RESEARCH OVERVIEW

by

Antonia Tulino

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Telecommunication Group Research Fields

Communication theory

Detection and Estimation theory

Information Theory

Signal Processing

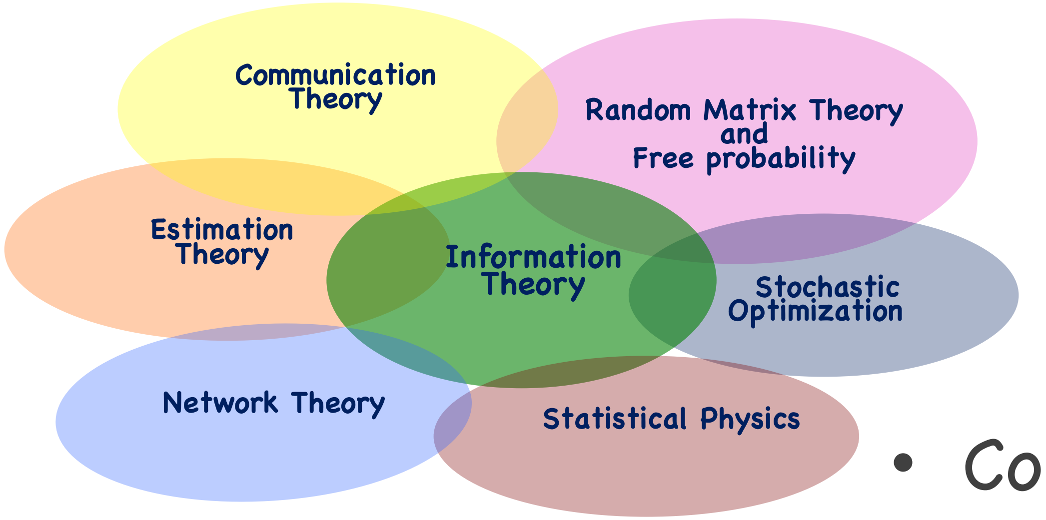
Networks

Statistical learning theory

Interdisciplinary Tools

- Stochastic Optimization
- Random Matrix Theory
- Statistical Physics
- Free Probability

Working at the Intersection: A Success Story



- Networks
  - Efficient Content Storage and Delivery
    - Cache-aided coded multicast
    - Distributed network compression
    - Dynamic Data
  - E2E Service Optimization and Dynamic Control in NG networks
    - NFV and Network Slicing
    - Mobile Edge Computing (MEC)
    - Real-time Stream processing

- Communication Systems
  - Single- multi- user MIMO
    - OFDM,
    - Space time block code
    - Precoding/beamforming
  - Sensor Networks
  - (Stocastic) Network densification
  - Frequency/time- selective channels
  - Capacity of Non-linear Optical channels

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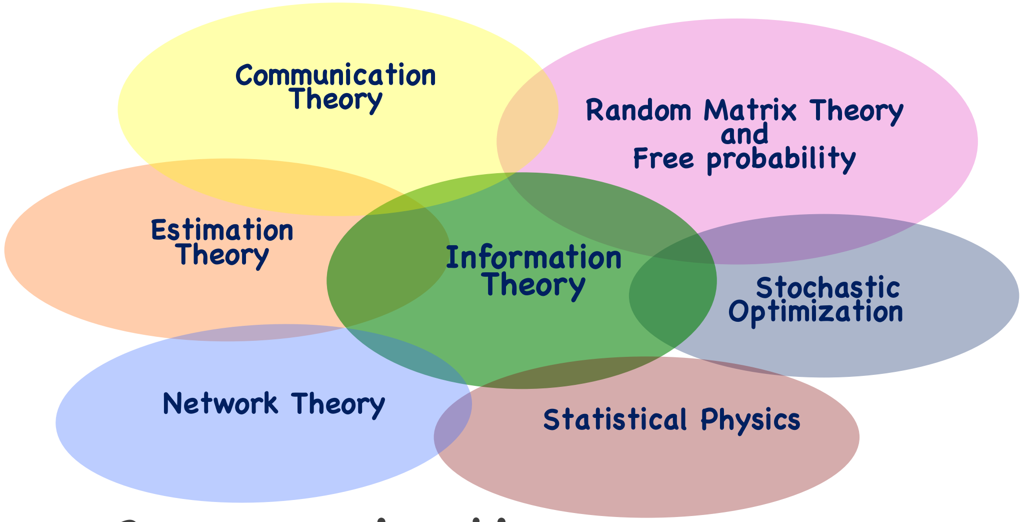


Communication Theory

Random Matrix Theory and Free probability

Estimation Theory

Information Theory

Stochastic Optimization

Network Theory

Statistical Physics

- Advance Wireless Communications

  Massive MIMO

  - Cooperative MIMO
  - NOMA
  - Low power/cost Architect. design for mmW Massive MIMO

  Smart-X (home, factory)
  Automotive

  Localization (Virtual Map)

  - Radar and Communication coexistence
  - NG Radar at mmW

- Statistical Learning

  Active learning

- Optical Communications

  Secrecy Capacity for Optical Com. & Multimode fibers

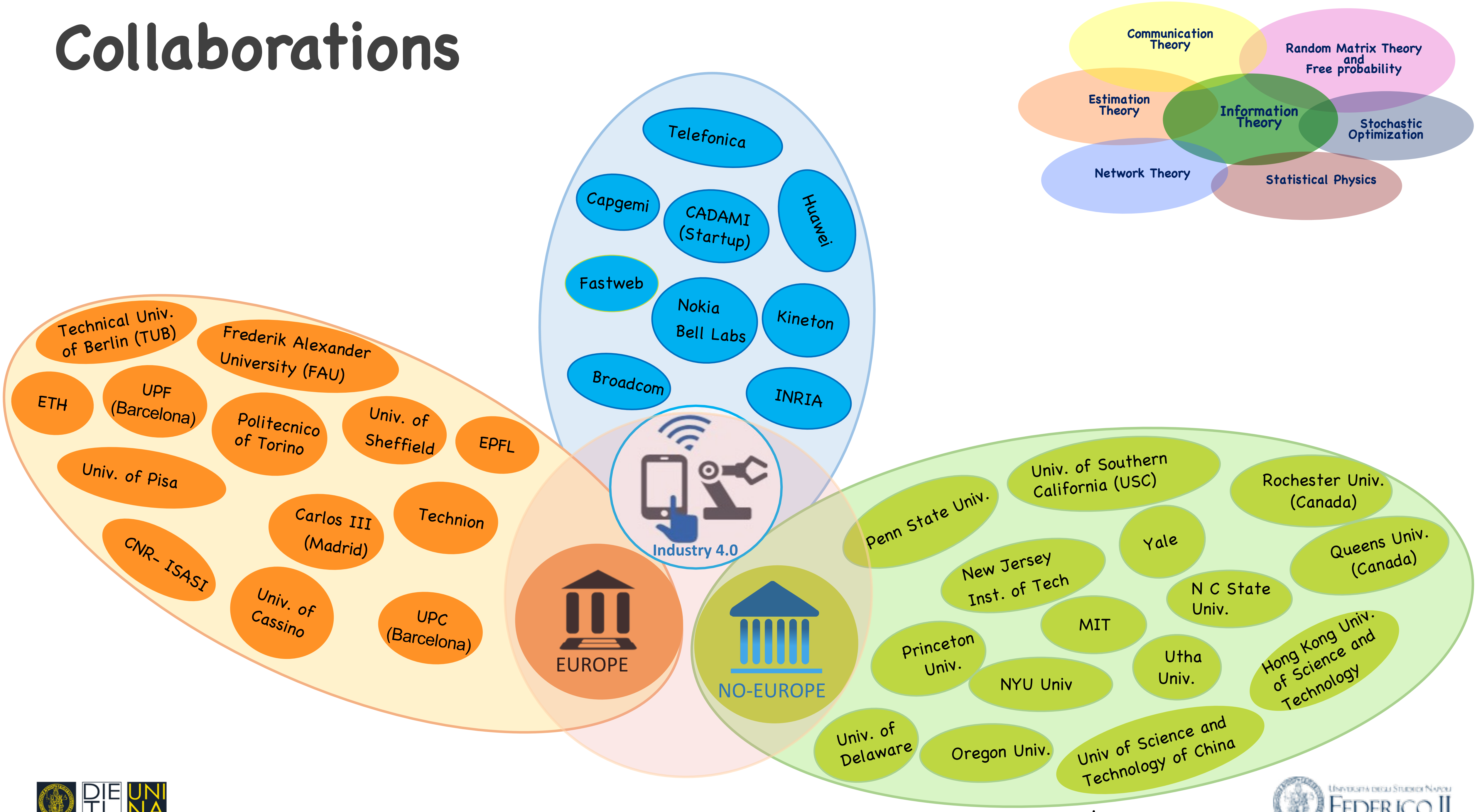
- Big Data

  Noisy Compressed Sensing

- Statistic

  Monotonicity of nonGaussianess

Collaborations



Communication Theory

Random Matrix Theory and Free probability

Estimation Theory

Information Theory

Stochastic Optimization

Network Theory

Statistical Physics

Industry 4.0

Telefonica

Capgemi

CADAMI (Startup)

Huawei

Fastweb

Nokia Bell Labs

Kineton

Broadcom

INRIA

EUROPE

Technical Univ. of Berlin (TUB)

Frederik Alexander University (FAU)

ETH

UPF (Barcelona)

Politecnico of Torino

Univ. of Sheffield

EPFL

Univ. of Pisa

Carlos III (Madrid)

Technion

CNR- ISASI

Univ. of Cassino

UPC (Barcelona)

NO-EUROPE

Penn State Univ.

Univ. of Southern California (USC)

Rochester Univ. (Canada)

Yale

Queens Univ. (Canada)

New Jersey Inst. of Tech

N C State Univ.

MIT

Princeton Univ.

Utha Univ.

NYU Univ

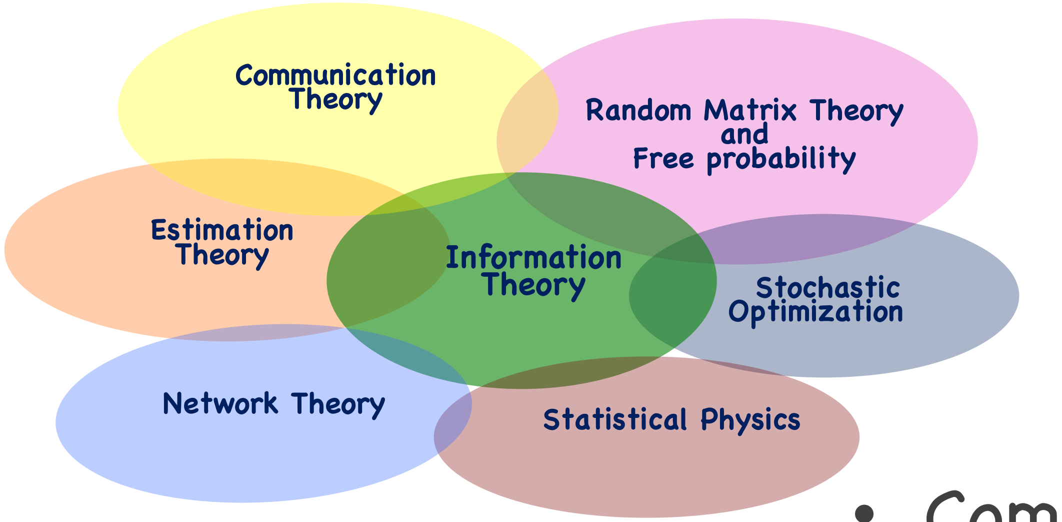
Hong Kong Univ. of Science and Technology

Univ. of Delaware

Oregon Univ.

Univ of Science and Technology of China

Working at the Intersection: A Success Story



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  - Precoding/beamforming

  Sensor Networks

  (Stocastic) Network densification

  Frequency/time- selective channels

  Capacity of Non-linear Optical channels

Collaborations

NOKIA Bell Labs

- Marc Roelands, Alessandra Sala, Narayan Raman, Nakjung Choi, Danny Raz (now Technion).

NYU NEW YORK UNIVERSITY

- Elza Erkip, Jaime Llorca, Parisa Hassanzadeh.

USC UNIVERSITY OF SOUTHERN CALIFORNIA

- Giuseppe Caire (now TUB), Andreas Molisch, Mingue Ji (now Utah), Hao Feng.

The University of Texas at Austin

- Alex Dimakis, Karthikeyan Shanmugam.

Massachusetts Institute of Technology

- Jianan Zhang, Abhishek Sinha, Eytan Modiano.

Yale University

- Konstantinos Poularakis, Leandros Tassiula.

UAB Universitat Autònoma de Barcelona

- Marc Barcelo, Jose Vicario, Antoni Morell

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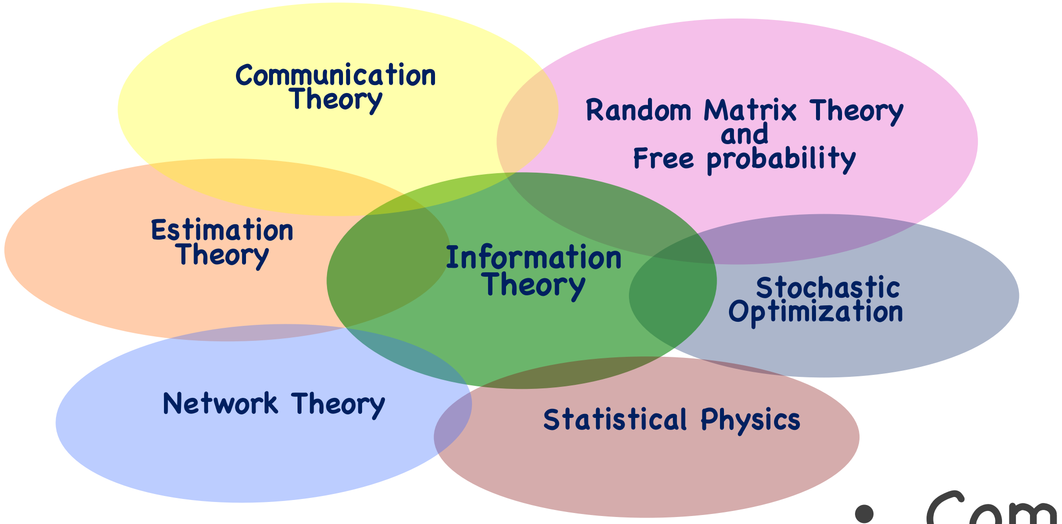

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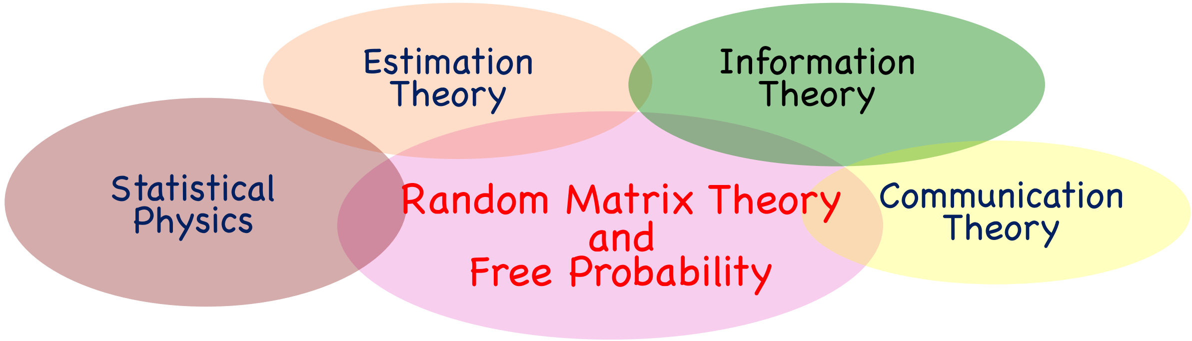
At the Intersections of Random Matrix theory & Free Probability with..


Estimation Theory

Information Theory

Statistical Physics

Random Matrix Theory and Free Probability

Communication Theory

- Communication Systems

  Single- multi- user MIMO

  - MIMO OFDM, N
  - Cooperative MIN
  - Precoding/beam
  - Space time bloc
  - Cooperative MIMO

  Frequency/time- selective channels

  (Stochastic) Network densification

- Advance Wireless Com.

  Massive MIMO

  mW

  gn for mmW Massive MIMO

- nmunications

  ity for Optical Com.

