Terahertz Nanocommunication and Networking: Emerging Applications, Approaches, and Open Challenges

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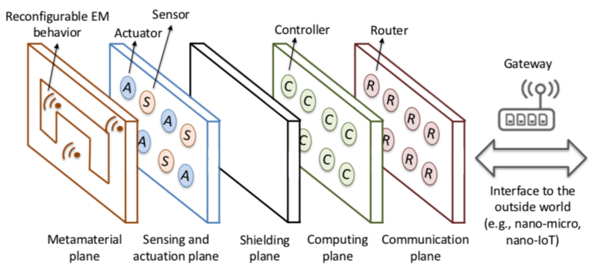
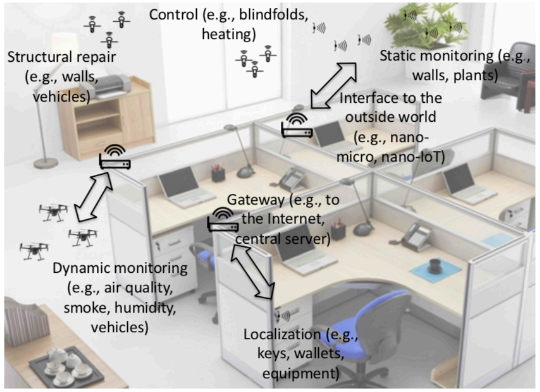
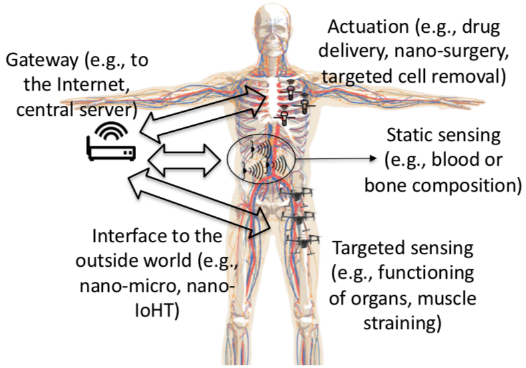
Terahertz Nanocommunication and Nanonetworking



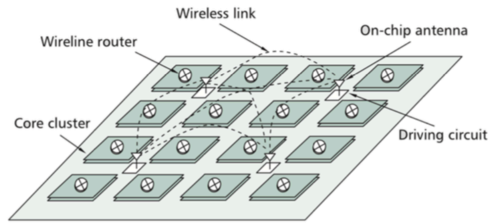
Software-defined metamaterials



Wireless robotic materials



In-body communication



On-chip communication

Lemic *et al.* "*Survey on Terahertz Nanocommunication and Networking: A Top-Down Perspective*", *https://arxiv.org/abs/1909.05703*, 2020

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Applications and Requirements

Requirements	Software-defined metamaterials	Wireless robotic materials	body-centric communication	On-chip communication
Network size	10^3 to 10^6 / 10^9	10 to 10^6	10^3 to 10^{12}	Up to 10^3
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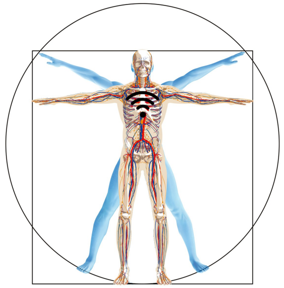
Additional features		localization	in-body communication localization & tracking	

- Different application domains → heterogeneous requirements;
- Some common denominators exist → applicability across application domains;
- Summarizing research across domains→ discussing feasibility across domains;

Applications vs. Projects

- In-body communication
  - Scalable Localization-enabled In-body Terahertz Nanonetwork (ScaLeITN)



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ScaLeITN

- Software-defined metamaterials
  - Hardware Platform for Software-driven Functional Metasurfaces (VISORSURF)

VISOR SURF

- On-chip communication
  - Wireless Plasticity for Massive Heterogeneous Computer Architectures (WiPLASH)

WiPLASH

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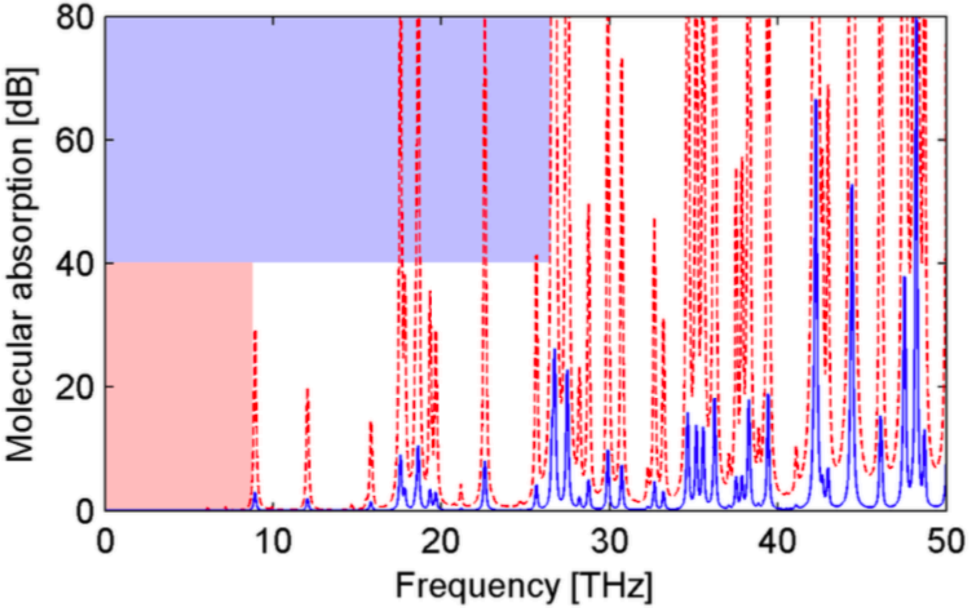
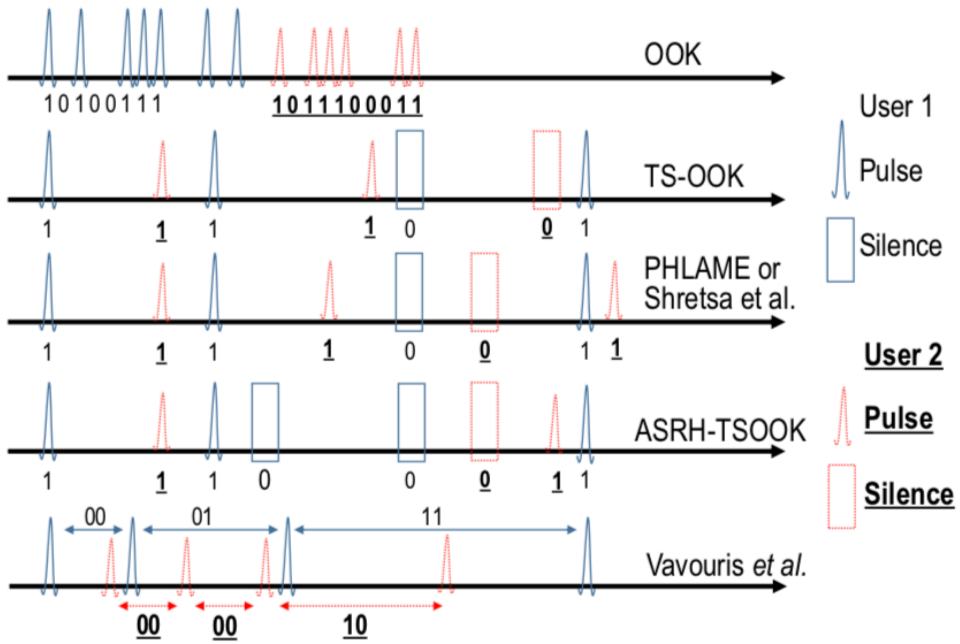
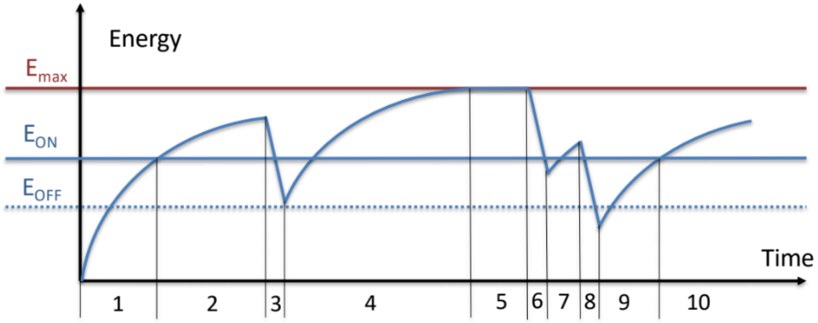
Problems – THz Frequencies





