Survey of Optimization and Performance Analysis Techniques." arXiv preprint arXiv:2006.06541 (2020).

[3]: Hu, Sha, and Fredrik Rusek. "Spherical large intelligent surfaces." In ICASSP 2020-2020 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), pp. 8673-8677. IEEE, 2020.

THz communications are rising

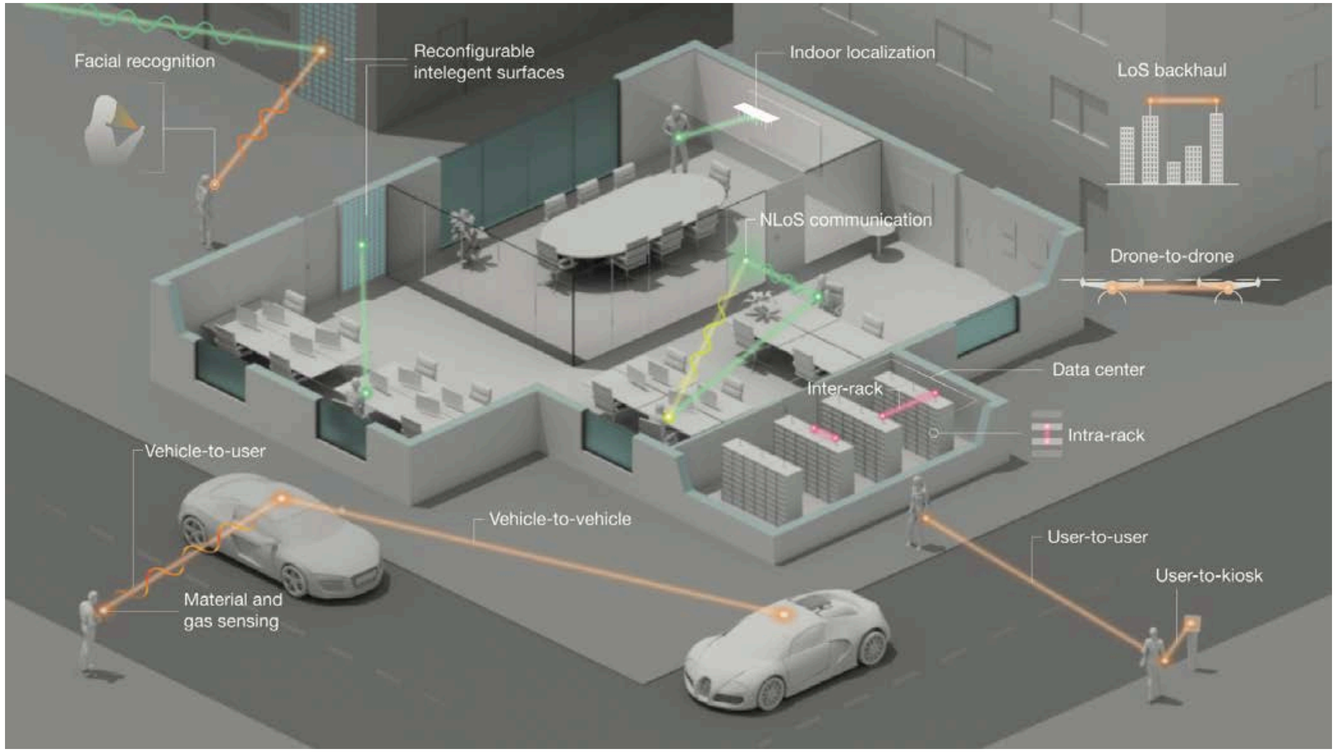


Figure created by Ivan Gromicho, Scientific Illustrator at King Abdullah University of Science and Technology (KAUST)

Merging of THz communications, sensing, imaging, and localization [1]

Last piece of the RF spectrum (0.1 – 10 THz) [2]

THz gap is closing: electronic, photonic, and plasmonic (graphene-based) technologies

Superior to mmWaves:

- Higher data rates (promised Terabit/second)
- Higher directionality and smaller footprints
- Less susceptible to free-space diffraction
- Higher resilience to eavesdropping

Different from optical communications:

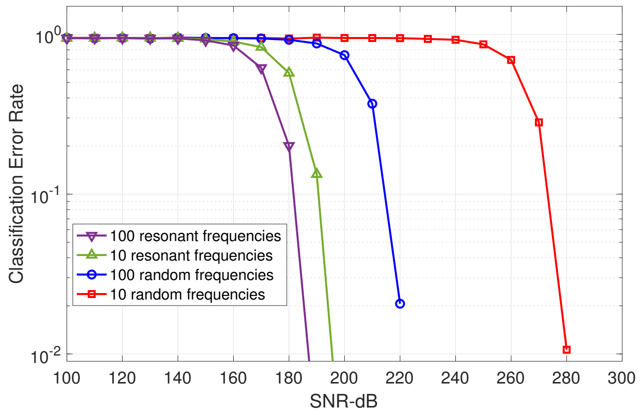
- Less affected by ambient light, atmospheric turbulence, scintillation, cloud dust, etc.
- Less delicate pointing, acquisition, and tracking
- Can better exploit reflections and array processing techniques