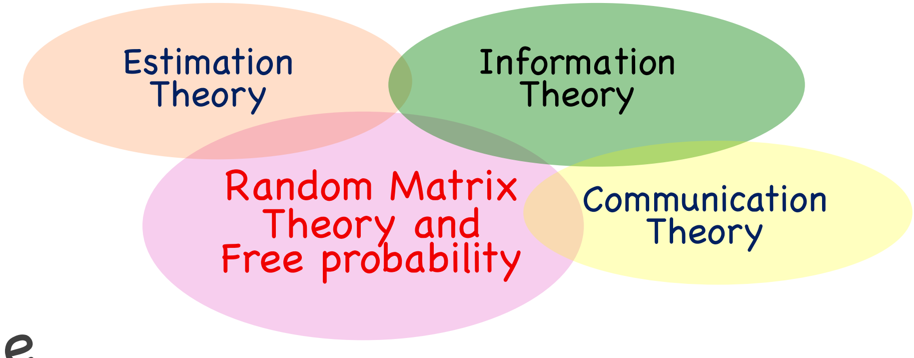
  Capacity for Non-linear Optical channels

- Big Data

  (Noisy) Analog Compression

Their solutions have contributed to new theoretical results in the field of random matrix theory and free probability

At the Intersections of Random Matrix theory & Free Probability with..



Random matrix: matrix-valued random variable

Random Matrix Theory: provides understanding of diverse properties (manly, statistics of matrix eigenvalues) of matrices with entries drawn randomly from various joint p.d.f.

Free probability: mathematical theory that studies non-commutative random variables.

"Freeness" or free independence property is the analogue of the classical notion of independence.

Initiated in 86 from the free group factors isomorphism problem (in operator algebras)

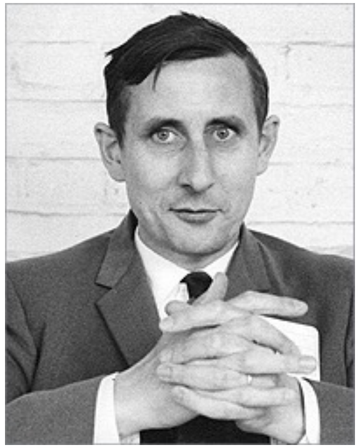
Random Matrix in Physical Systems

Nuclear Physics

To model the nuclei of heavy atoms
(spacings between the lines in the spectrum of
a heavy atom nucleus)

Multivariate Statistics

For statistical analysis of
large samples



Number Theory

To model the distribution of zeros
of the Riemann zeta function
Connected to the Hilbert-Pólya
conjecture

Theoretical neuroscience

To model: network of
synaptic connections
between neurons in the
brain
And dynamical behavior of
randomly connected neural
networks

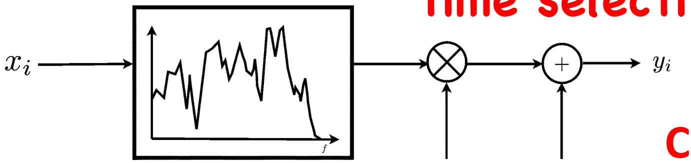
Random Matrix in Communications

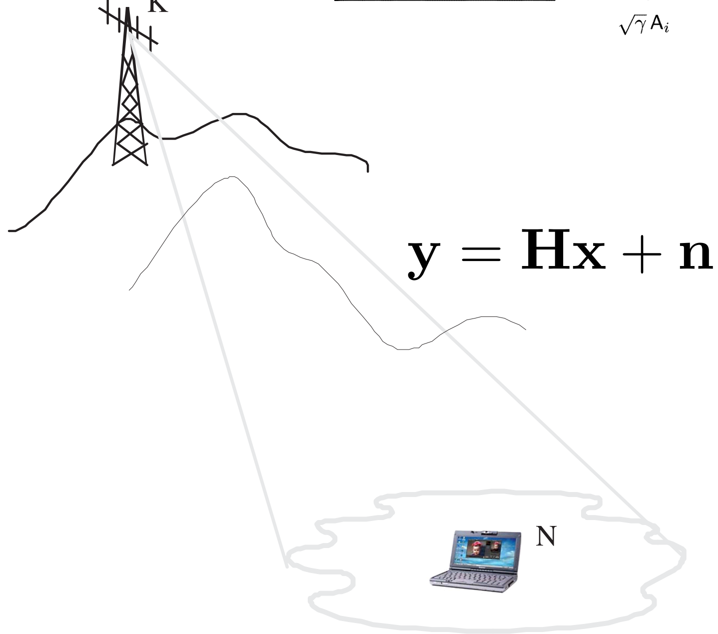
output $\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$ input

N×K channel matrix

Frequency selective

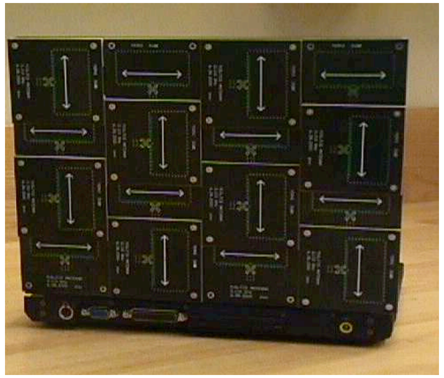
time selective





$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

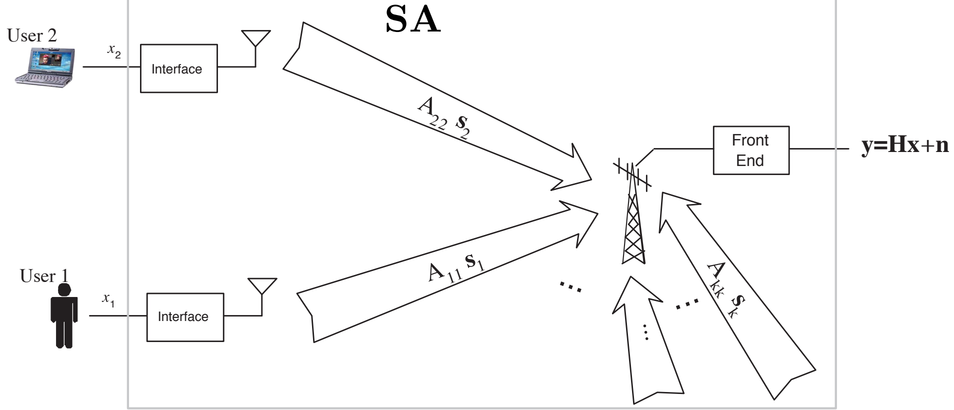
Crosspolarized Antennas



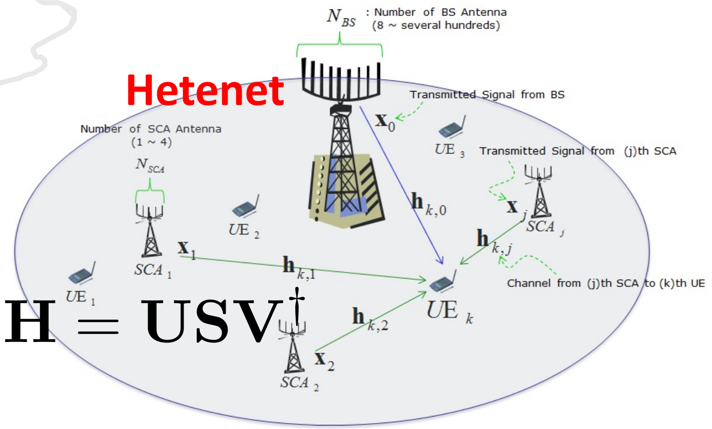
$$\mathbf{H}=\mathbf{P}^{1/2}\circ\mathbf{S}$$

Code Division Multiple Access (CDMA)

$$\mathbf{y} = \underbrace{\mathbf{H}}_{\mathbf{SA}}\mathbf{x} + \mathbf{n} = \mathbf{SAx} + \mathbf{n}$$



Hetenet



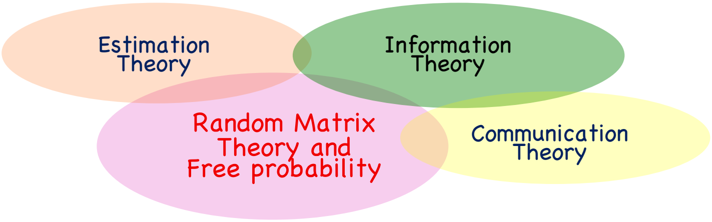
COMP
MC-CDMA
Random Precoding Diversity
Progressive Scattering
Sensor networks

$$\mathbf{H} = \mathbf{USV}^{\dagger}$$

Massive MIMO (LSA)

$$\mathbf{H} = \sqrt{\mathbf{\Phi}_R}\mathbf{S}\sqrt{\mathbf{\Phi}_T}$$

At the beginning...



Three classical (random) matrix ensembles:

Toeplitz Matrix

$$[\Sigma]_{i,j} = \sigma_{i-j}$$

Grenander-Szego'58

Wishart

$$\mathbf{X} = \mathbf{H}\mathbf{H}^{\dagger}$$

Marcenko-Pastur'67

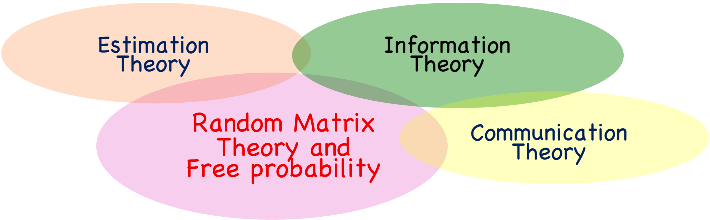
Weighted Wishart

$$\mathbf{X} = \mathbf{H}\mathbf{D}\mathbf{H}^{\dagger}$$

Silverstein-Bai'95

What about arbitrary structure and distributions

Filling the Gap...



New random matrix results:

- Φ_R, Φ_T arbitrary
- $\mathbf{W}$ i.i.d.

Massive MIMO

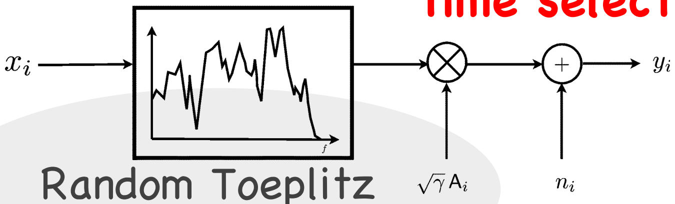
Kronecker Model

$$\mathbf{H} = \sqrt{\mathbf{\Phi}_R}\mathbf{W}\sqrt{\mathbf{\Phi}_T}$$

Frequency selective

- **F** Fourier matrix
- **A,C** strong mixing process

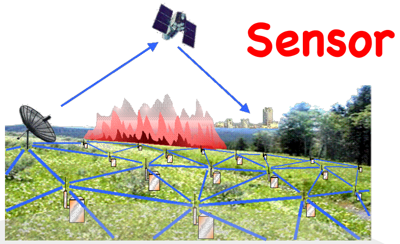
time selective



Random Toeplitz

$$\mathbf{H} = \mathbf{AFC}$$

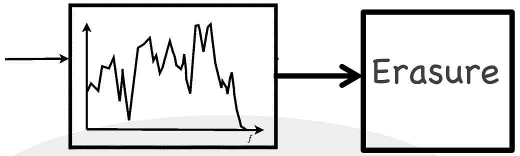
Sensor Networks



d-Fold Vandermonde

$$\mathbf{V}_{\nu(\ell),q} = \frac{1}{\sqrt{N^d}} e^{-j2\pi\ell^\dagger \mathbf{x}_q}$$

Frequency selective



RandomToeplitz

$$\mathbf{H} = \mathbf{AFC}$$

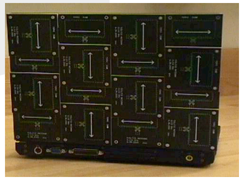
- $\mathbf{\Sigma}$ Toeplitz (random) matrix
- $\mathbf{A}, \mathbf{E}$ i.i.d

Doubly Regular

$$\mathbf{H} = \mathbf{P}^{1/2} \circ \mathbf{W}$$

- $\mathbf{W}$ i.i.d.

Cross-polarized Antennas

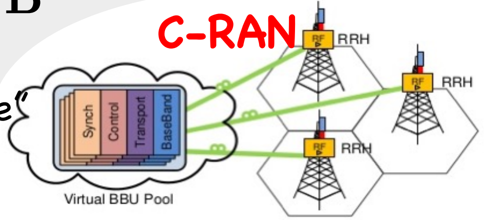


"Free" Products

$$\mathbf{H} = \mathbf{AGB}$$

- A,G, B "Free"

C-RAN

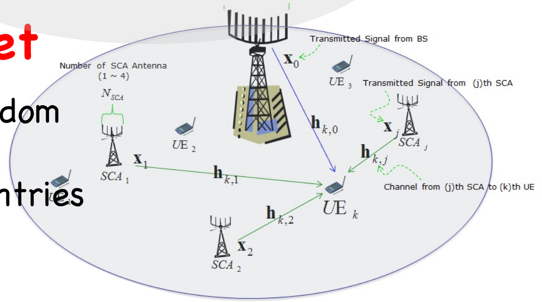


UIU-Model

$$\mathbf{H} = \mathbf{USV}^\dagger$$

Hetenet

- $\mathbf{U}, \mathbf{V}$ random unitary
- $\mathbf{H}$ ind. entries



Random Matrix in Communications

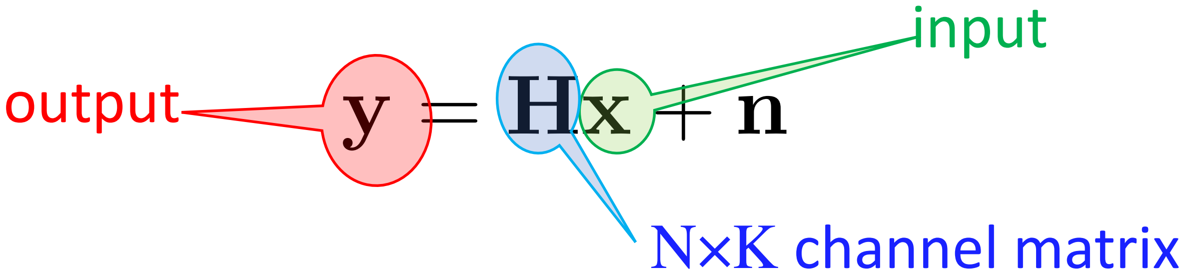
$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

- $\boldsymbol{x}$= K-dimensional complex-values input vector
- $\mathbf{y}$= N-dimensional complex-values output vector
- $\boldsymbol{n}$ = N-dimensional additive Gaussian noise
- $\boldsymbol{H}$= N×K-random channel matrix known at the receiver

Random Matrix Theory and Free probability help in the characterization of **H** when the number of dimensions K and N goes to infinity:

K, N -> ∞ , K/N=const

Random Matrix in Communications



input

output

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

N×K channel matrix

(K, N -> ∞)

(Asymptotic) characterization of **H** and in particular of its eigenvalues of allows characterize

- maximum throughput (Information measurement)
- mean error in the signal reconstruction of x from y (Estimation measurement)

Does asymptotic regime limit the applicability of the result?

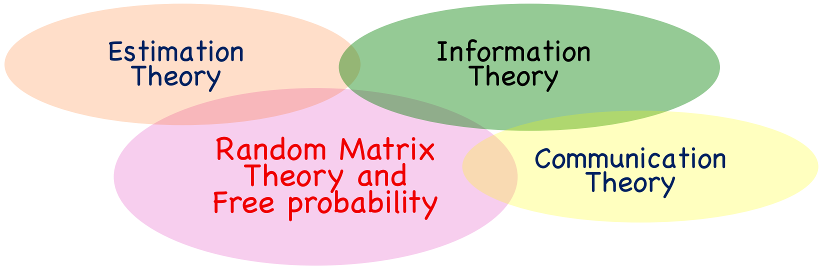
→

8 = ∞

Although exac stem regime, it provide very tigh nance approx. for realistic system dimensions.