Problems – Intermittency

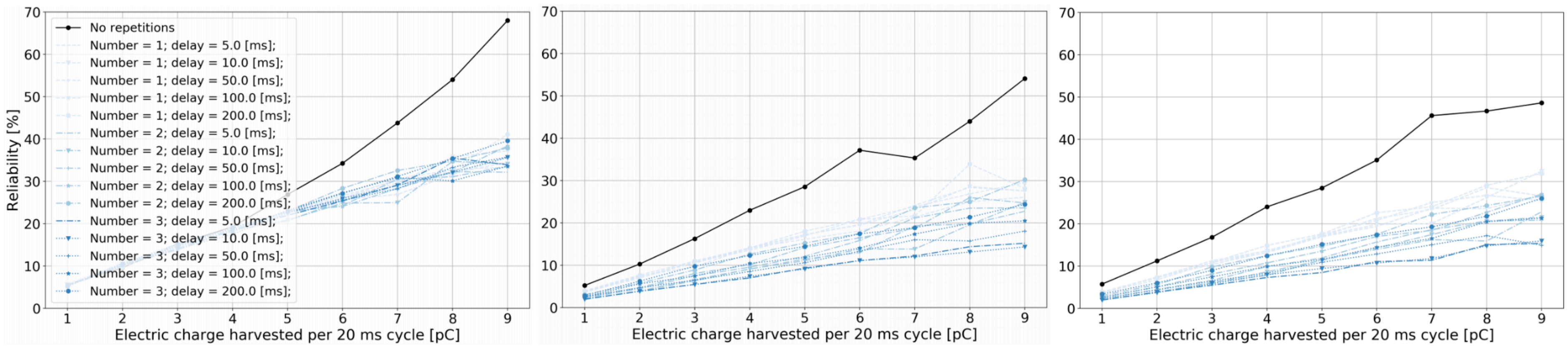


1: Node turned off, harvesting energy;
2: Node turned on, harvesting energy;
3: Node receiving packet, packet received;
4: Node turned on, harvesting energy;
5: Energy storage full, not harvesting energy;
6: Node receiving packet, packet received;
7: Node turned on, harvesting energy;
8: Node receiving packet, packet not received;
9: Node turned off, harvesting energy;
10: Node turned on, harvesting energy;

E_{max} – storage capacity

E_{ON} – turn-on threshold

E_{OFF} – turn-off threshold



(a) E_{ON}=100 pJ, E_{OFF}=40 pJ (b) E_{ON}=300 pJ, E_{OFF}=40 pJ (c) E_{ON}=300 pJ, E_{OFF}=100 pJ

Lemic *et al.* "*Assessing the Reliability of Energy Harvesting Terahertz Nanonetworks for Controlling Software-Defined Metamaterials*", ACM NanoCom, 2019

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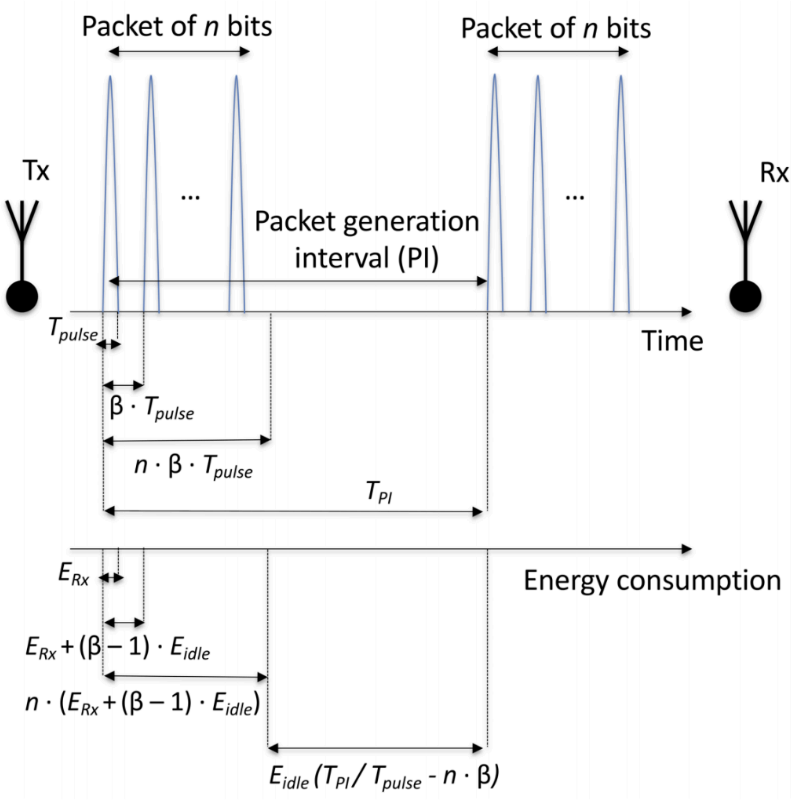
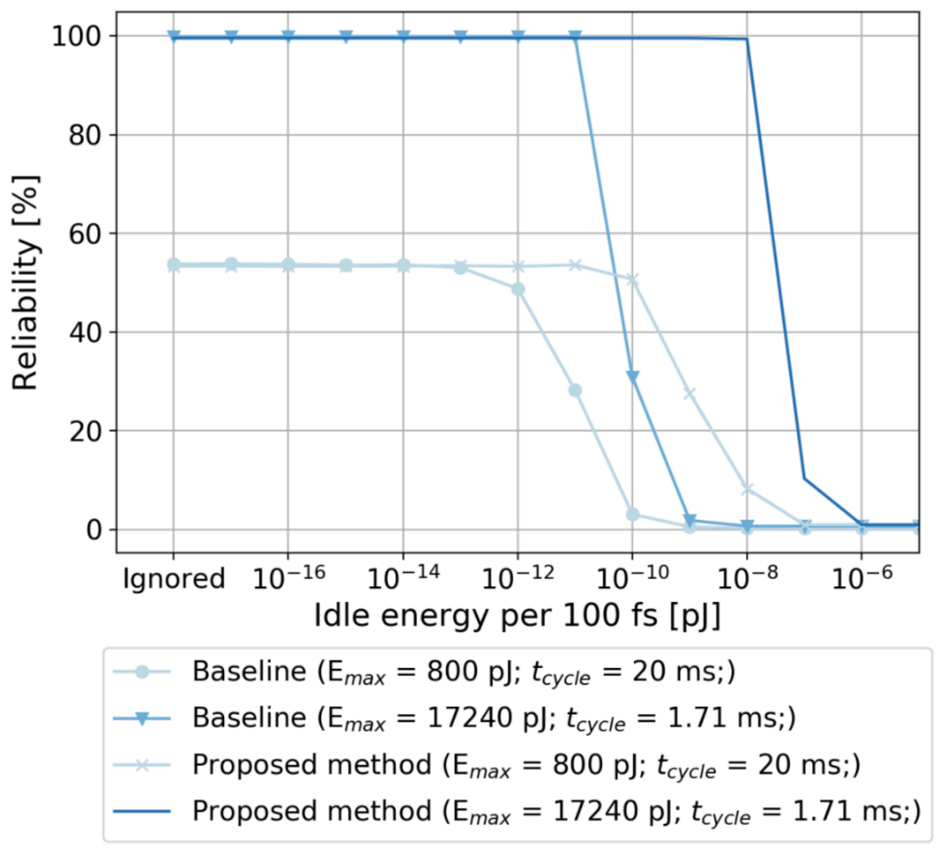
Problems – Energy Consumption





Lemic, *et al.* "*Idling Energy Modeling and Reduction in Energy Harvesting Terahertz Nanonetworks*", IEEE Journal on Emerging and Selected Topics in Circuits and Systems (JETCAS), 2020