[1] Sarieddeen, Hadi, Nasir Saeed, Tareq Y. Al-Naffouri, and Mohamed-Slim Alouini. "Next generation terahertz communications: A rendezvous of sensing, imaging, and localization." IEEE Communications Magazine 58, no. 5 (2020): 69-75.

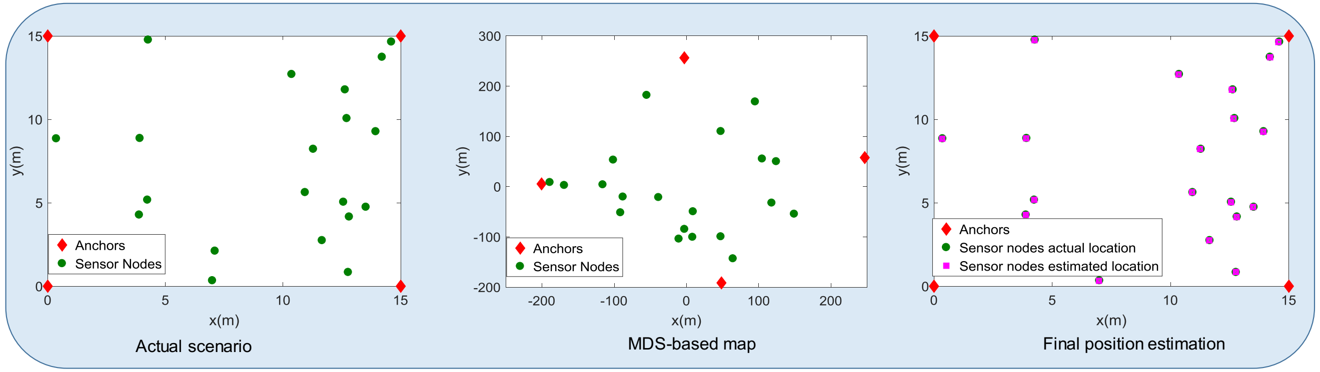
[2] Elayan, Hadeel, Osama Amin, Basem Shihada, Raed M. Shubair, and Mohamed-Slim Alouini. "Terahertz band: The last piece of RF spectrum puzzle for communication systems." IEEE Open Journal of the Communications Society 1 (2019): 1-32.

THz systems bring new opportunities for localization and sensing

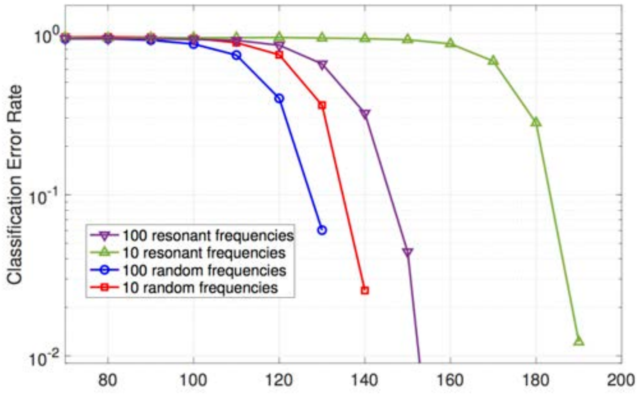
- Unique THz spectral fingerprints enable THz gas and material sensing
- THz time-domain spectroscopy (transmission-based and reflection-based)
- THz frequency-domain spectroscopy provides better flexibility
- Very high delay resolution with ultra-wide bandwidth
- Provide environment maps of cm-level accuracy
- Full three-dimensional high-contrast images
- Public health applications - assisting in airborne virus detection



Carrier-based O_2 sensing



Multidimensional scaling (MDS) for THz network localization with an accuracy of 2.4 cm



Carrier-based H_2O sensing

[1] Sarieddeen, Hadi, Nasir Saeed, Tareq Y. Al-Naffouri, and Mohamed-Slim Alouini. "Next generation terahertz communications: A rendezvous of sensing, imaging, and localization." IEEE Communications Magazine 58, no. 5 (2020): 69-75.
[2] Sarieddeen, Hadi, Mohamed-Slim Alouini, and Tareq Y. Al-Naffouri. "An Overview of Signal Processing Techniques for Terahertz Communications." arXiv preprint arXiv:2005.13176 (2020).