Filling the Gap…

New Information Theoretical Limits:

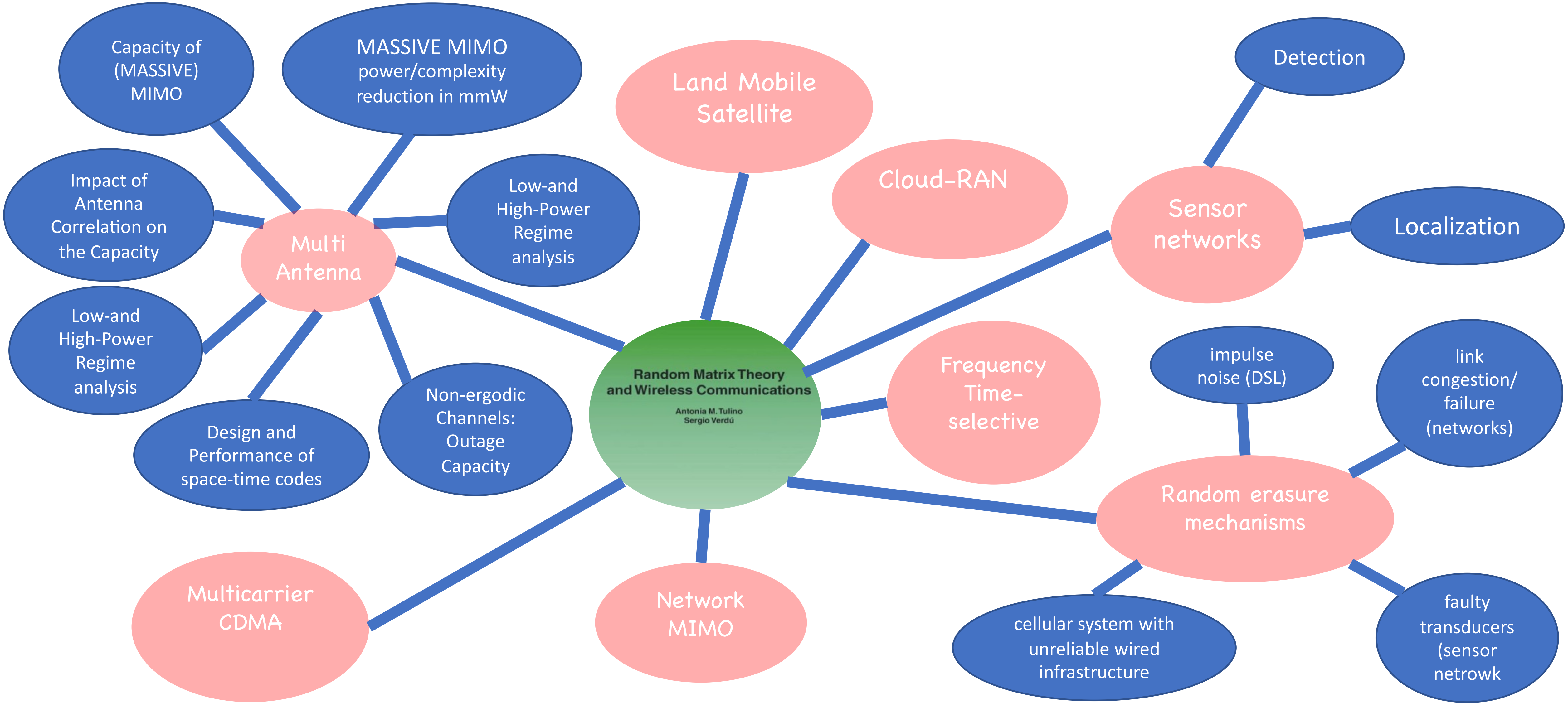


Estimation Theory

Information Theory

Random Matrix Theory and Free probability

Communication Theory



Random Matrix Theory and Wireless Communications

Antonia M. Tulino
Sergio Verdú

Multi Antenna

- Capacity of (MASSIVE) MIMO
- MASSIVE MIMO power/complexity reduction in mmW
- Low-and High-Power Regime analysis
- Impact of Antenna Correlation on the Capacity
- Low-and High-Power Regime analysis
- Design and Performance of space-time codes
- Non-ergodic Channels: Outage Capacity

Land Mobile Satellite

Cloud-RAN

Sensor networks

- Detection
- Localization

Frequency Time-selective

Random erasure mechanisms

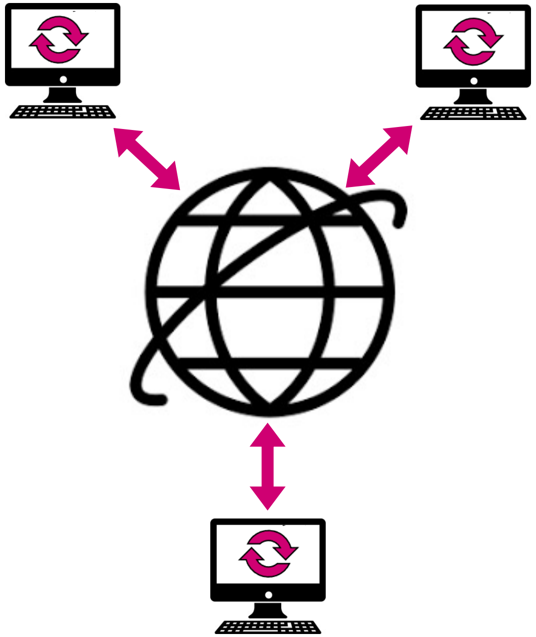
- impulse noise (DSL)
- link congestion/ failure (networks)
- cellular system with unreliable wired infrastructure
- faulty transducers (sensor netrowk

Network MIMO

Multicarrier CDMA

TOWARDS REAL-TIME AUGMENTED COGNITION

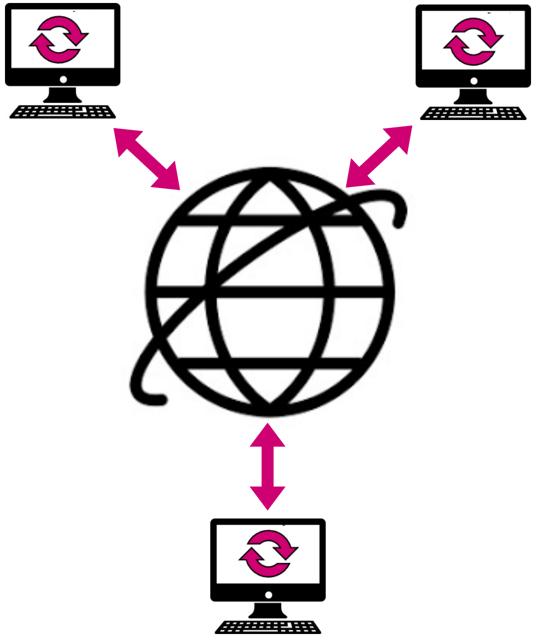
Communication



- Resource limited
- Interaction limited

TOWARDS REAL-TIME AUGMENTED COGNITION

Communication



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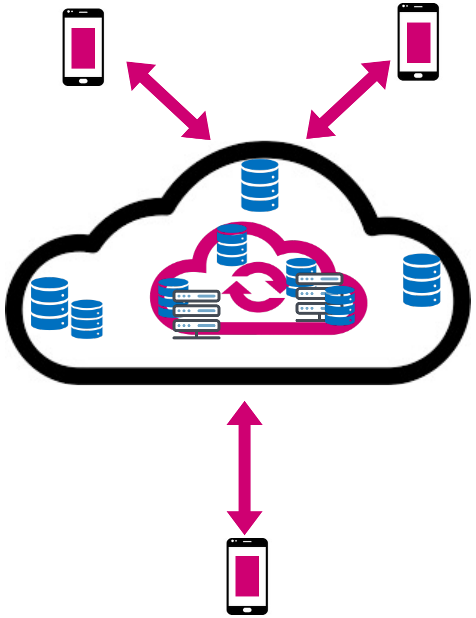
Content Distribution



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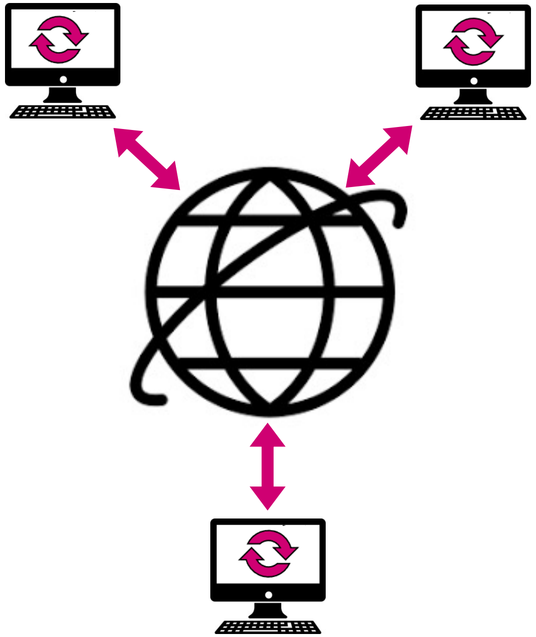

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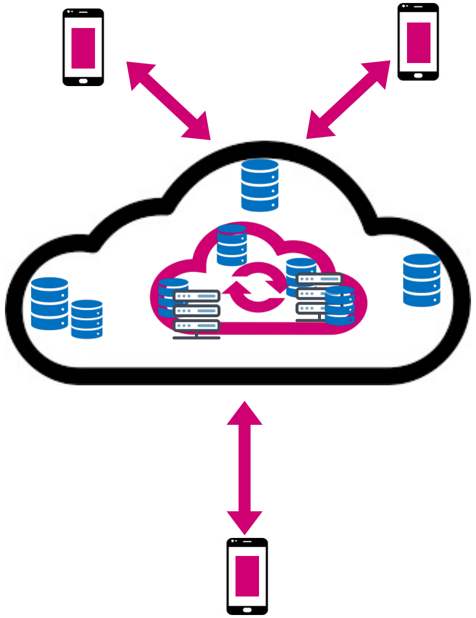
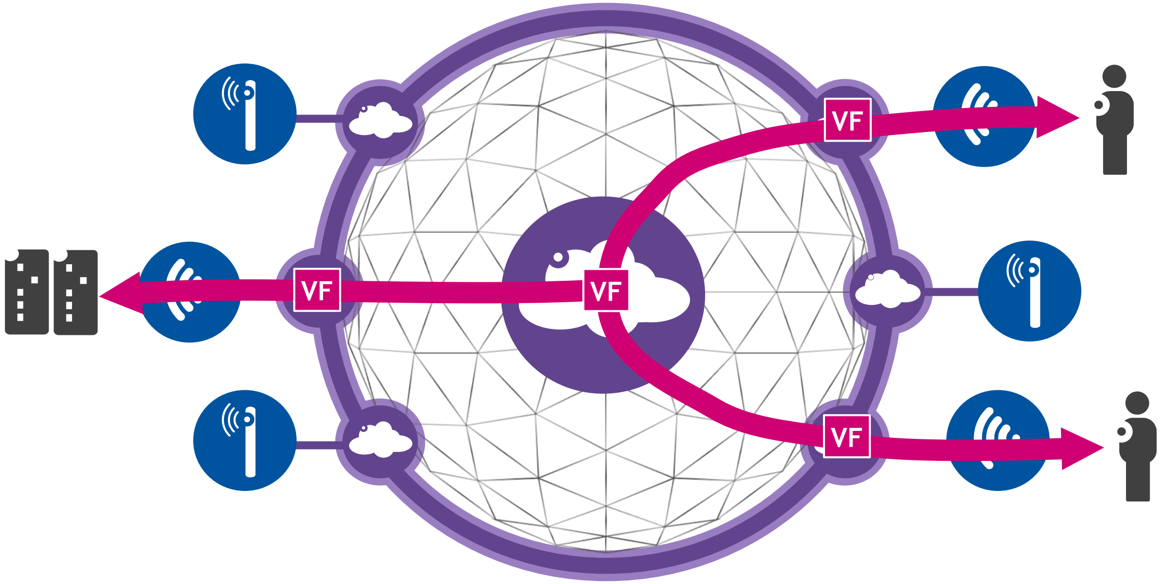


- Resource intensive
- Interaction limited

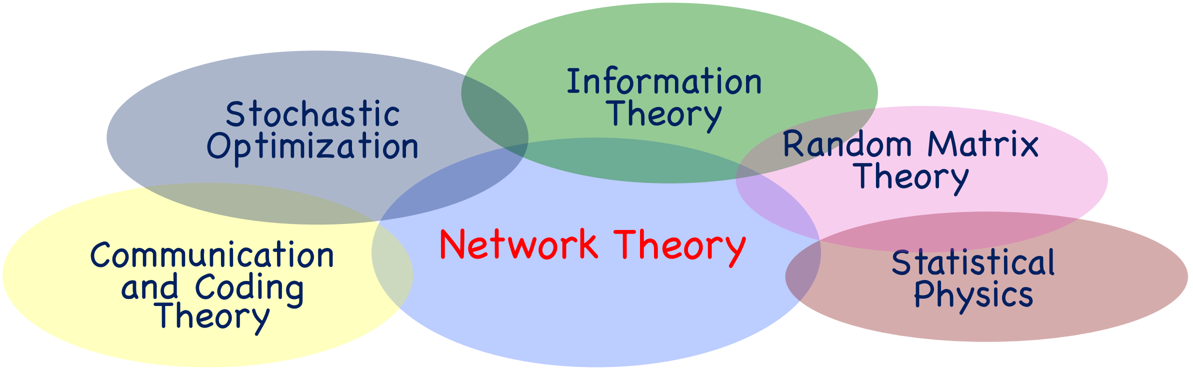
Real-time Computation



- Resource intensive
- Real-time interaction

Bridging the time-scale gap between information capture/sensing, analysis/processing, and delivery/consumption

At the Intersections of Network Theory with..



Vision:

5G & beyond cloud-integrated networks will become universal general-purpose compute platforms, with large variety of services and applications deployed in the form of slices within a common physical infrastructure.

- Content Networks

  Efficient Content Storage and Delivery
  - Cache-aided coded multicast
  - Distributed network compression
  - Dynamic Data

→

- Computing Networks

  E2E Service Optimization and Dynamic Control in NG cloud-integrated networks
  - NFV and Network Slicing
  - Mobile Edge Computing (MEC)
  - Real-time Stream processing

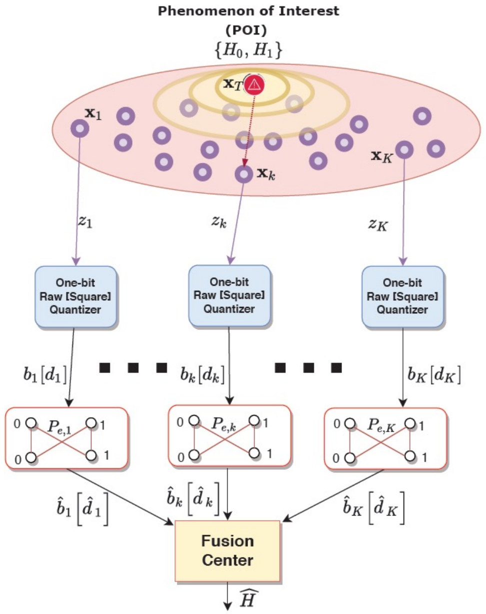
TOPICS CONNECTED TO SENSOR NETWORKS…

The age of Green Internet-of-Things (G-IoT) [for more details see slides 78-82]

- **Reconfigurable and programmable metasurfaces** to obtain dynamically switching EM functions, yielding more freedom and flexibility with respect to conventional phased antenna arrays.
- **Objective**: **joint exploitation of space and time dimensions** to allow additional degrees like:
    - Improved information rates
    - Channel estimation
    - Physical-layer security
    - Sensing and data fusion
    - Wireless E-health

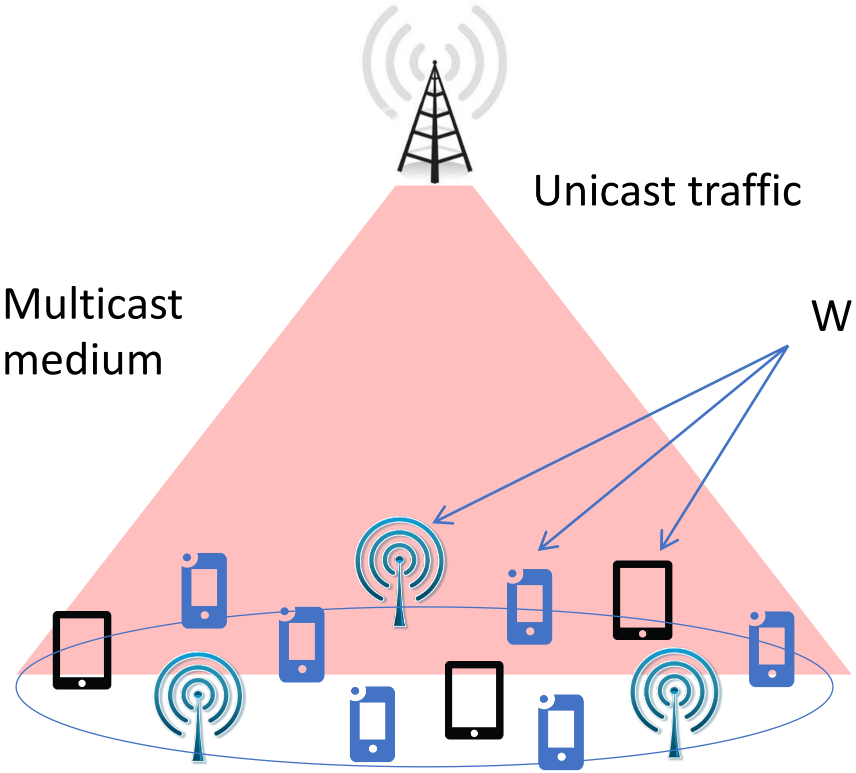
DECENTRALIZED INFERENCE WITH SENSING UNCERTAINTY

[for more details see slides 83-87]



- **Objective: detecting a localized POI (Phenomenon of Interest), whose position and emitted amplitude not known in advance.**
- **Open issues**
    - Development of sophisticated models for accounting both complex sensing phenomena and 5G/B5G communication systems (ambient backscattering, massive MIMO, RISs, etc).
    - Design of low-complexity fusion rules originated/elicited from composite hypothesis testing problems, including also quickest detection scenarios
    - Sensor Quantizer design, including adaptivity by means of active testing

The Wireless Bottleneck



Unicast traffic

Multicast medium

Wireless edge caching

Asynchronous content reuse

Caching

The Wireless Bottleneck

Approaches

- FemtoCaching: Caching at the infrastructure side (SBS, Helpers)

M: Memory at femtocaching

m: numero di files

NO Scalable

$$R \approx \Theta\left(\frac{m}{M}\right)$$

Rate ≈ $\mathcal{L}oad$ ≈ Delay

Requires infrastructure nodes to grow linearly with the users.