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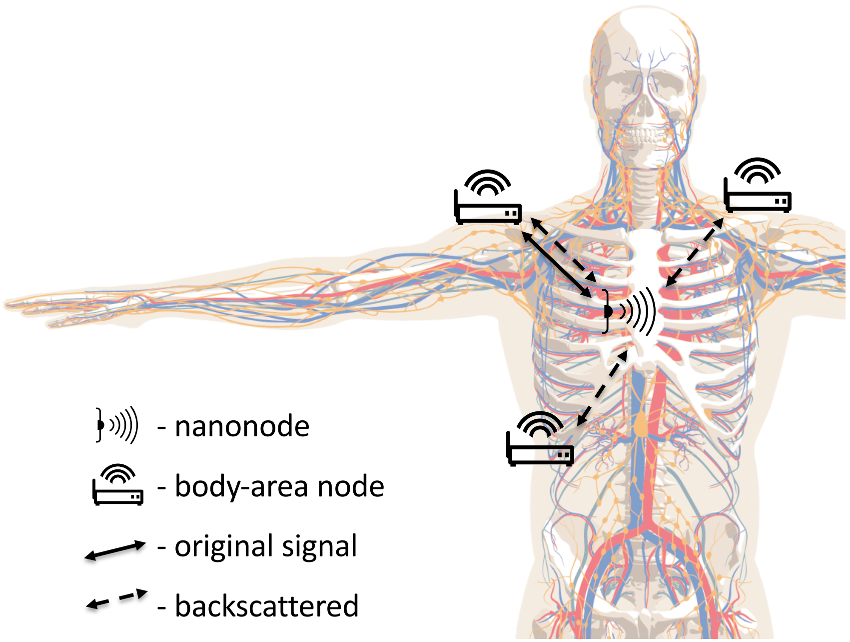
Potential Solution – Localization

- Localization required → how to localize?
- Backscatter-based localization in THz frequencies:
  - Benefit – no energy consumption of the nanonodes (they can be asleep);
  - Challenges: THz in-body propagation, multiple responses;

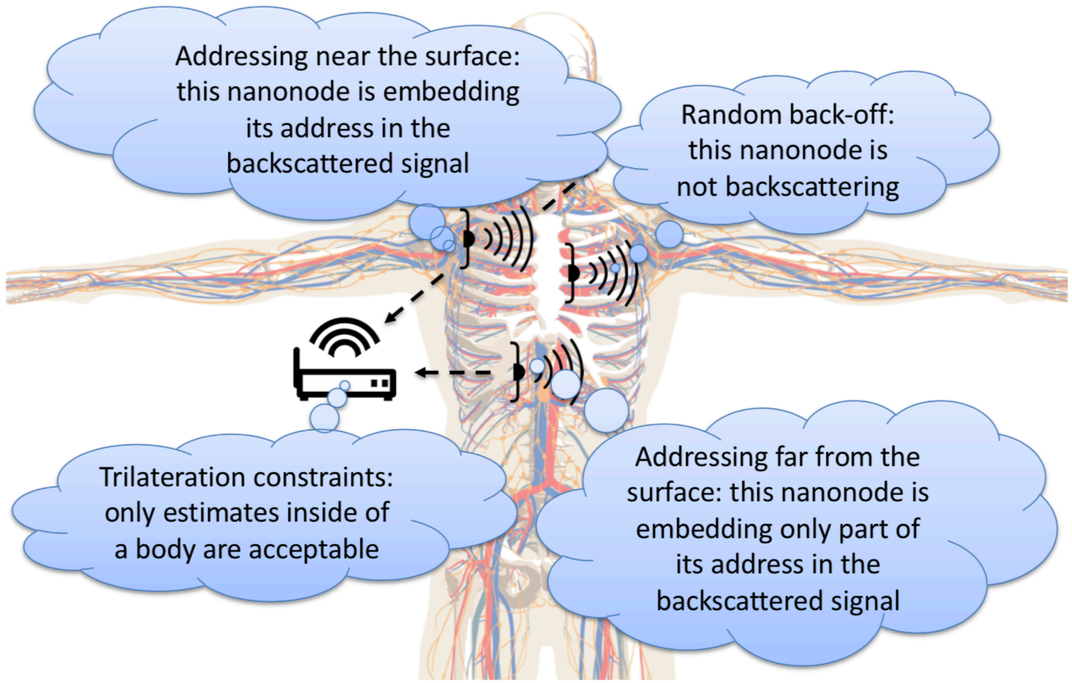


Potential Solution – Localization

- How many BAN nodes, their P_{Tx} and locations on the body?
- How strong the backscattered signals must be?

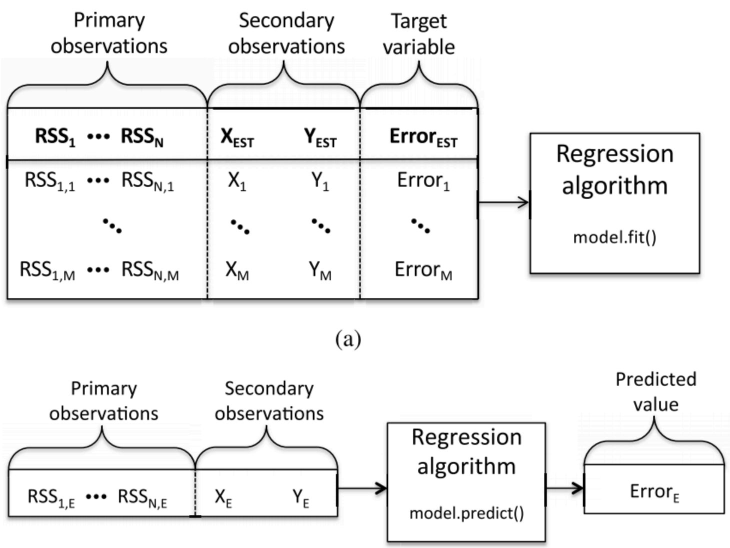
→ to achieve certain accuracy. Latency and reliability?

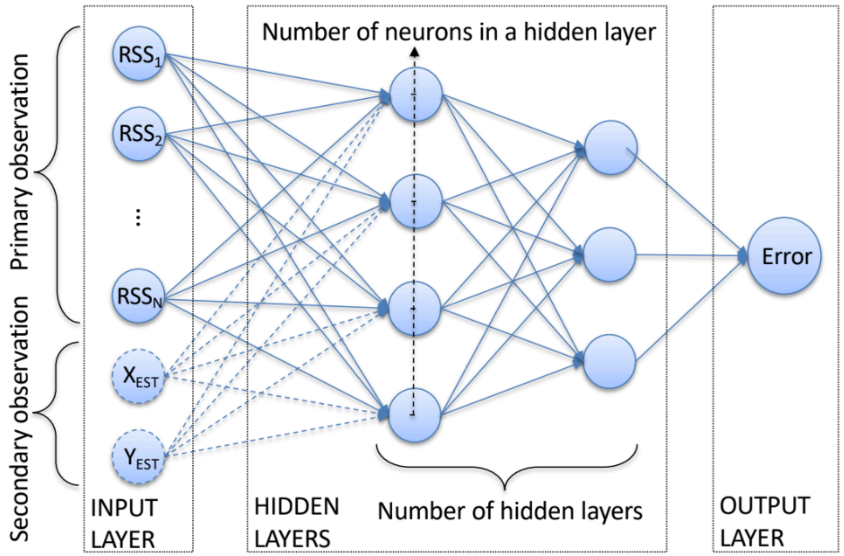
- Multiple responses?



Estimating Localization Reliability

- High-precision drug-delivery, nanosurgery → location should be correct!
- Challenges: training data collection, adaptation to new localization algorithms;





Lemic *et al.* "*Regression-Based Estimation of Individual Errors in Fingerprinting Localization*", IEEE Access, 2019

Lemic *et al.* "*Artificial Neural Network-based Estimation of Individual Localization Errors in Fingerprinting*", IEEE CCNC, 2020