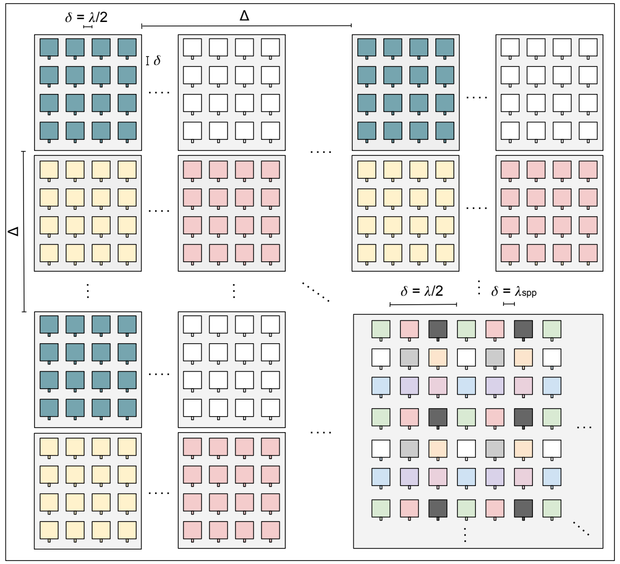
IRS systems are particularly useful for THz communications

Importance of THz-operating LISs

- Distributed THz access points or signal repeaters
- Extremely high data rates and efficient wireless charging
- Favorable THz propagation environments and transceiver design constraints
- THz sensing/imaging at longer distances with finer spatial resolution

Importance of THz-operating IRSs

- Enhance the performance of multipath-limited THz systems
- Coherent large THz-operating antenna arrays are not mature
- The THz relaying technology is also not mature
- THz-operating metamaterials and metasurfaces are advancing
- Electrically large IRSs can be realized in relatively small footprints
- Enhance the performance of sensing and localization (see around corners)



Frequency-interleaved antenna maps – spatial tuning
(same colors indicate same frequencies)

Regular specular surfaces behave like electrical mirrors

[1]: Sarieddeen, Hadi, Mohamed-Slim Alouini, and Tareq Y. Al-Naffouri. "Terahertz-band ultra-massive spatial modulation MIMO." IEEE Journal on Selected Areas in Communications 37, no. 9 (2019): 2040-2052.

[2] Sarieddeen, Hadi, Mohamed-Slim Alouini, and Tareq Y. Al-Naffouri. "An Overview of Signal Processing Techniques for Terahertz Communications." arXiv preprint arXiv:2005.13176 (2020).

[3]: Faisal, Alice, Hadi Sarieddeen, Hayssam Dahrouj, Tareq Y. Al-Naffouri, and Mohamed-Slim Alouini. "Ultra-massive MIMO systems at terahertz bands: Prospects and challenges." ," IEEE Vehicular Technology Magazine (2020).

Dense THz-operating arrays enable holographic communications

Joint holographic imaging, positioning, and wireless communications [1,2]

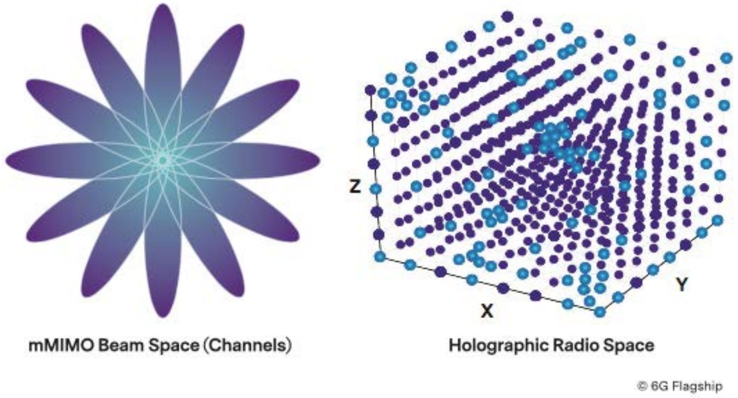
- Increased energy efficiency and suppressed power leakage
- Pixelated ultra-high resolution (localized throughput)
- Ultra-high density spatial multiplexing
- Highly accurate positioning
- Improved security
- Reduced EM field exposure