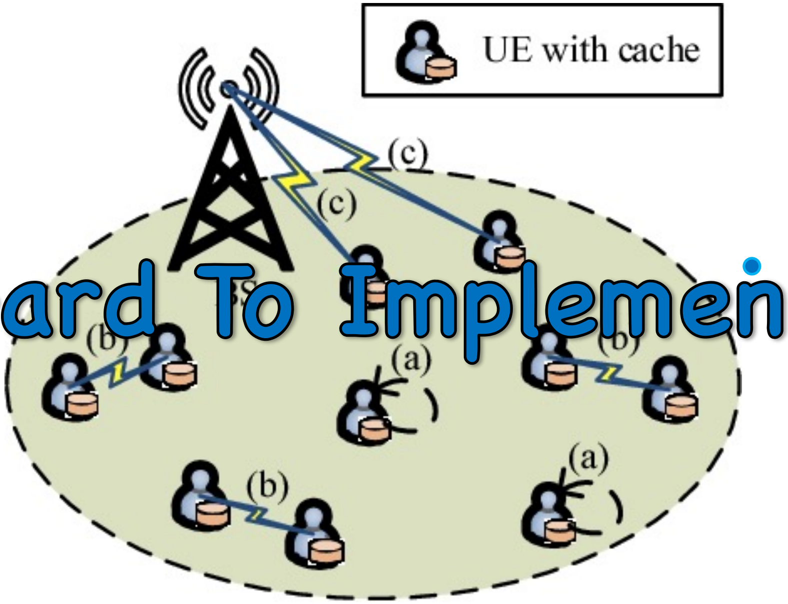
The Wireless Bottleneck

Approaches

- D2D Caching: content replication and multi-hop.

M: Memory at user device

m: numero di files



Hard To Implement

$$R \approx \Theta\left(\frac{m}{M}\right)$$

Rate ≈ *Load* ≈ Delay

Requires no infrastructure but very hard to implement

- no good D2D standard in place,
- coordination across a large network

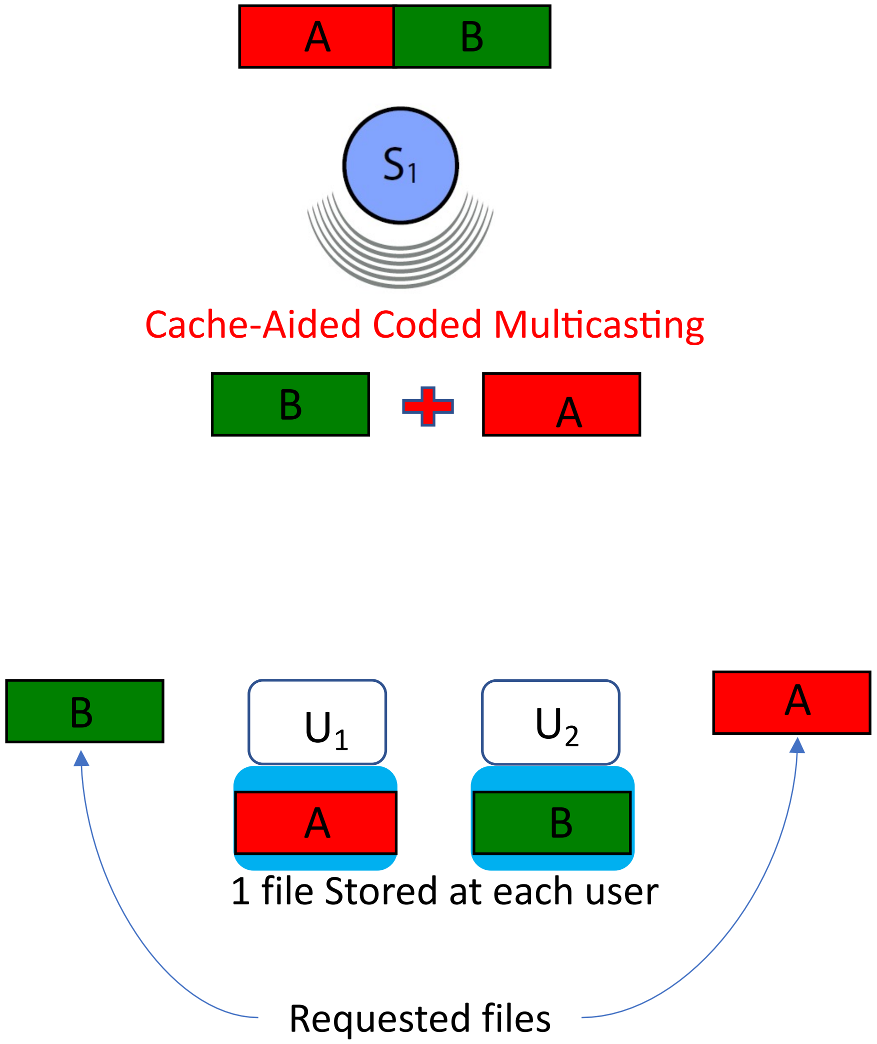
The Wireless Bottleneck

Question:
Can we achieve scalability with finite infrastructure and no D2D communication?

Yes we can!

Cache-Aided Coded Multicast:

- J. Llorca, A.M. Tulino K. Guan, and D. Kilper, 2013 Network-coded caching-aided multicast for efficient content delivery".
- M. Ji, A. M. Tulino, J. Llorca, and G. Caire, 2014 "On the average performance of caching and coded multicasting with random demands."

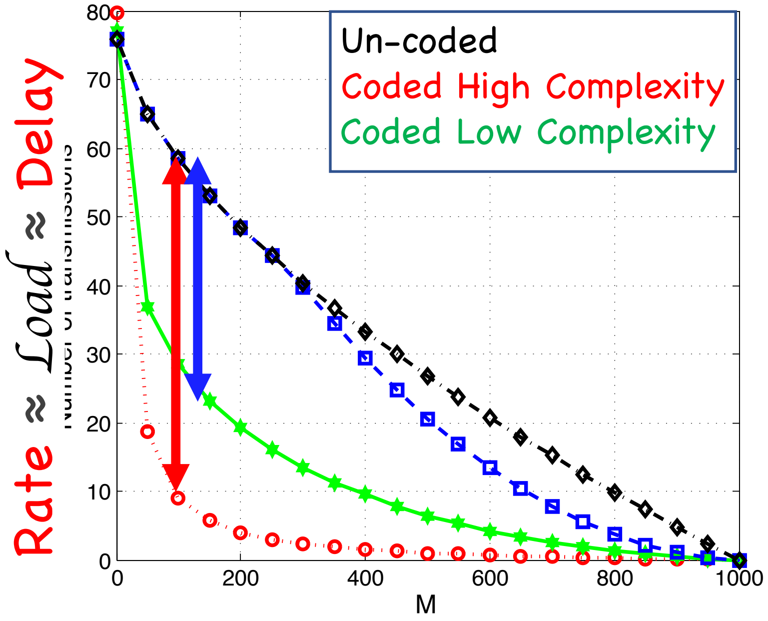


Main Idea: leverages side information at wireless edge caches to efficiently serve jointly multiple unicast demands via common multicast transmissions, leading to load reductions that are proportional to the aggregate cache size. (Network Coding)

The Wireless Bottleneck

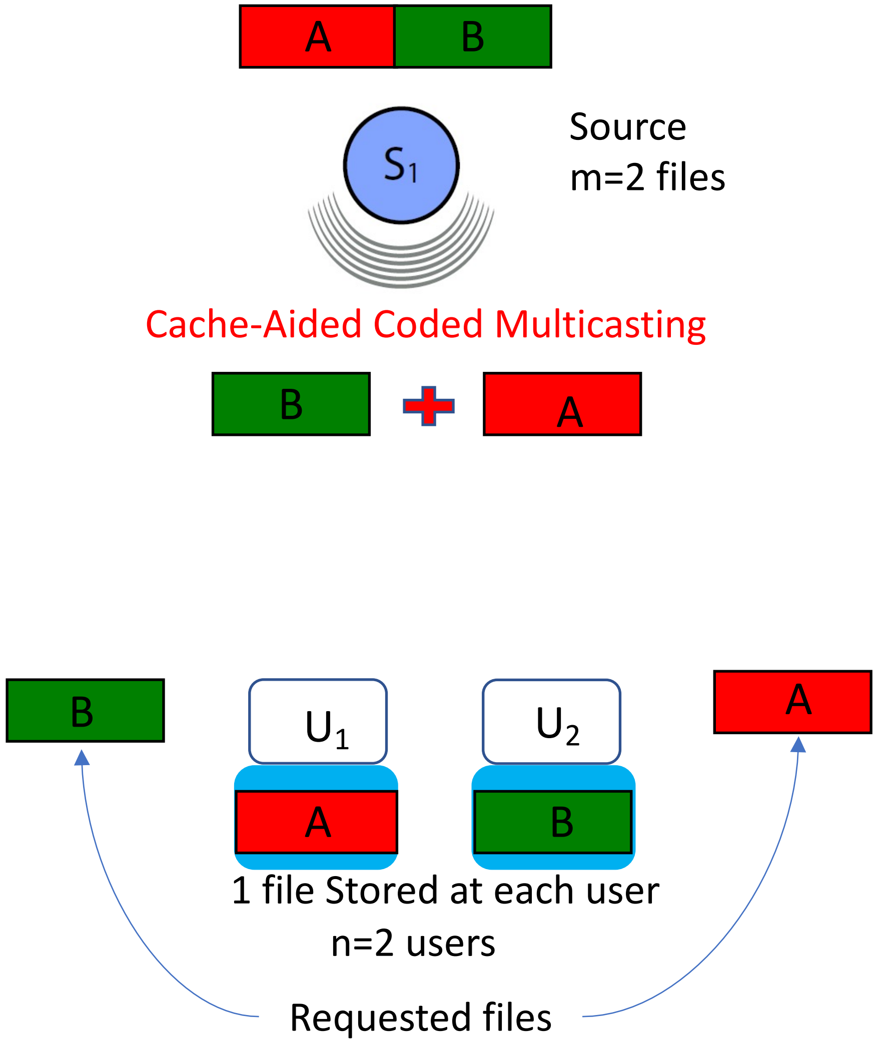
Cache-Aided Coded Multicast:

- M. Ji, A. M. Tulino, J. Llorca, and G. Caire, 2014 "On the average performance of caching and coded multicasting with random demands."



Theoretical unbounded gains

Practically significative gains



Source
m=2 files

Cache-Aided Coded Multicasting

1 file Stored at each user
n=2 users

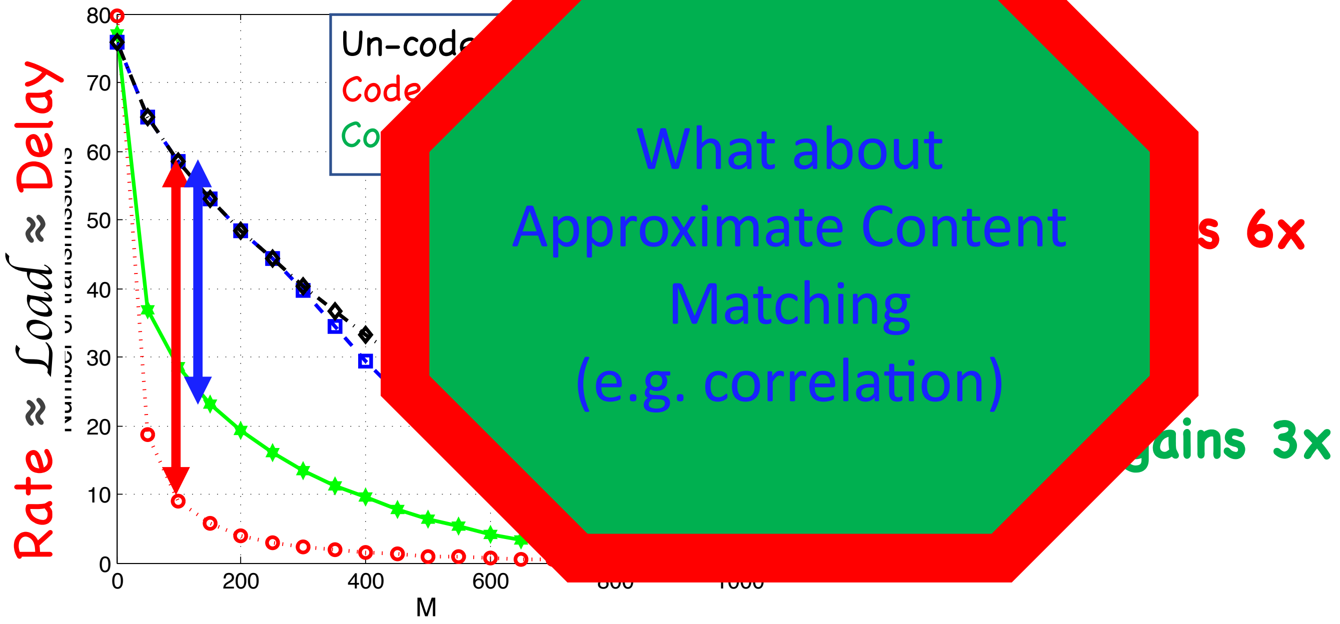
Requested files

Main Idea: leverages side information at wireless edge caches to efficiently serve jointly multiple unicast demands via common multicast transmissions, leading to load reductions that are proportional to the aggregate cache size. (Network Coding)

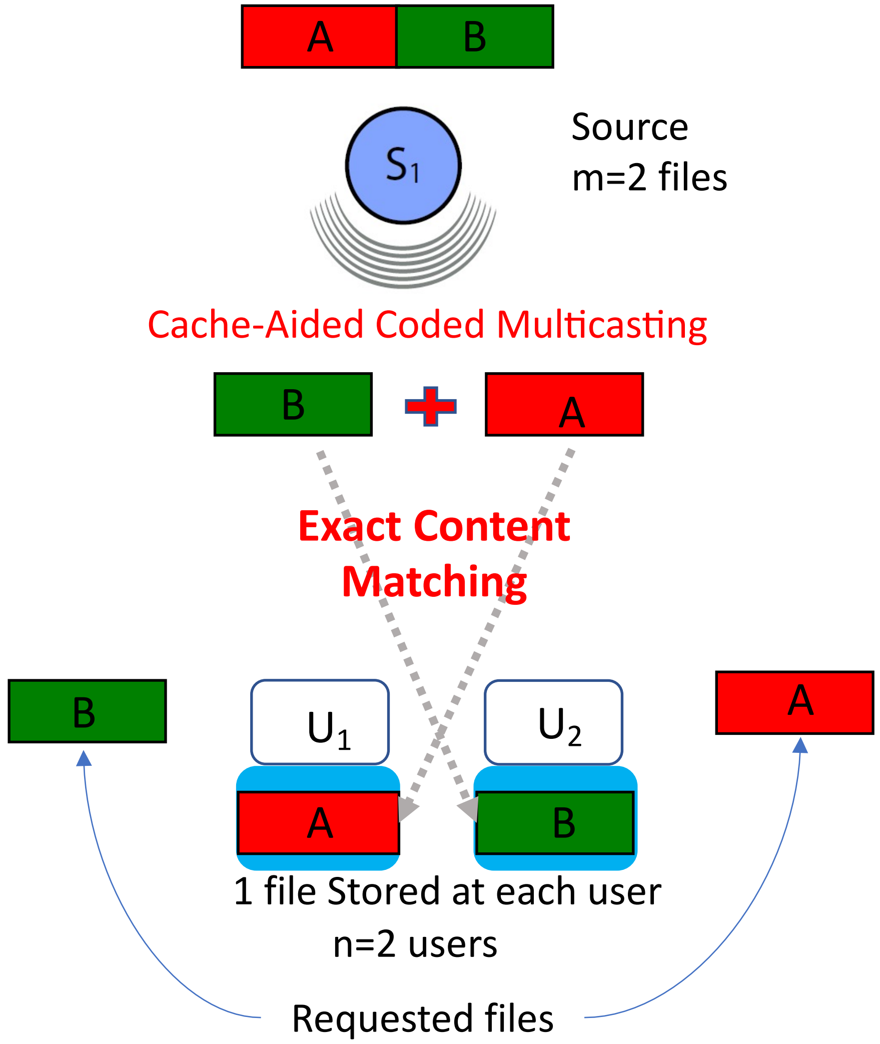
The Wireless Bottleneck

Cache-Aided Coded Multicast:

- M. Ji, A. M. Tulino, J. Llorca, and G. Caire, 2014 "On the average performance of caching and coded multicasting with random demands."