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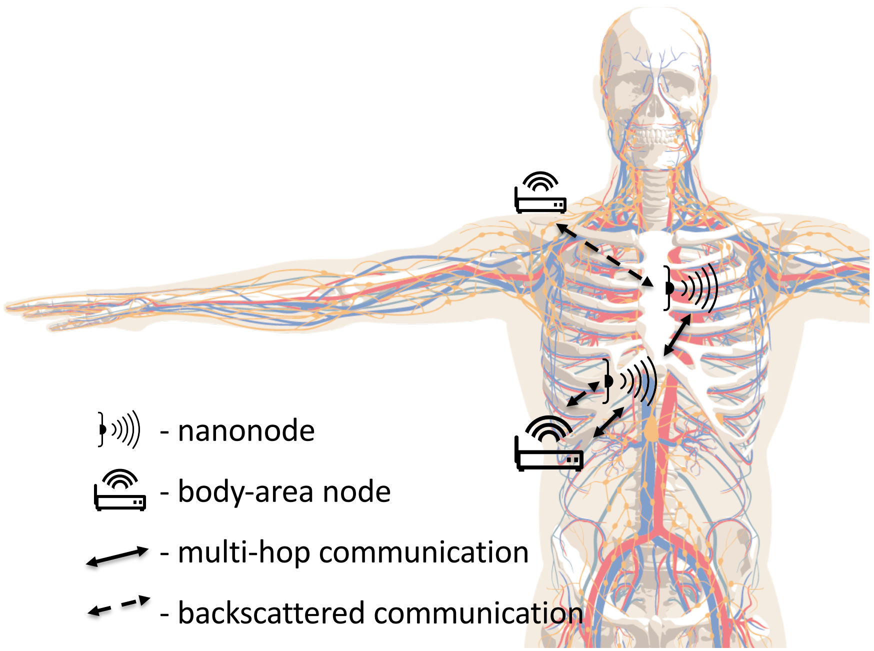
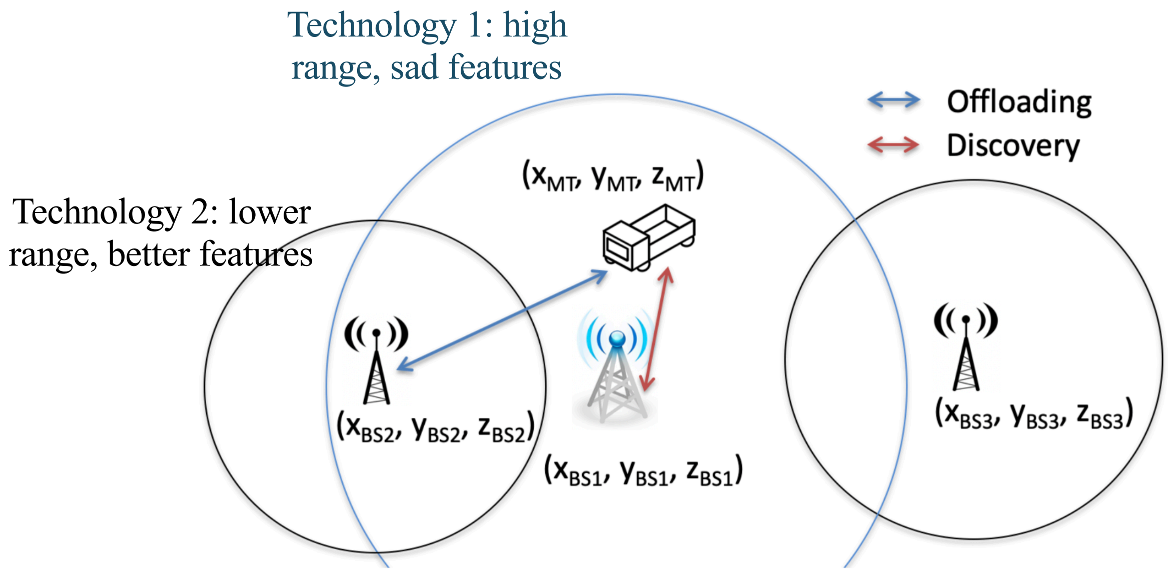
Potential Solution – Communication

- Localization required → why not using it in communication?
- Location-aware multi-hop communication:
  - Benefit: controlled wake-up of some nanonodes without sync;
  - Challenges: Addressing, data amount/type vs. transmission distance;



Location-aware Multi-hop Communication



$$\mathbb{E}(\mathrm{SNR}) = a + b\mu_Z + c\log\sigma + \frac{c}{2}\mathbb{E}(\psi(U(\lambda/2)+3/2)) - \frac{c}{2}\log 2$$

EVALUATION (LoRa & SigFox):

- 80% of correct negative decisions;
- 95% of correct positive decisions;

Lemic *et al.* "*Location-based Discovery and Vertical Handover in Heterogeneous Low-Power Wide-Area Networks*", IEEE Internet of Things Journal, 2019

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Conclusions

- Intermittency → energy harvesting nanonodes;
- Energy consumption modelling → nanonodes;
- Nano-localization → software defined metamaterials, wireless robotic materials;
- Localization quality → software defined metamaterials, wireless robotic materials;
- Location-aware communication → software defined metamaterials, …

Applications vs. Projects

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ScaLeITN

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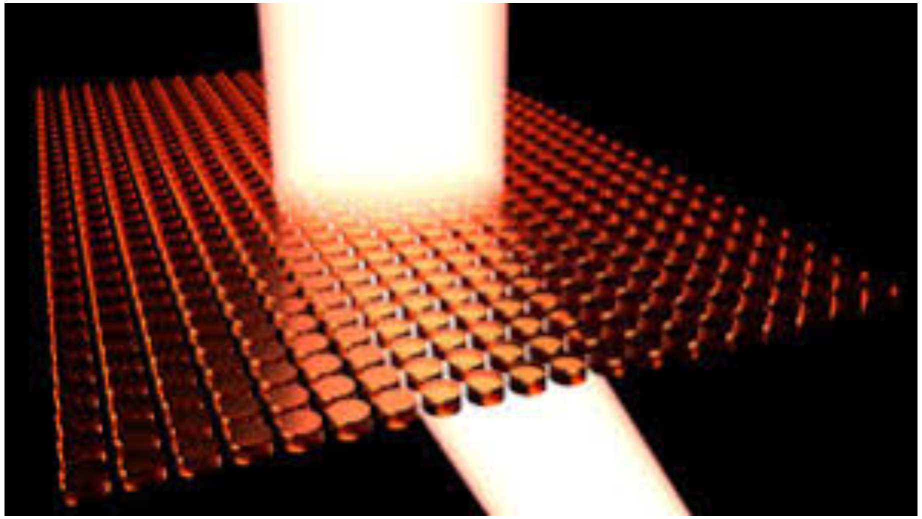
Motivation

Metasurfaces are planar structures composed of arrays of subwavelength elements (unit cells) that enable unprecedented control of electromagnetic waves



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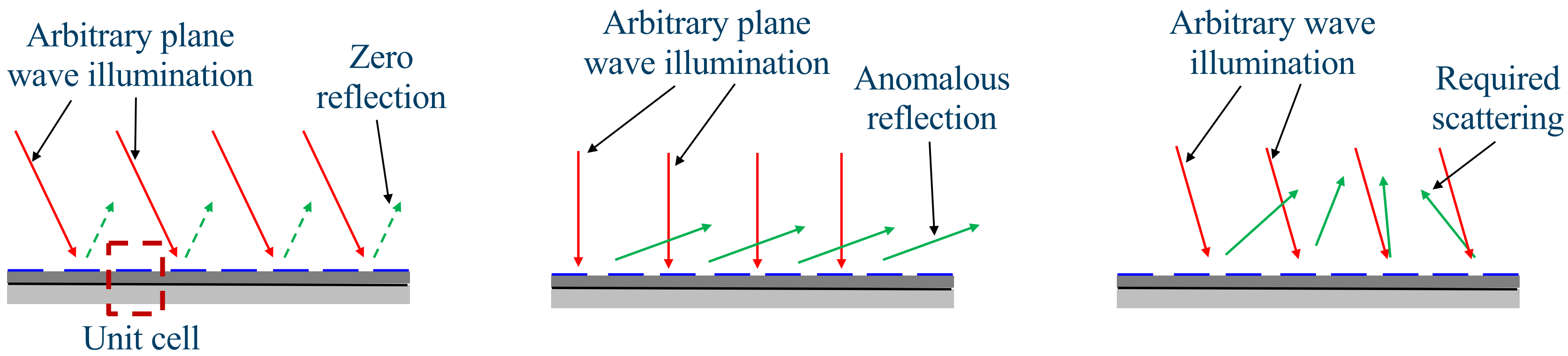
Opportunity



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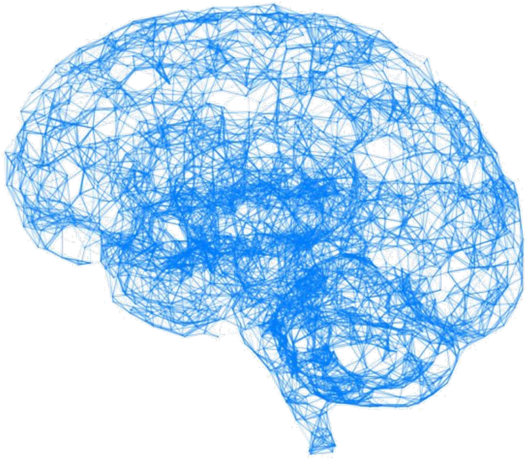
Opportunity