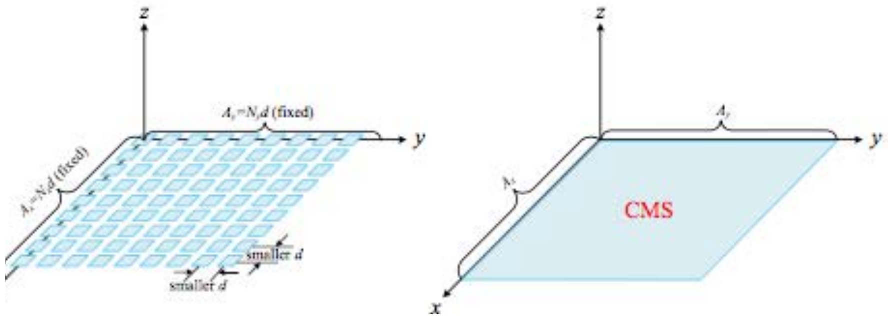
Spatially continuous electromagnetic aperture

Ideal holographic LISs/IRSs approximated by more practical ultra-dense IRSs

Densely packing sub-wavelength unit cells (quasi-continuous apertures)

Feasible with miniaturized THz electronic components [3]





[1]: Rajatheva, Nandana, Italo Atzeni, Emil Bjornson, Andre Bourdoux, Stefano Buzzi, Jean-Baptiste Dore, Serhat Erkucuk et al. "White paper on broadband connectivity in 6G." arXiv preprint arXiv:2004.14247 (2020).

[2]: Huang, Chongwen, Sha Hu, George C. Alexandropoulos, Alessio Zappone, Chau Yuen, Rui Zhang, Marco Di Renzo, and Mérouane Debbah. "Holographic MIMO surfaces for 6G wireless networks: Opportunities, challenges, and trends." IEEE Wireless Communications 27, no. 5 (2020): 118-125.

[3]: Wan, Ziwei, Zhen Gao, Marco Di Renzo, and Mohamed-Slim Alouini. "Terahertz Massive MIMO with Holographic Reconfigurable Intelligent Surfaces." arXiv preprint arXiv:2009.10963 (2020).

Challenges and solutions for IRS-assisted THz communications

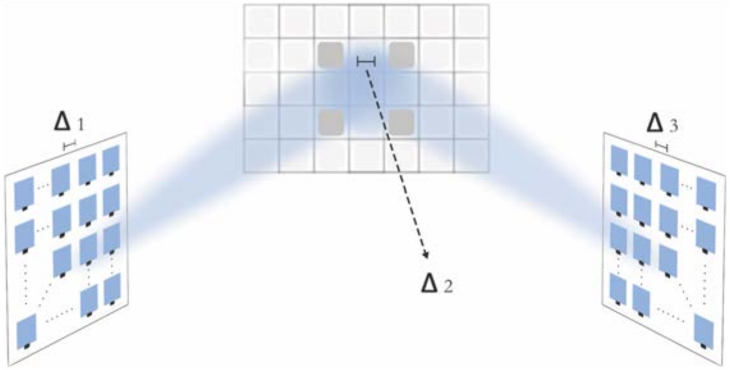
Challenges (solutions in signal processing techniques):

- System noise level
- Propagation/absorption losses and blockage
- Environment changes and humidity
- Misalignment and mutual coupling,
- Spherical wave and beam squint effects

THz components are energy constrained:

- THz-operating energy harvesting software-defined metamaterials [3]

THz IRSs are highly-localized access point extenders as opposed to structures that enrich multipath scattering



Three-level spatial tuning with IRSs to overcome channel correlation [1,2]

[1]: Sarieddeen, Hadi, Mohamed-Slim Alouini, and Tareq Y. Al-Naffouri. "Terahertz-band ultra-massive spatial modulation MIMO." IEEE Journal on Selected Areas in Communications 37, no. 9 (2019): 2040-2052.

[2] Sarieddeen, Hadi, Mohamed-Slim Alouini, and Tareq Y. Al-Naffouri. "An Overview of Signal Processing Techniques for Terahertz Communications." arXiv preprint arXiv:2005.13176 (2020).

[3]: Lemic, Filip, Sergi Abadal, and Jeroen Famaey. "Toward localization in terahertz-operating energy harvesting software-defined metamaterials: context analysis." In Proceedings of the 7th ACM International Conference on Nanoscale Computing and Communication, pp. 1-6. 2020.

Research directions

- IRSs for heterogeneous mmWave/THz, free-space optics, and visible light applications
- Cooperative localization/tracking (dense BSs, LISs, IRSs, users, IoT) – Sensor fusion
- IRS-assisted cell-free massive MIMO
- Novel application of machine learning tools for fingerprint localization
- Novel reconfigurable meta-surfaces (graphene-based)
- Novel applications: IRS-assisted drone-aided communications, through-wall imaging, etc.
- Optimized placement of base stations and metasurfaces (an inverse problem of channel modeling)
- Body-centric and bio-applications (backscattered waves report sensed data)
- Edge/cloud computing, security, and privacy
- Signal processing and resource allocation for the convergence of IRS-assisted communications and sensing

Thank you!

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