What about Approximate Content Matching (e.g. correlation)

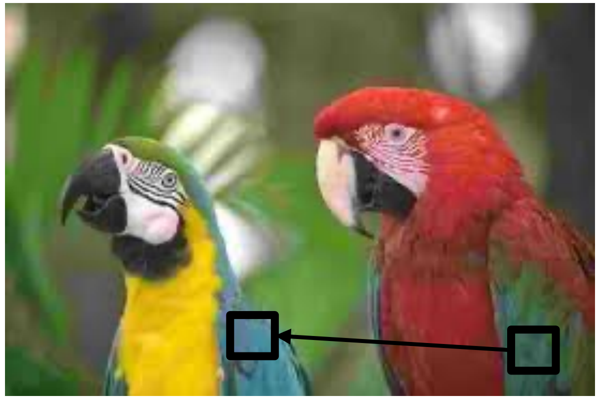


Main Idea: Reducing the load over the network by looking for content stored in the network that exact matches the information that we need to deliver in order to satisfy user demand. Moving towards real-time (personalized media dominated) services exact cache hits are almost non-existent.

Dynamic end-to-end network compression

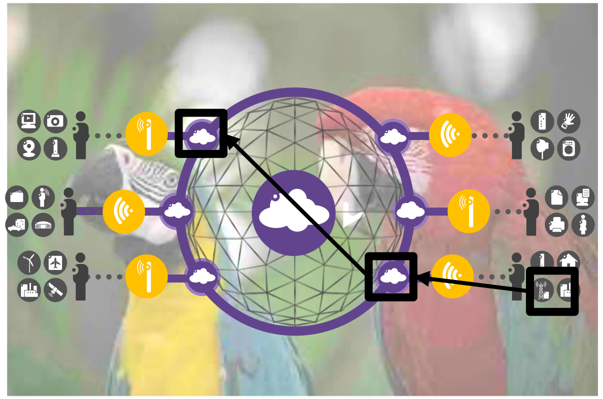
compressing information as it travels through the network

FROM STATIC LOCAL COMPRESSION TO DYNAMIC NETWORK COMPRESSION



Static local compression is myopic to spatiotemporal information lifecycle

We still compress information based solely on local intra-file correlations, without taking into account increasingly relevant network-wide spatiotemporal correlations

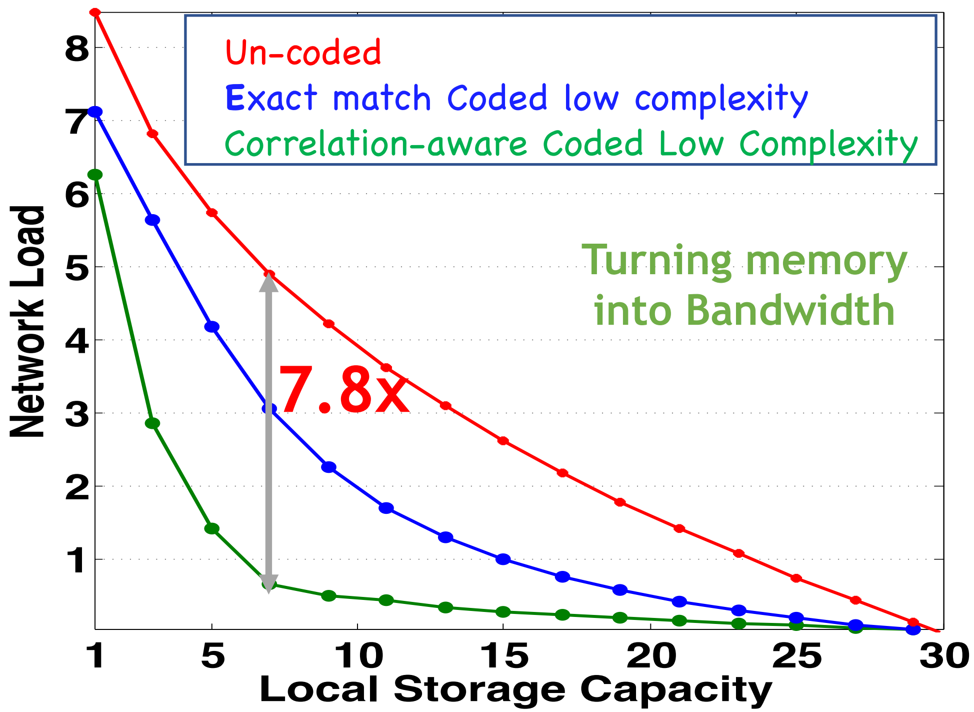


Dynamic e2e compression adaptively exploits redundancy throughout the network

Exploiting cloud network wide spatiotemporal redundancy to push the fundamental limits of information compression

Previously stored information are exploited as references for network compression during delivery

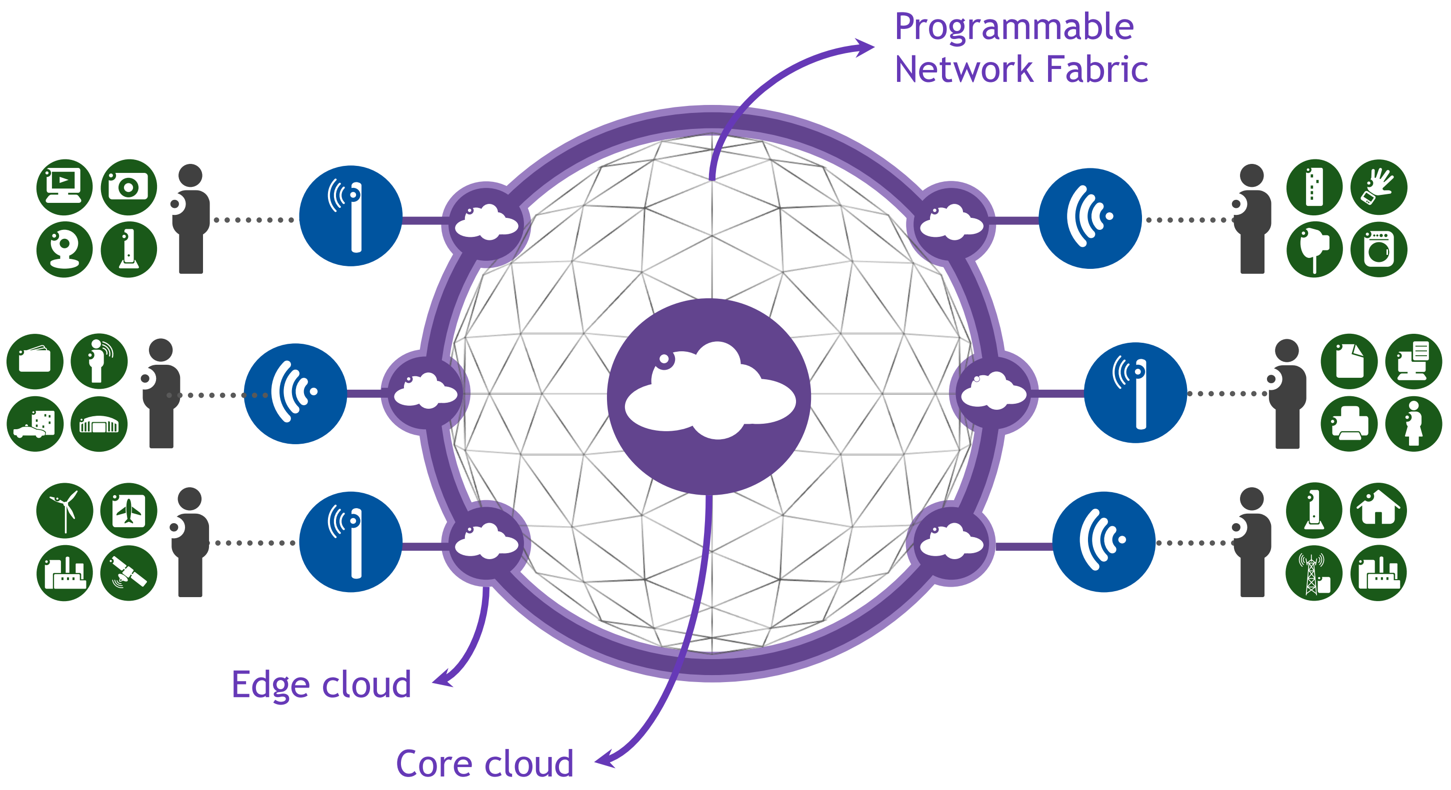
Towards E2E network compression



8X network load reduction beyond local compression and unicast delivery

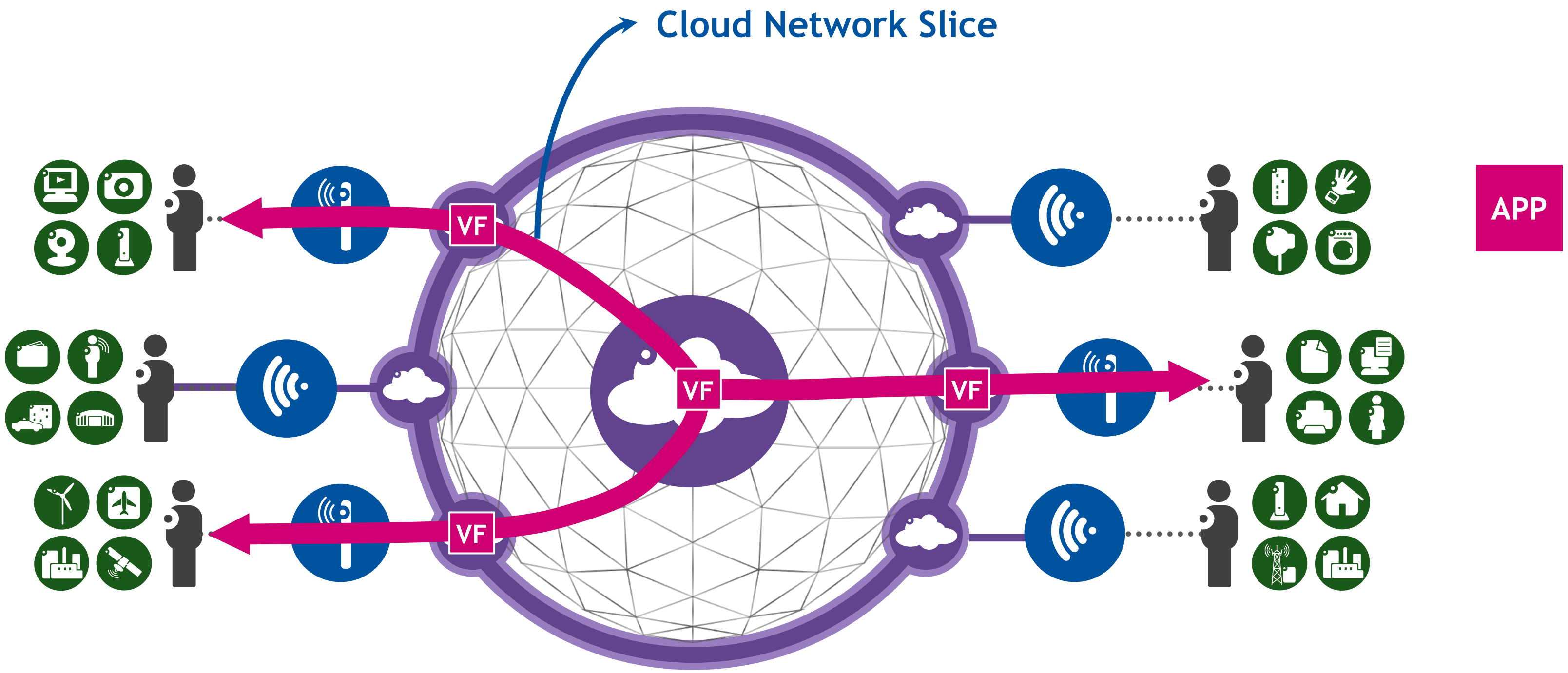
Content distribution network: 10 journal publications, 15 conference papers,2 book Chapters, 1 best conf. paper award, 900+ google citations, 16 patents (4 Licensed)

CLOUD-INTEGRATED NETWORKS AS UNIVERSAL COMPUTE PLATFORMS



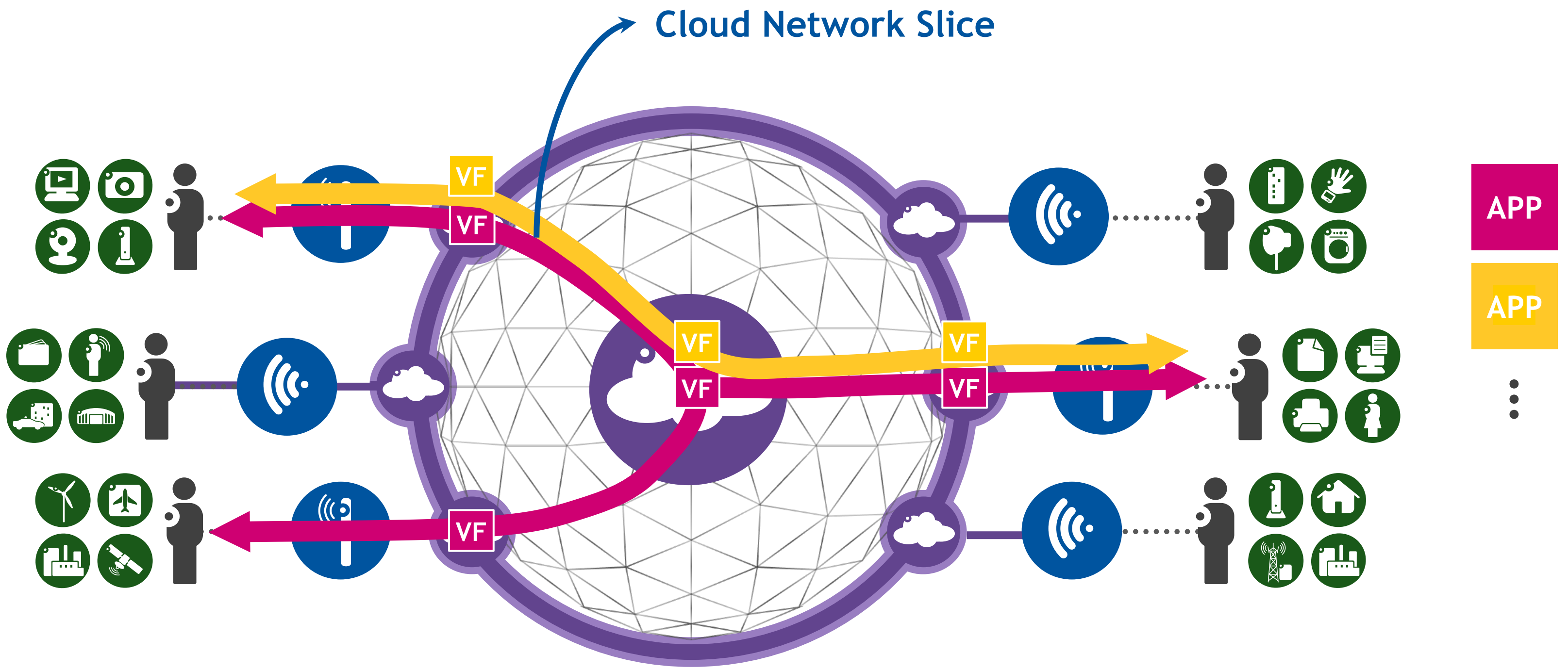
(5G & beyond) cloud-integrated networks will become universal general-purpose compute platforms, where a large variety of services and applications will be deployed in the form of slices within a common physical infrastructure.