Metasurface + Intelligence



Opportunity: Applications in 6G

Hybrid precoding design

Simple beamforming at THz

Indoor signal focusing

Non-Orthogonal Multiple Access

Index modulation

Energy efficient multi-user MISO

Beyond Max-SNR: Joint Encoding

UAV communications

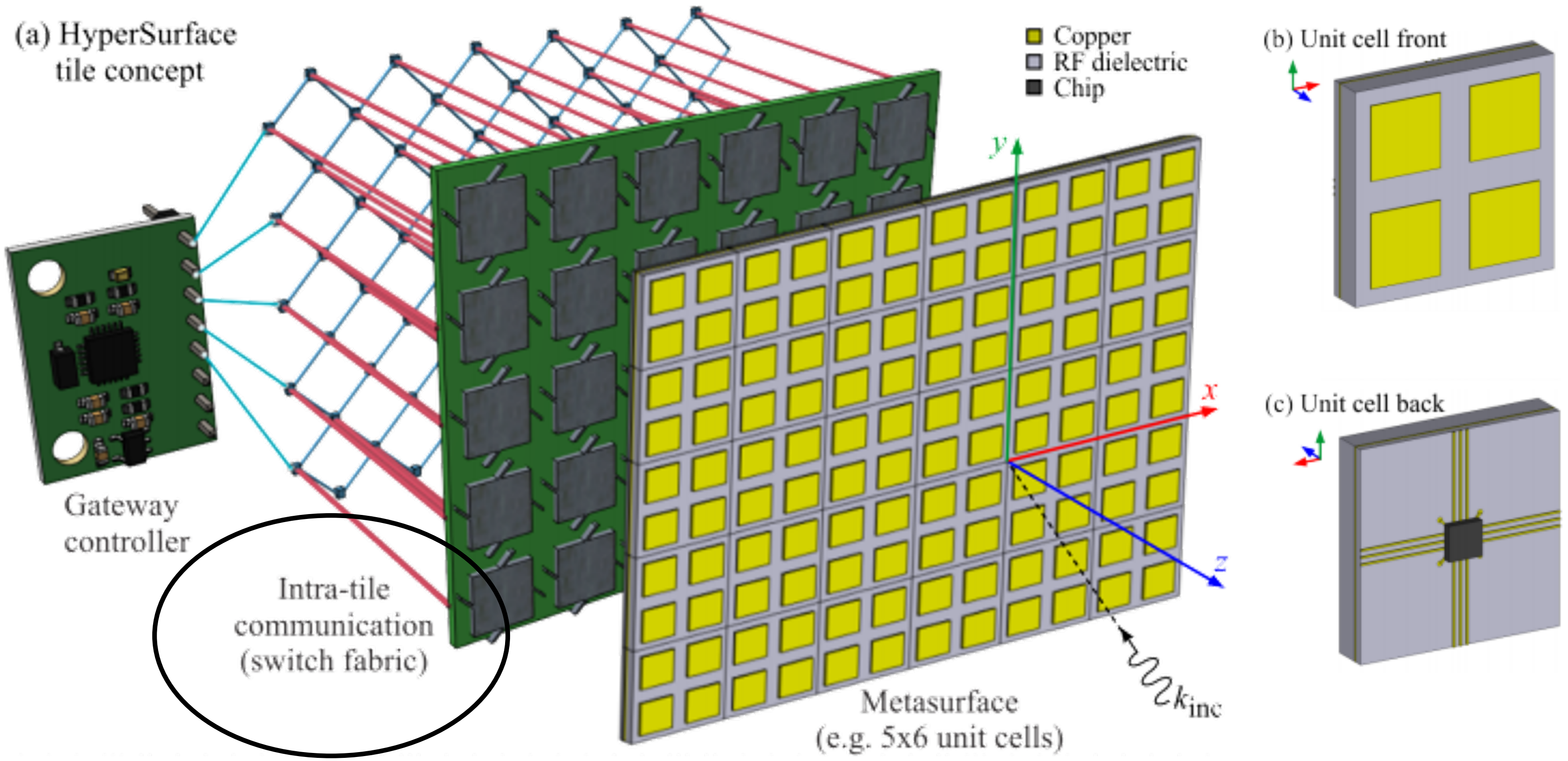
Indoor beaming for VR applications

Weighted sum-rate maximization

Wireless Power Transfer

Two-way Communications

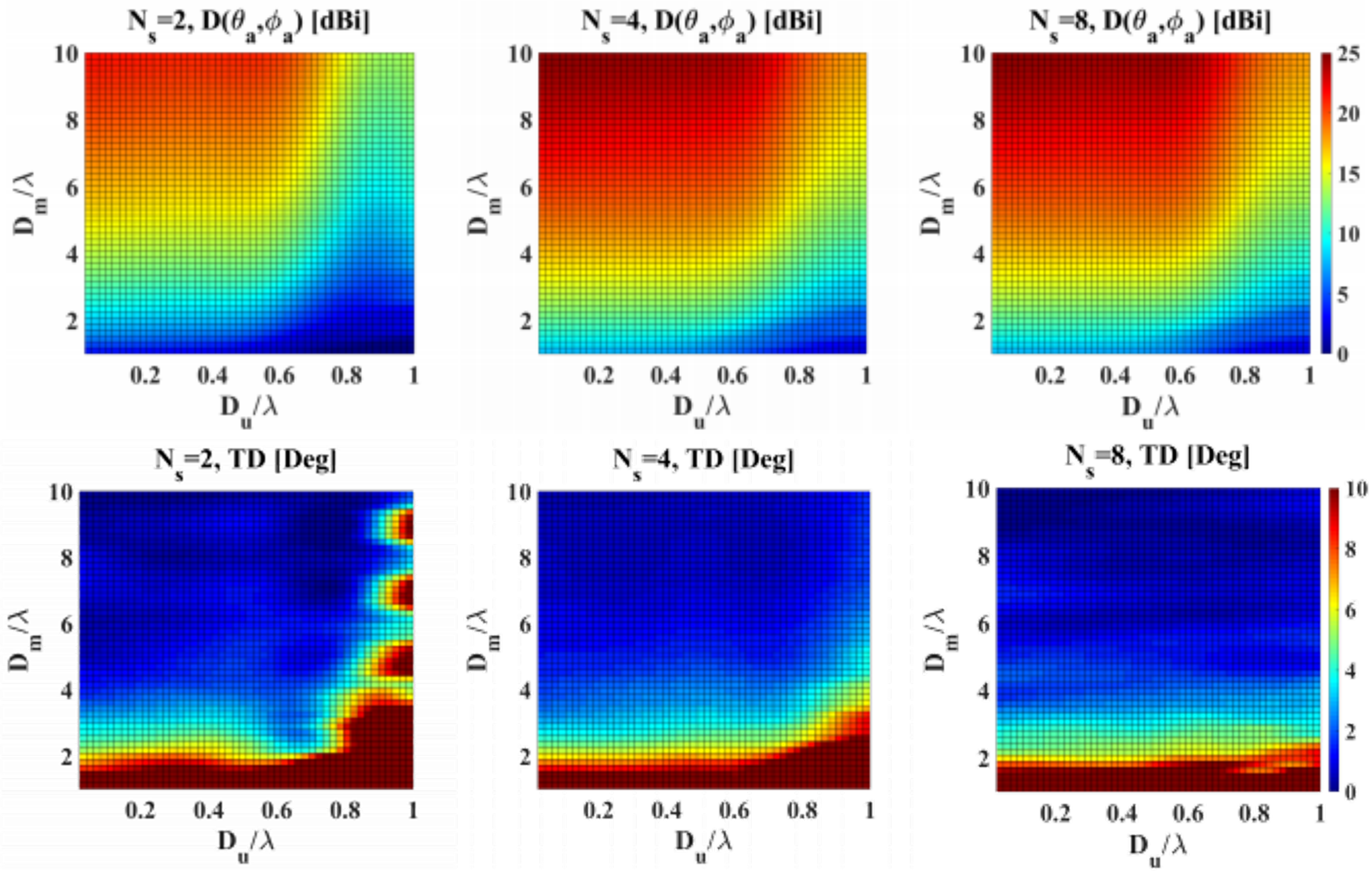
Intelligent metasurfaces: the HyperSurface



Challenges of SDMs

- Dimensioning the metasurfaces and, thus, their internal network for an application
  (beam steering)
- Understanding the internal communication needs
- Designing the intra-surface network accordingly

Dimensioning of metasurfaces



H. Taghvaee, S. Abadal, et al, "Scalability Analysis of Programmable Metasurfaces for Beam Steering," IEEE Access, 2020.

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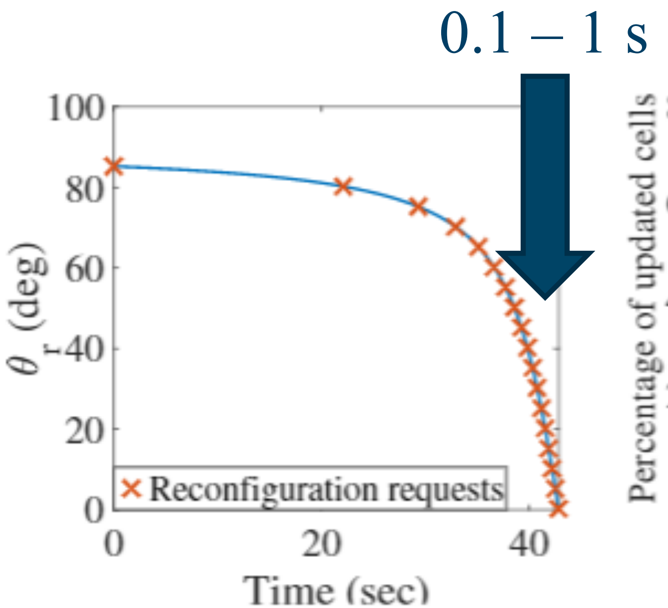
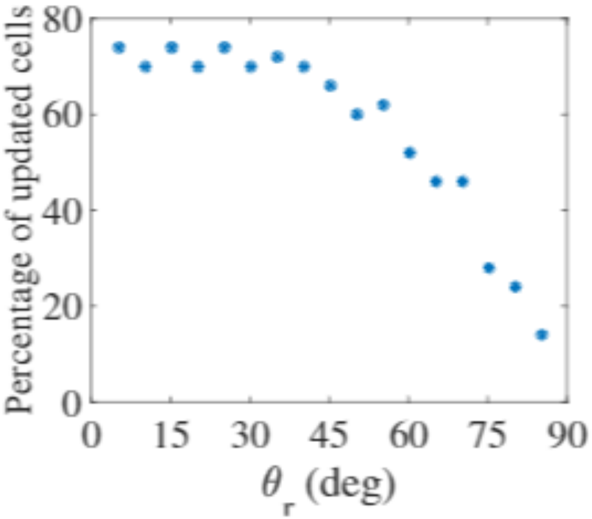
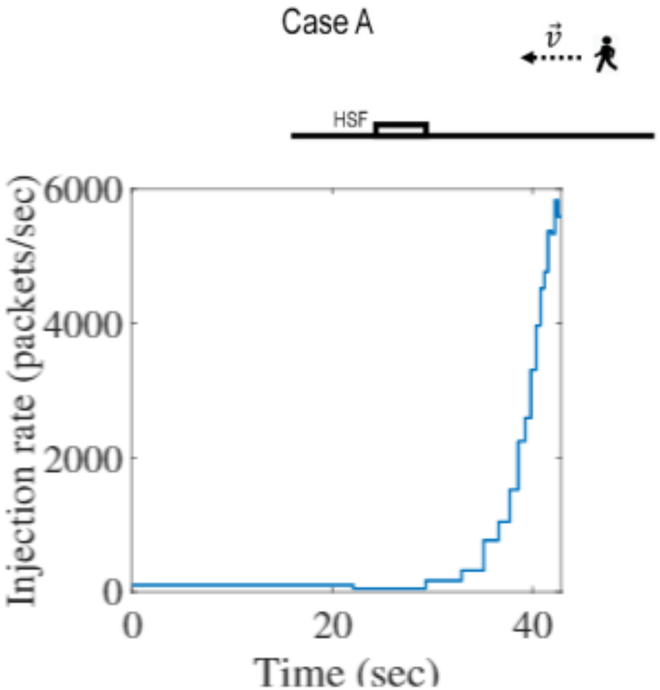
Understanding communication needs



Reconfiguration requests during the tracking of the object (admissible delay)



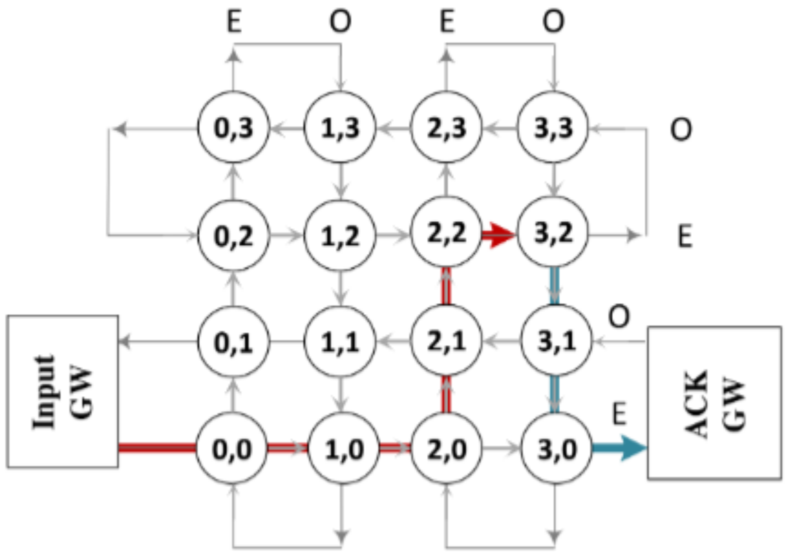
Percentage of reconfigured cells versus the azimuth angle of the reflected signal



Throughput requirements in packets per second

Intra-surface network design

- Communication requirements not very stringent, but resources are limited
- mmWave: one chip per λ
- I/O pins for communication among chips are expensive
  - Choice of topology is limited
  - Impacts routing, fault tolerance
  - Bandwidth is low



D. Kouzapas, et al., "Towards Fault Adaptive Routing in Metasurface Controller Networks," Journal of Systems Architecture, vol. 106, no. 101703, June 2020.

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Outstanding questions

- How much will these metasurfaces consume, cost?
- Can we use energy harvesting to power them and have perpetual operation?
- Given the I/O constraints of the chips, do we want **wireless communication within the metasurface**?
- Which technologies will allow us to do that?

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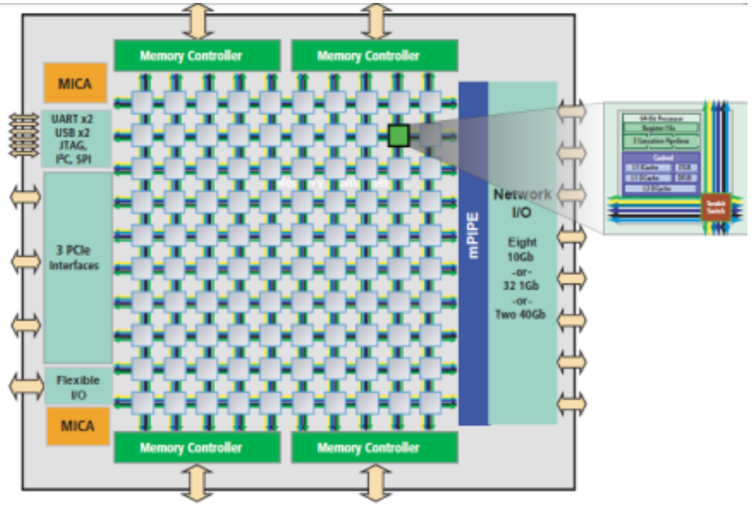
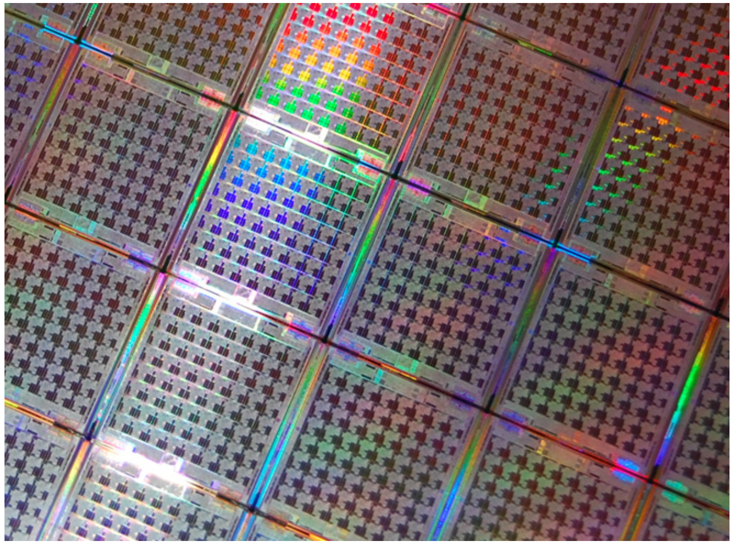
Motivation