CLOUD-INTEGRATED NETWORKS AS UNIVERSAL COMPUTE PLATFORMS



Every human experience will be supported by a collection of services running over a cloud-integrated network.

CLOUD-INTEGRATED NETWORKS AS UNIVERSAL COMPUTE PLATFORMS

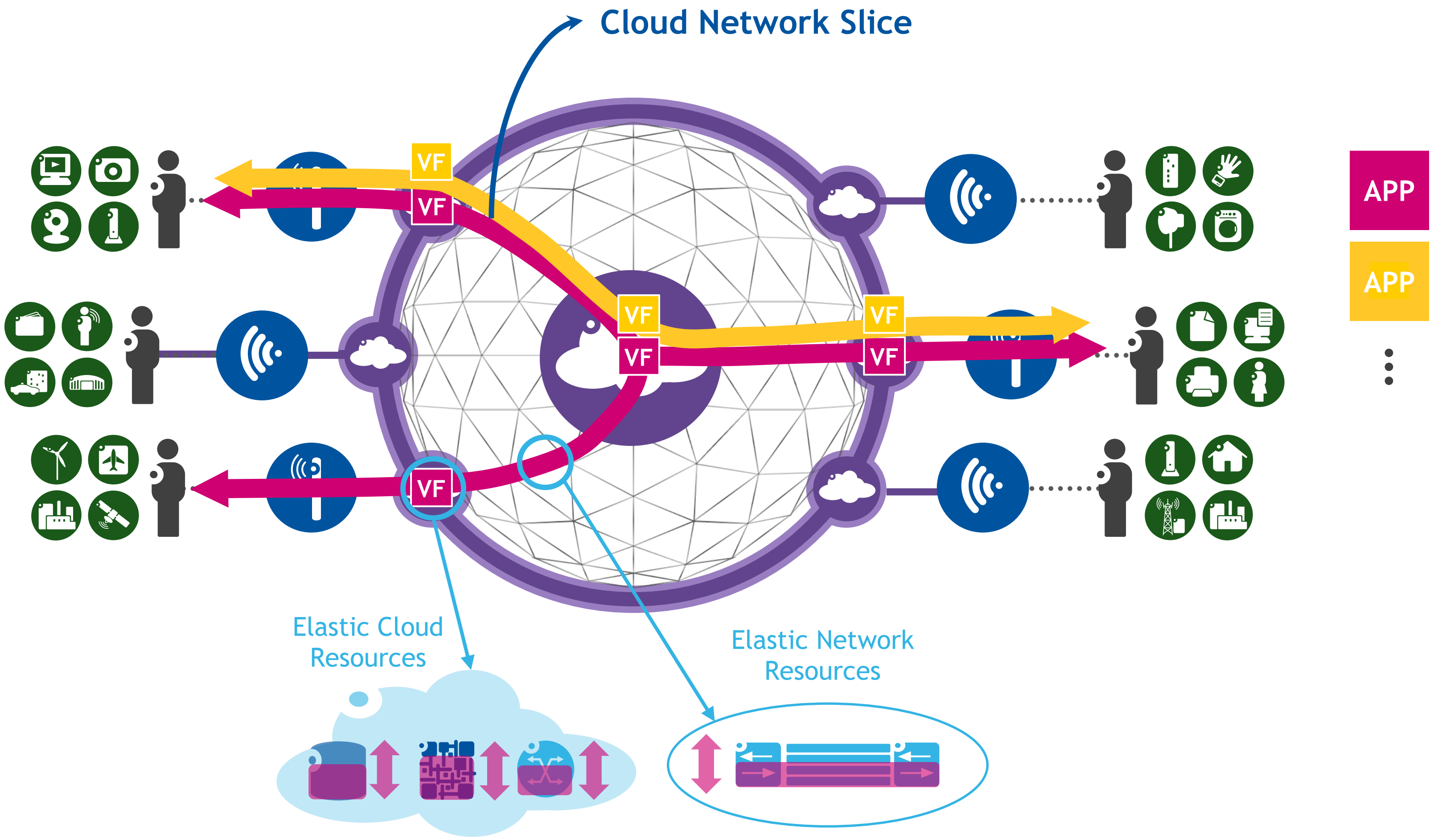


These services take information sources from the physical world, route them through multiple functions instantiated across the cloud network until delivering output flows that create some form of augmented value for the end user

M. Weldon, "The Future X Network: A Bell Labs Perspective," CRC PRESS, October 2015.

CLOUD-INTEGRATED NETWORKS AS UNIVERSAL COMPUTE PLATFORMS

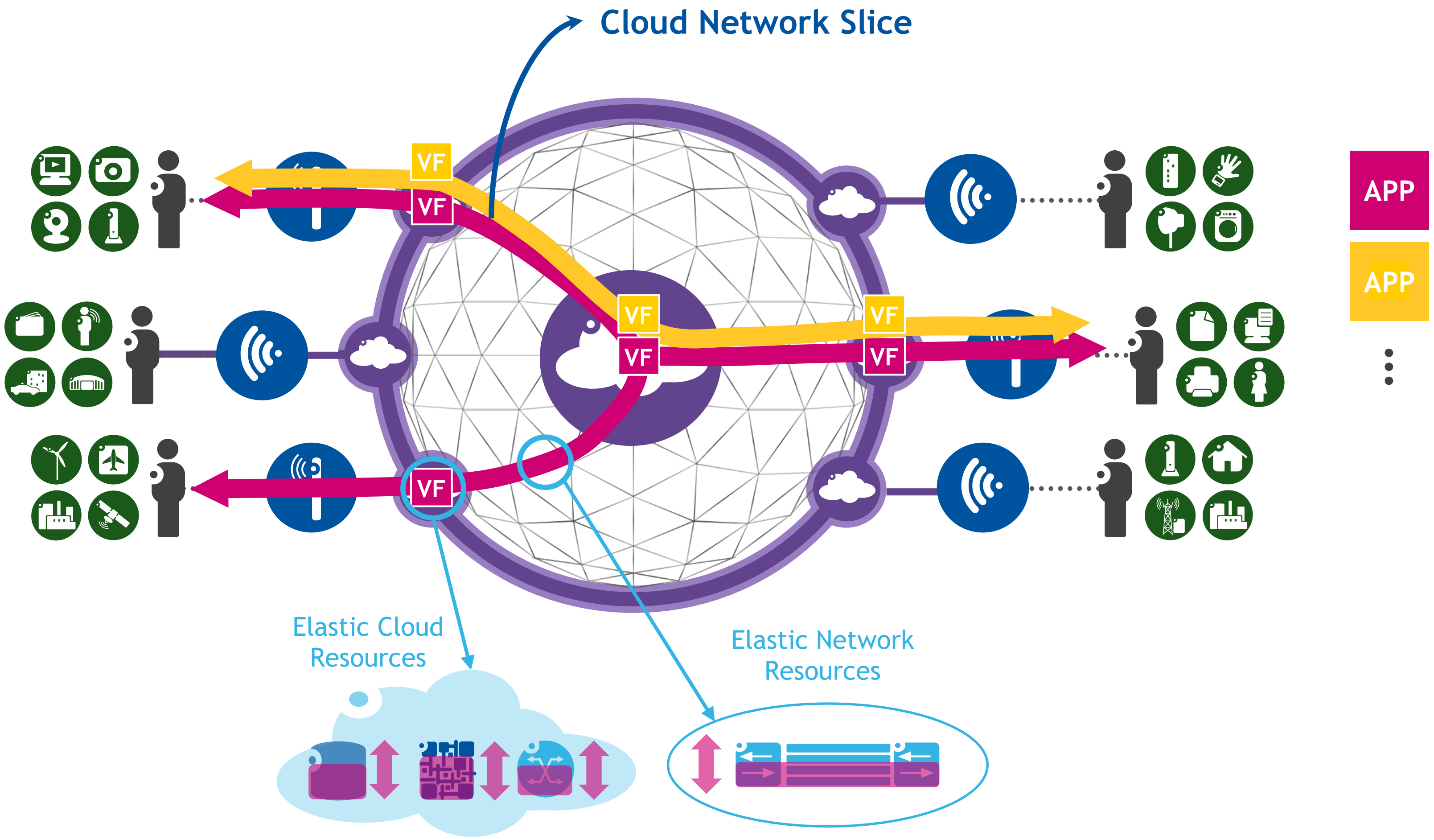
- Key enablers
  - Network function virtualization (NFV)
  - Software defined networking (SDN)



CLOUD-INTEGRATED NETWORKS AS UNIVERSAL COMPUTE PLATFORMS

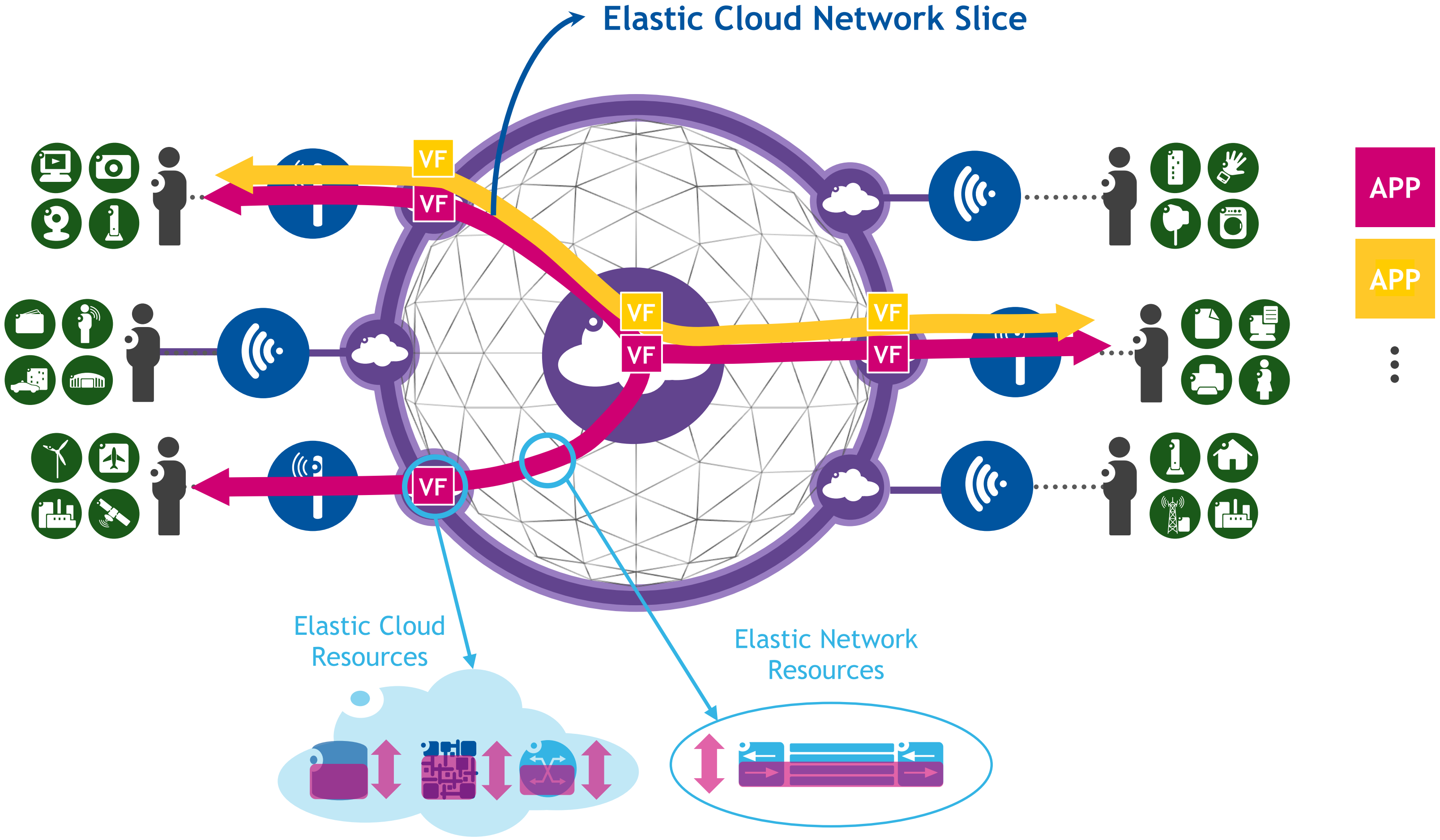
- Key enablers
  - Network function virtualization (NFV)
  - Software defined networking (SDN)

- Ideal for next generation services (both resource and latency sensitive)
  1) Network services
     - 5G slices
  2) Automation services
     - Smart X, IoT
  3) Augmented experience services
     - Virtual X, Augmented X



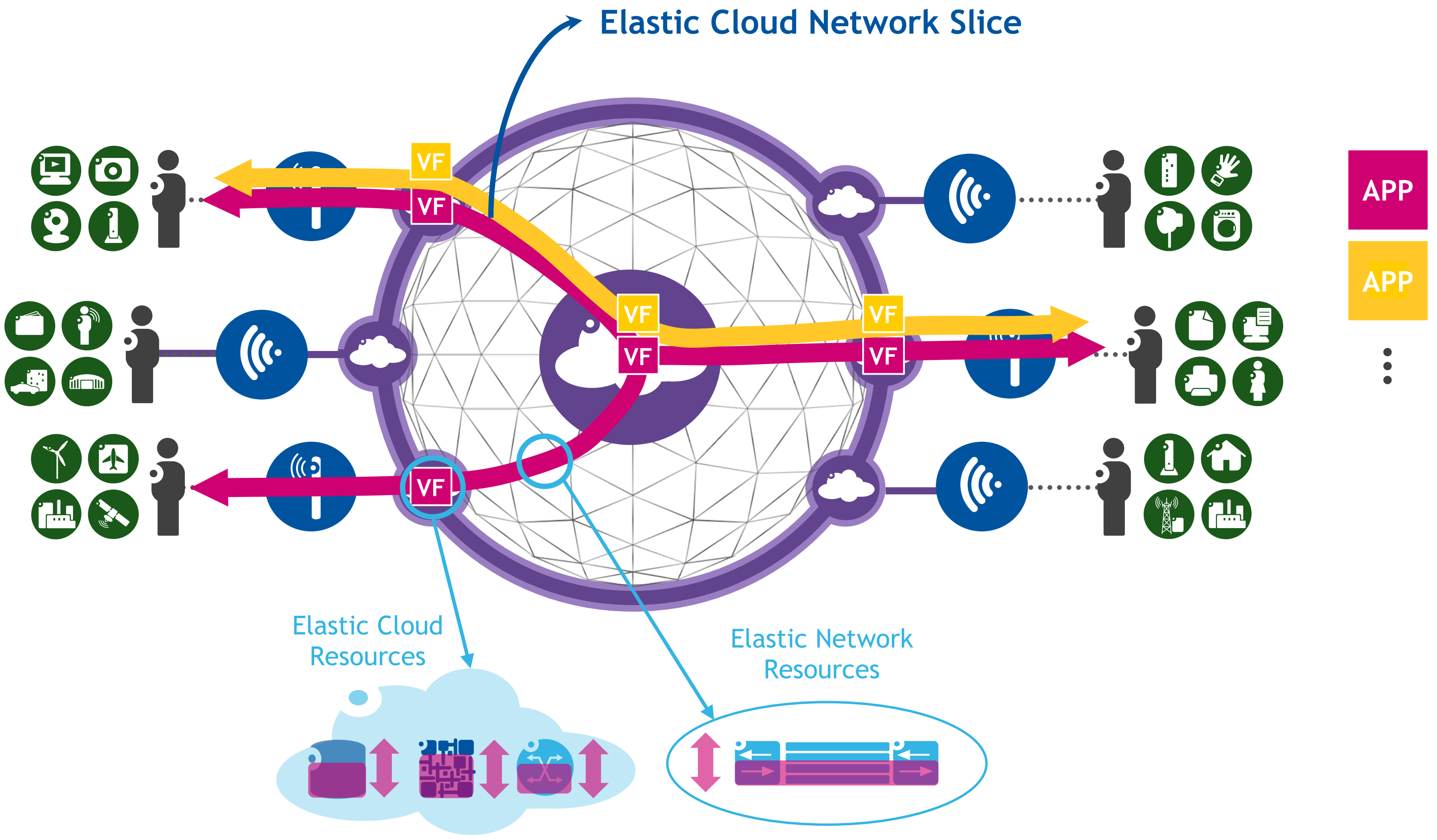
CLOUD-INTEGRATED NETWORKS AS UNIVERSAL COMPUTE PLATFORMS