- Multicore processors make computations in parallel and share data and synchronize via a Network-on-Chip (NoC)
- The design of the NoC is critical:
  - Slows down the processor if it has delays
  - Can be responsible of 30-50% of the power consumption of the processor





Motivation

Higher Speed

Requires

More Cores

Slower, less efficient, less programmable processors

Wor

Het

Performance

(Long range, broadcast)

Increases pressure

NoC Load

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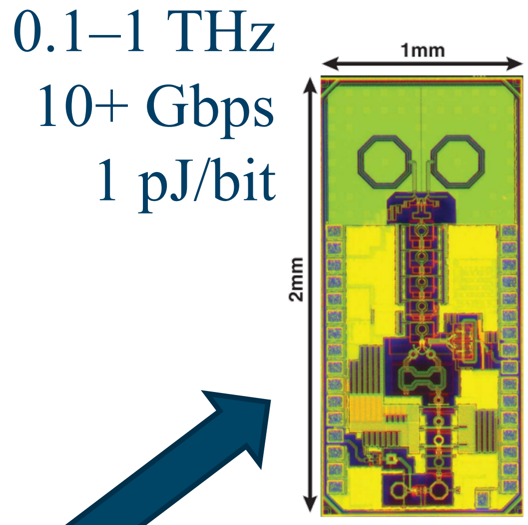
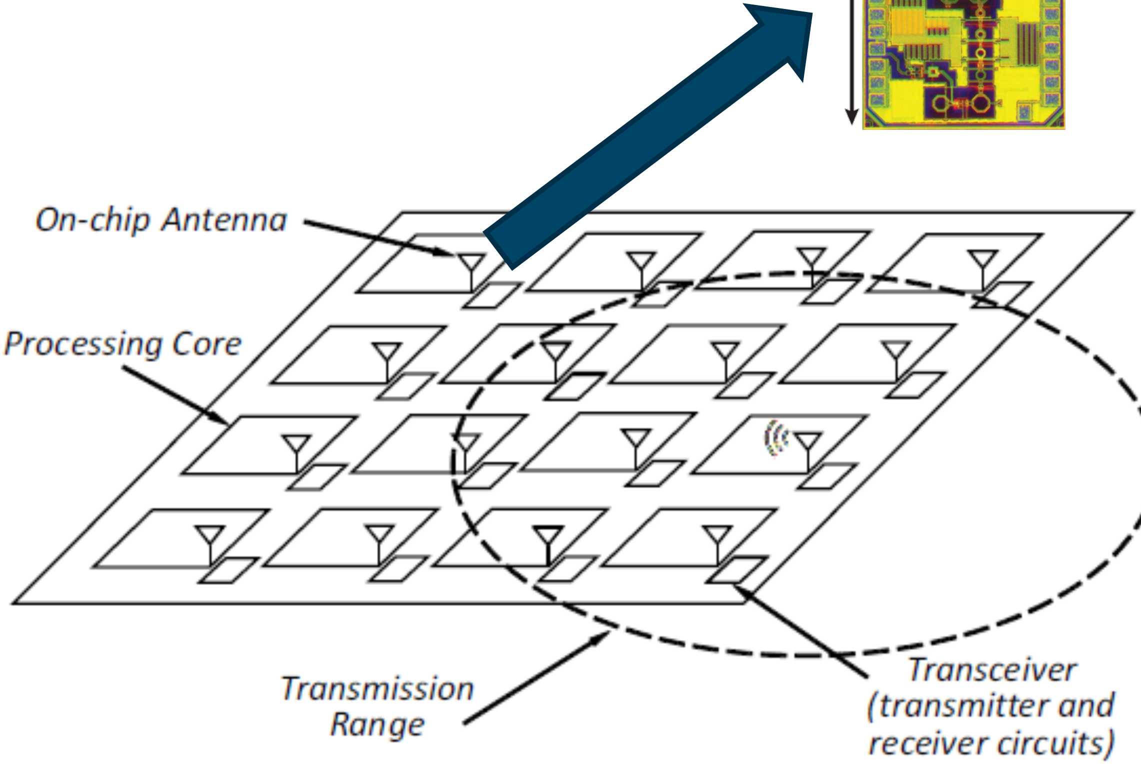
Opportunity

Fix problems with wireless as a complement of existing networks

- Low latency
- Inherently broadcast
- Flexible





Challenges

- Characterizing the wireless channel within the chip
- Understanding the potential gains

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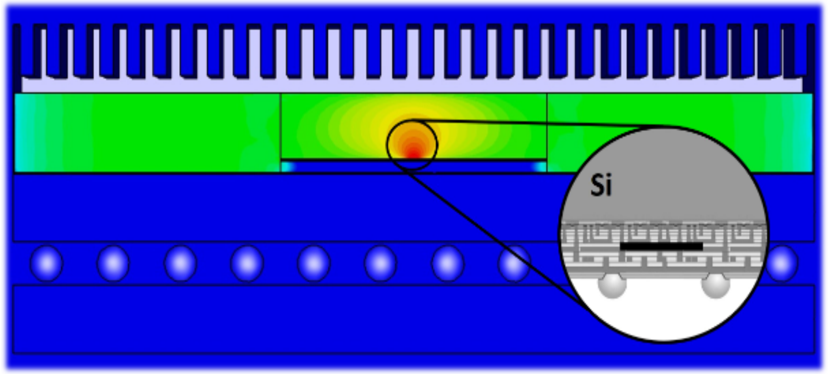
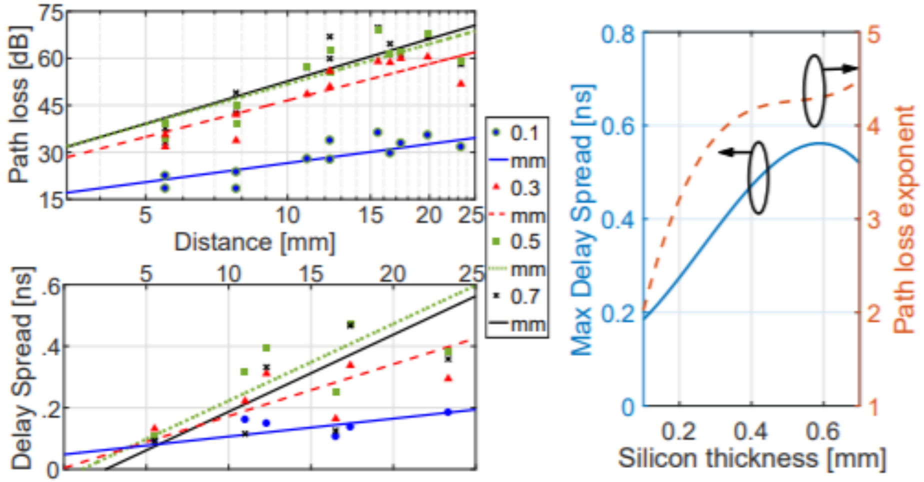
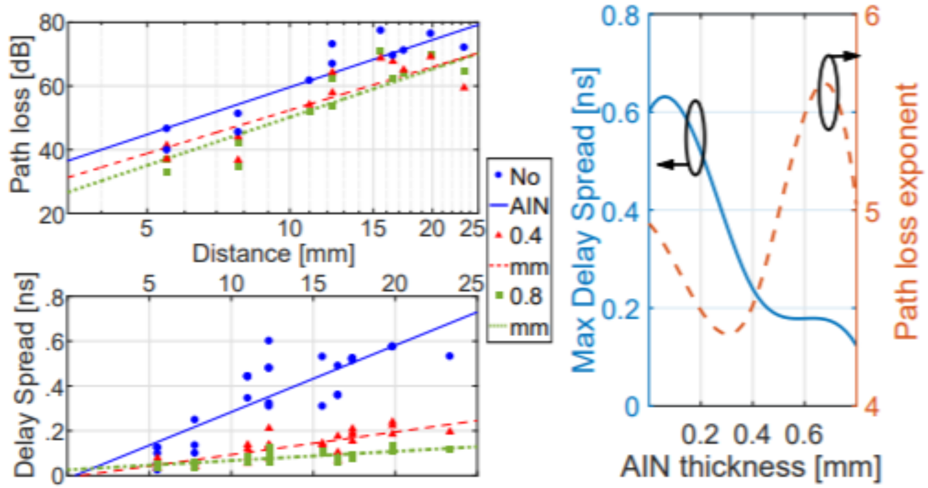
Channel characterization