- Opportunities
  - Users can consume resource- and interaction-intensive applications from resource-limited devices
  - Operators can reduce costs and create new value-added services
  - Overall sustainability



CLOUD-INTEGRATED NETWORKS AS UNIVERSAL COMPUTE PLATFORMS

- Opportunities
  - Users can consume resource- and interaction-intensive applications from resource-limited devices
  - Operators can reduce costs and create new value-added services
  - Overall sustainability
- Challenges
  - Optimized elastic consumption of compute/storage/network resources
  - **End-to-end autonomous configuration and control**

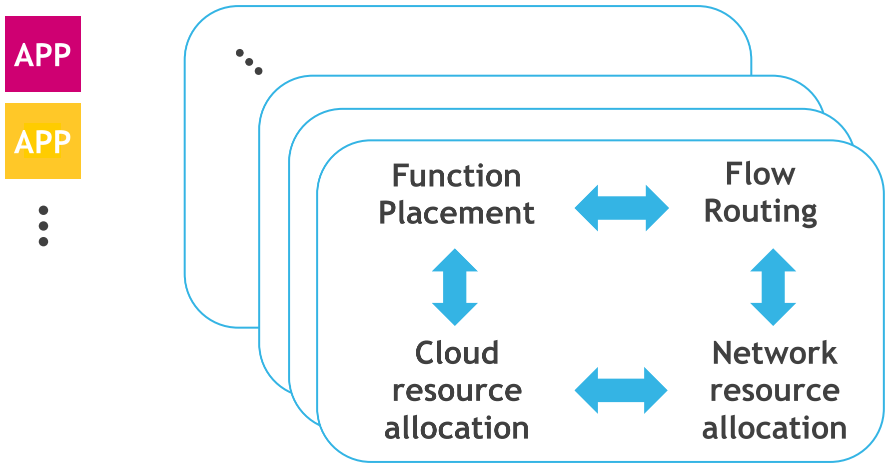


Elastic Cloud Network Slice

Elastic Cloud Resources

Elastic Network Resources

JOINT END-TO-END SERVICE OPTIMIZATION



APP

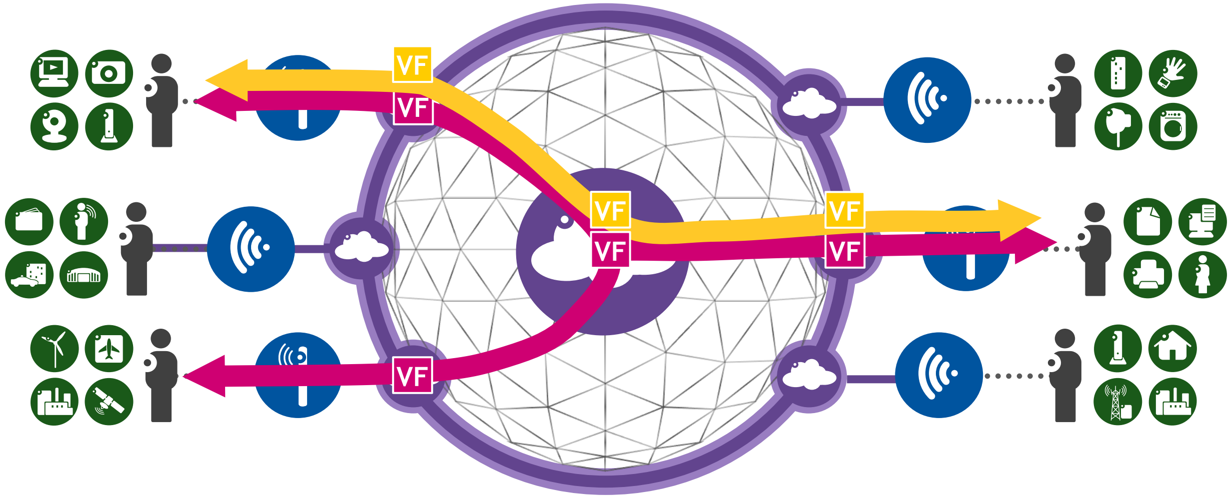
APP

Function Placement

Flow Routing

Cloud resource allocation

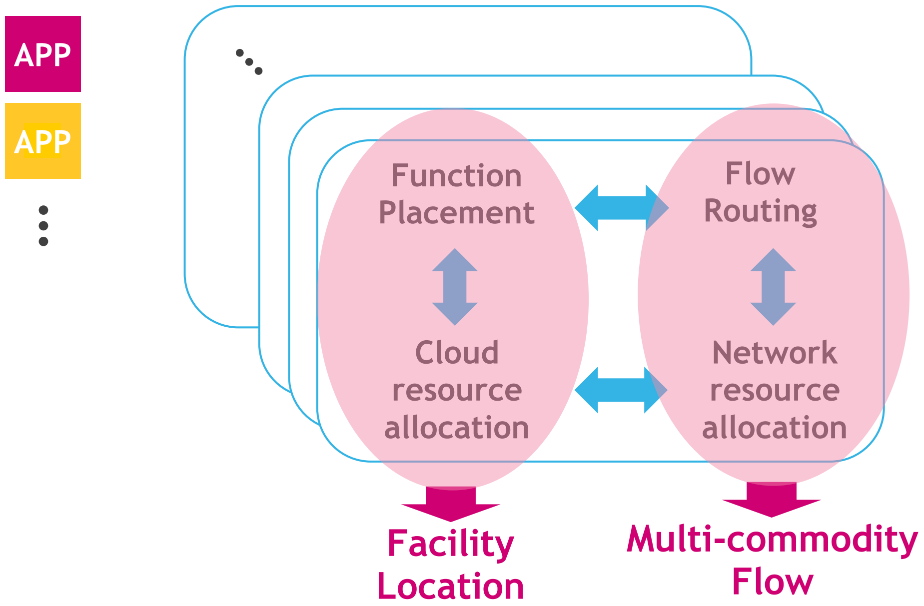
Network resource allocation

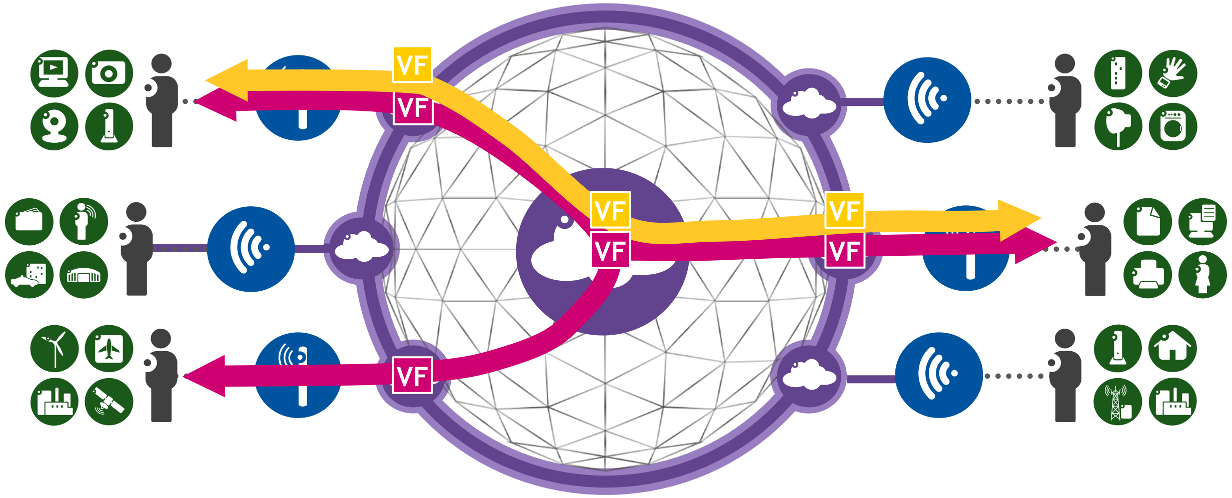


- Function placement
  - Function chaining, splitting, and replication
- Flow routing
  - Flow scaling
  - Mix of unicast and multicast traffic

EXISTING APPROACHES

COMPLEX DISJOINT SOLUTIONS

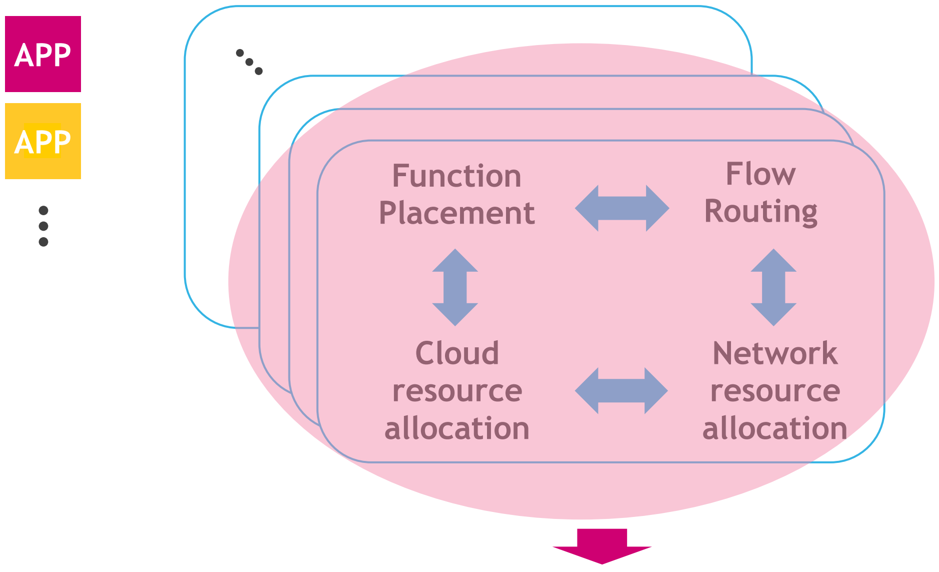




Separate data/function placement, flow routing, cloud and network resource allocation

- Driven by old vision of cloud and network separation
- No joint placement/routing optimization
- Unacceptable QoE, limited knowledge augmentation, and/or unsustainable costs with resource overprovisioning.

CLOUD NETWORK FLOW APPROACH



APP

APP

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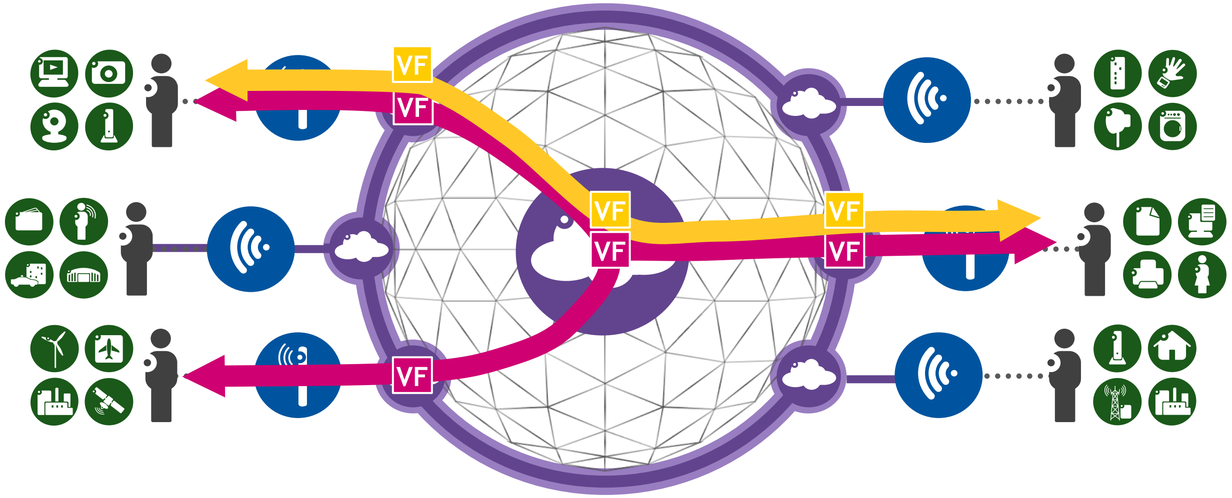
Function Placement

Flow Routing

Cloud resource allocation

Network resource allocation

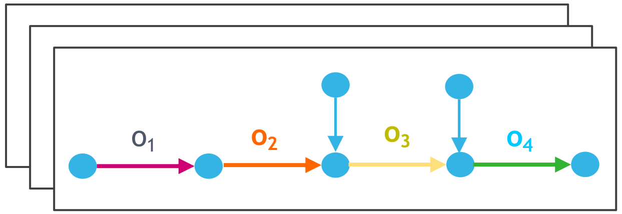
CLOUD NETWORK FLOW



- Comprehensive model
  - Arbitrary flow chaining, scaling, splitting, and replication
  - Arbitrary traffic mix (unicast and multicast flows)
  - Non-isomorphic embeddings
- Approximation guarantees

CLOUD NETWORK FLOW

Service Graph



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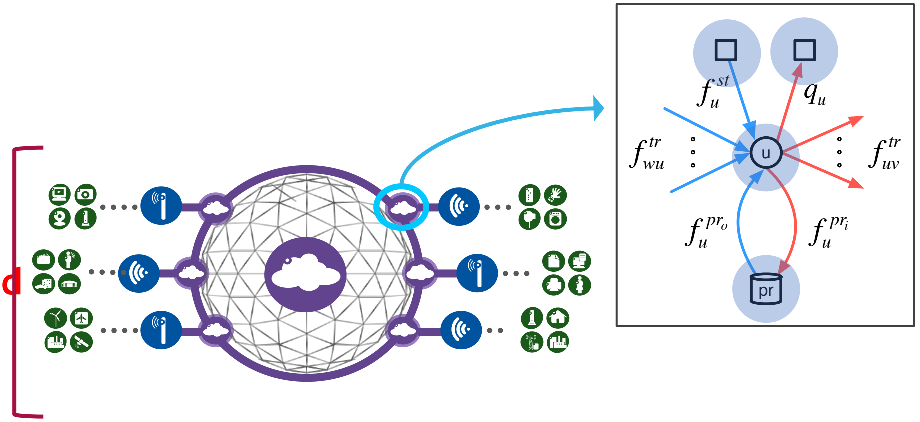
Cloud-Augmented Graph



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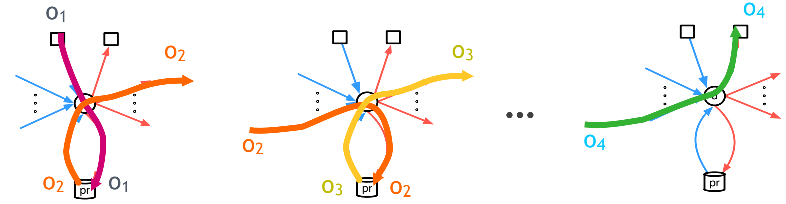
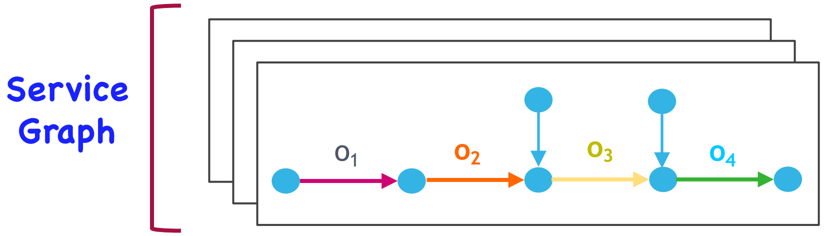
Cloud Network Flow