- Field distribution
- Path loss
- Delay spread



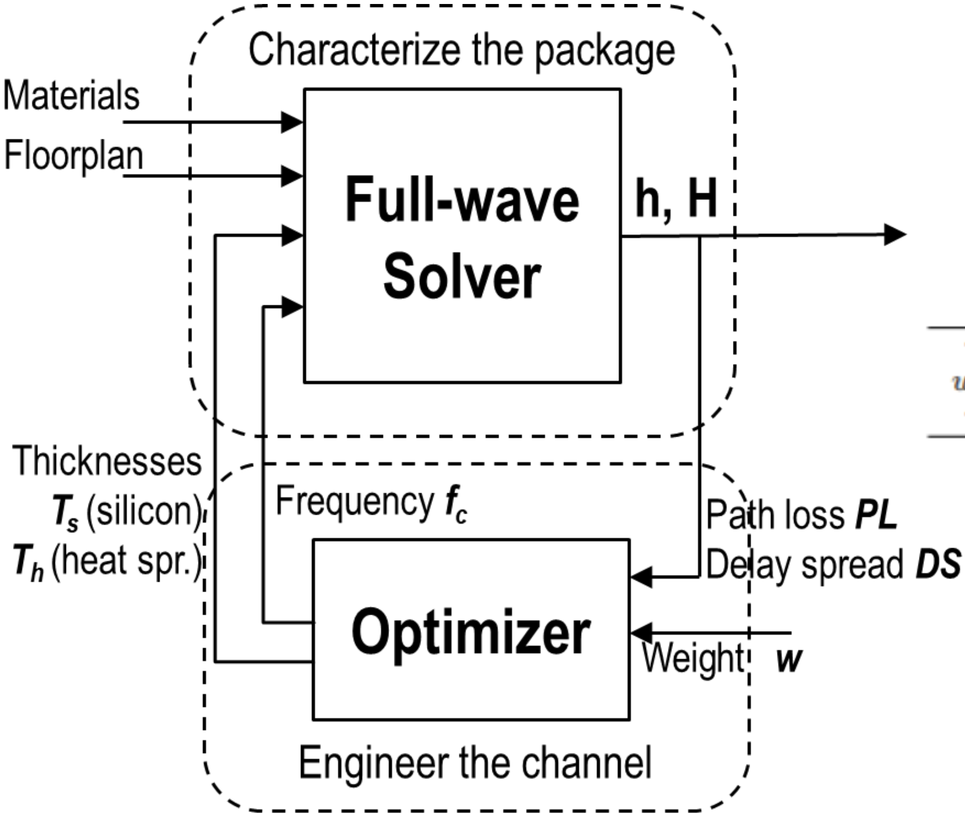


(a) Scaling with silicon thickness T_s ($T_h = 0.2$ mm)



(b) Scaling with heat spreader thickness T_h ($T_s = 0.7$ mm)

Channel engineering



- We can engineer the channel!

TABLE I
SUMMARY OF THE OPTIMIZED PACKAGE DESIGNS

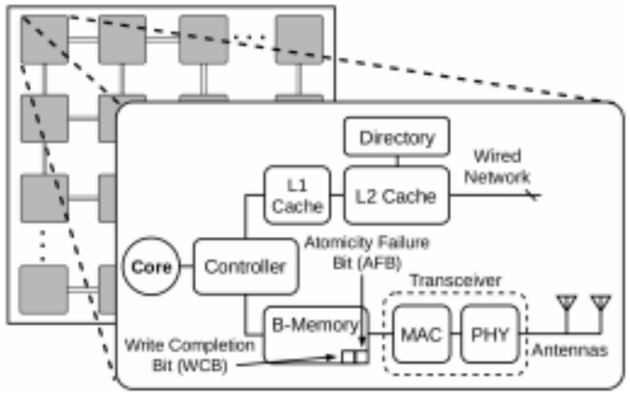
	τ_{rms} (ns)	B_c (GHz)	L_{max} (dB)	L_{avg} (dB)	n
$w = 0$	0.07	14.02	58.62	42.76	3.28
$w = 0.5$	0.15	6.76	45.49	36.48	1.74
$w = 1$	0.59	1.69	28.55	21.88	1.32
Std.	0.52	1.92	75.62	54.57	4.61

X. Timoneda, S. Abadal, A. Franques, D. Manessis, J. Zhou, J. Torrellas, E. Alarcón, and A. Cabellos-Aparicio, "Engineer the Channel and Adapt to it: Enabling Wireless Intra-Chip Communication," IEEE Transactions on Communications, vol. 68, no. 5, pp. 3247-3258, 2020.

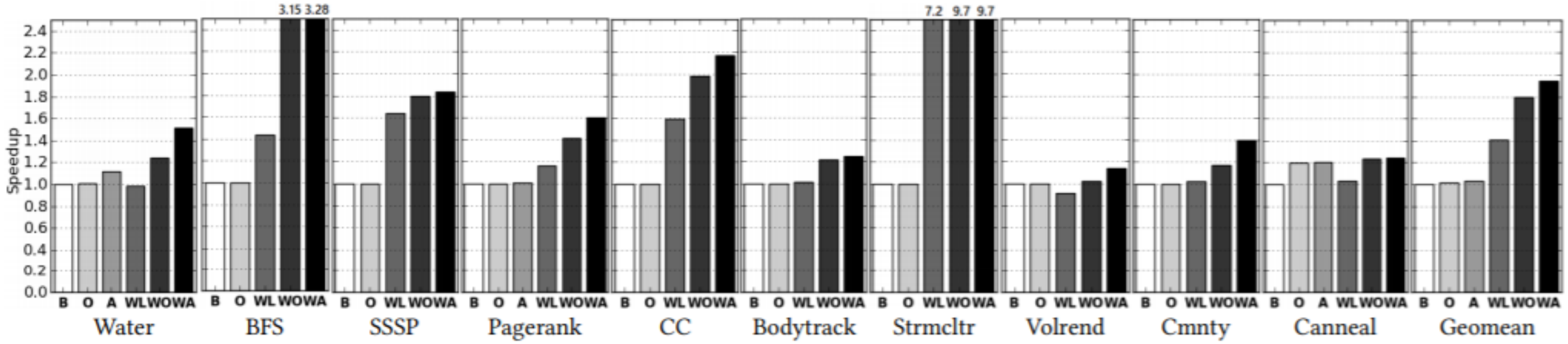
Wireless computer architecture

- Applications run in 2X faster in average
- Computing energy reduced by 40%

(this is a lot in computer architecture)



V. Fernando, et al., "Replica: A Wireless Manycore for Communication-Intensive and Approximate Data," in ASPLOS '19.



Outstanding questions

- Which protocols will allow us to achieve the expected gains?
- What if we reach THz frequencies?
- What if we can do beaming for on-chip communication?
- Which technologies allow us to do that?

Conclusions (II)

- Software-defined metamaterials and on-chip networks are two area-constrained environments with high impact where wireless THz nanonetworks could play a disruptive role
- We studied the context and potential gains, now it is time to think about the protocols that best fit these scenarios (existing or new?)
- No application will be possible if nano-THz hardware does not live up to its promise. Which technology will provide that? CMOS? SiGe BiCMOS? Graphene?

Acknowledgments

EU MSCA IF
ScaleITN

https://sites.google.com/view/scaleitn

www.visorsurf.eu
Twitter
Facebook

www.wiplash.eu
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Terahertz Nanocommunication and Networking: Emerging Applications, Approaches, and Open Challenges

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