CLOUD NETWORK FLOW

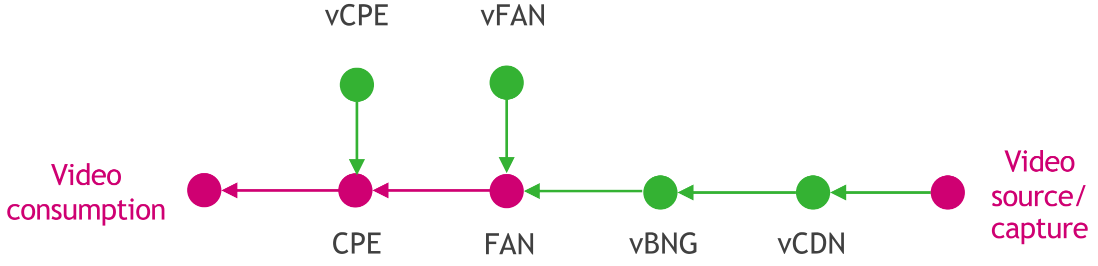
1. Service Graph



- Directed acyclic graph that encodes the relationship between service functions and associated input/output flows

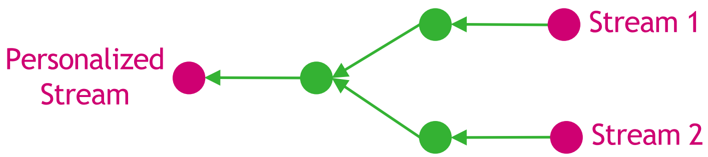
APP

Network Service
(e.g., Fixed Residential Video)



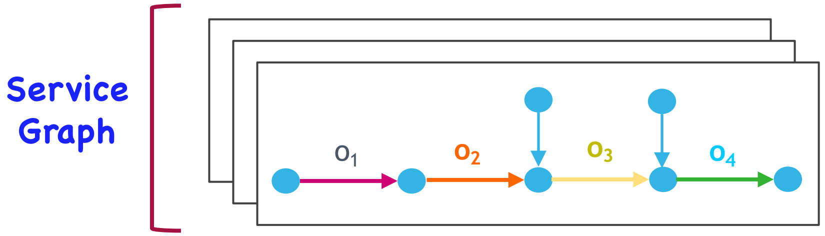
APP

Vertical Service
(e.g., Augmented Reality)



CLOUD NETWORK FLOW

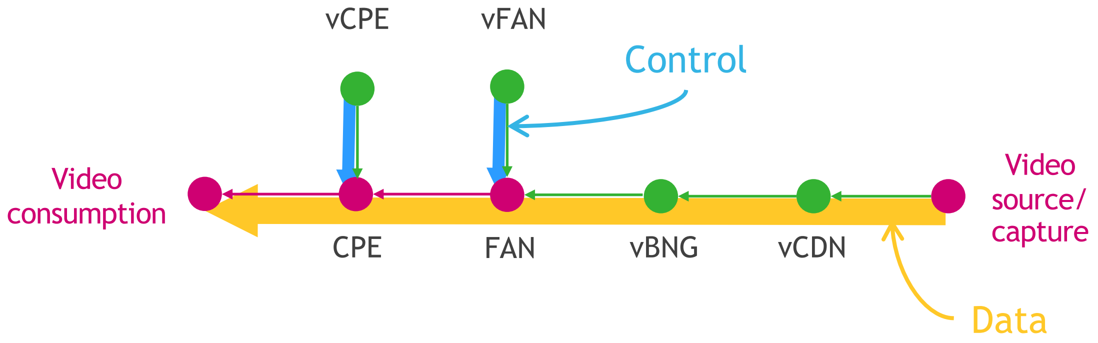
1. Service Graph



- Directed acyclic graph that encodes the relationship between service functions and associated input/output flows
- Control/data plane as well as hardware/software based functions
- Heterogeneous function complexity (proc. res. units per flow unit) and flow scaling (output flow units per input flow unit)

APP

Network Service
(e.g., Fixed Residential Video)



APP

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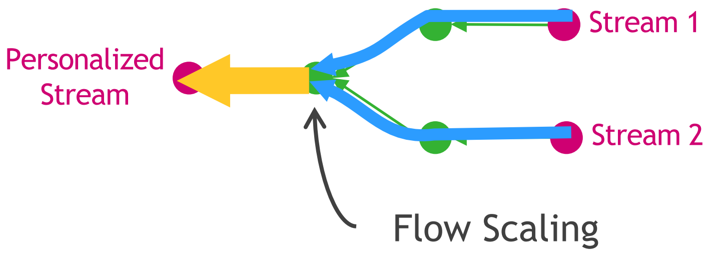
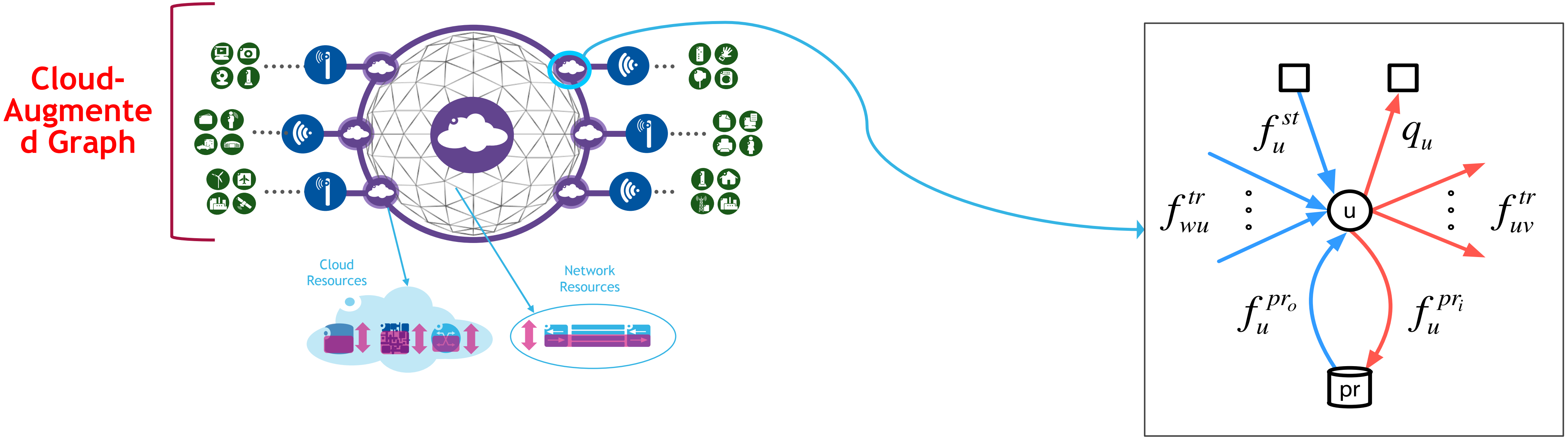


CLOUD NETWORK FLOW

2. Cloud-augmented graph



CLOUD NETWORK FLOW

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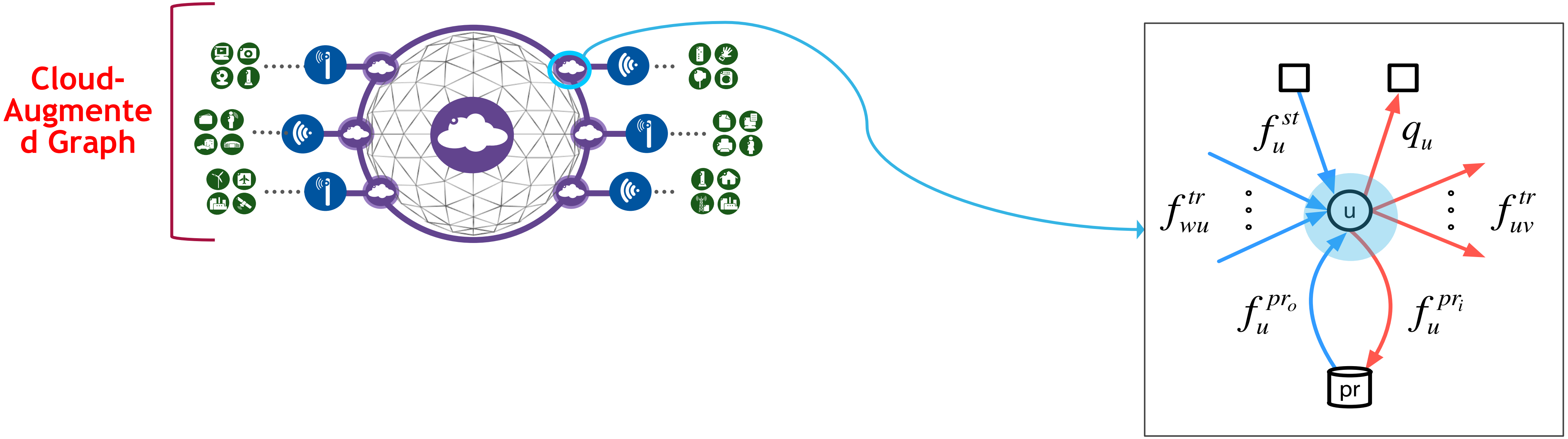

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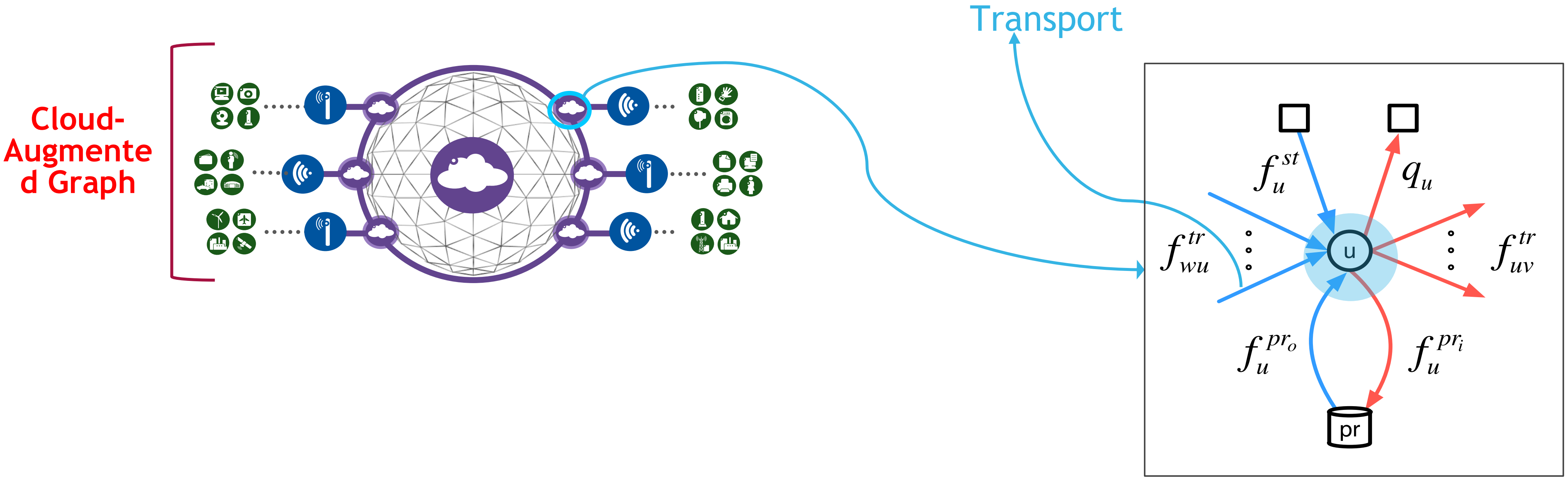

CLOUD NETWORK FLOW

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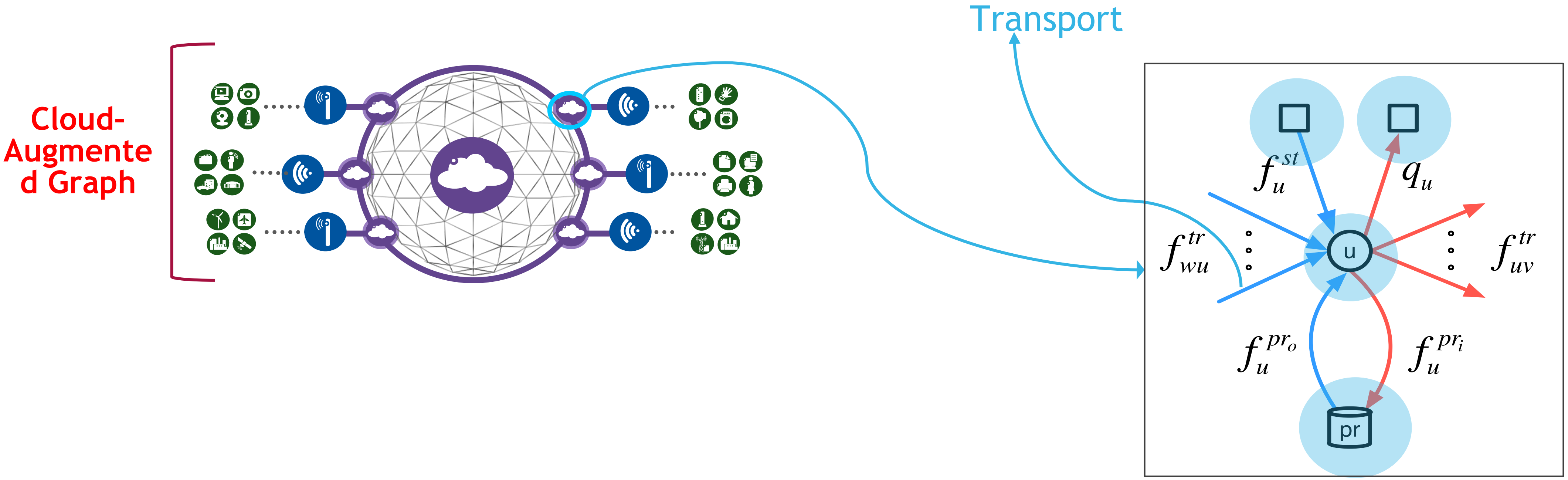

CLOUD NETWORK FLOW

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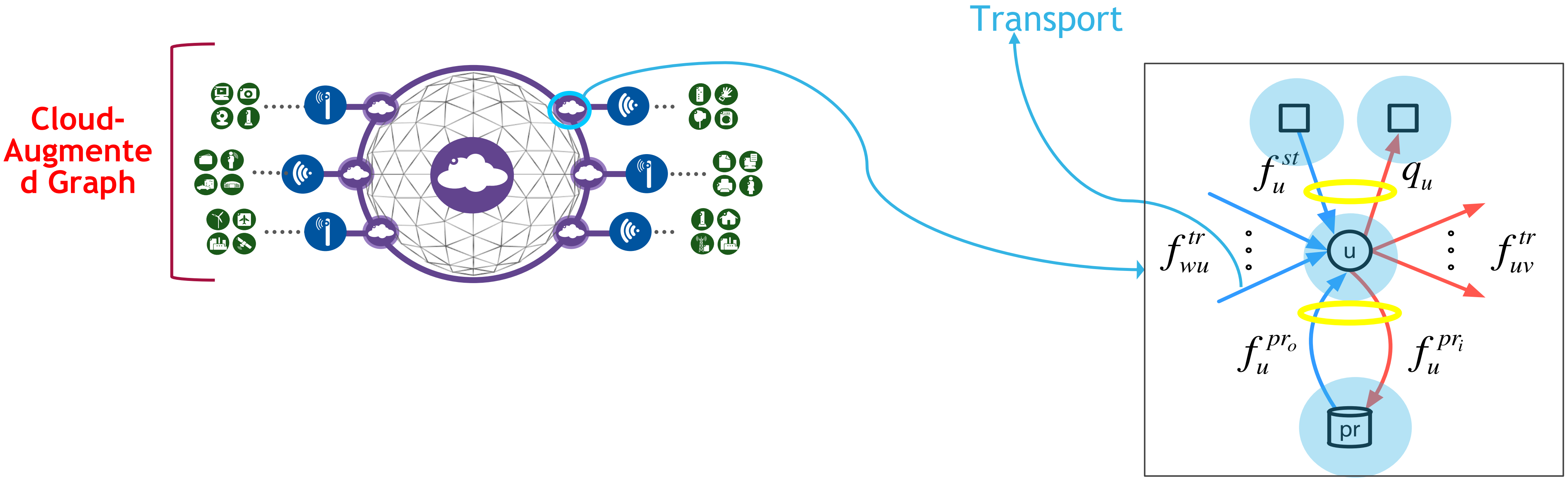

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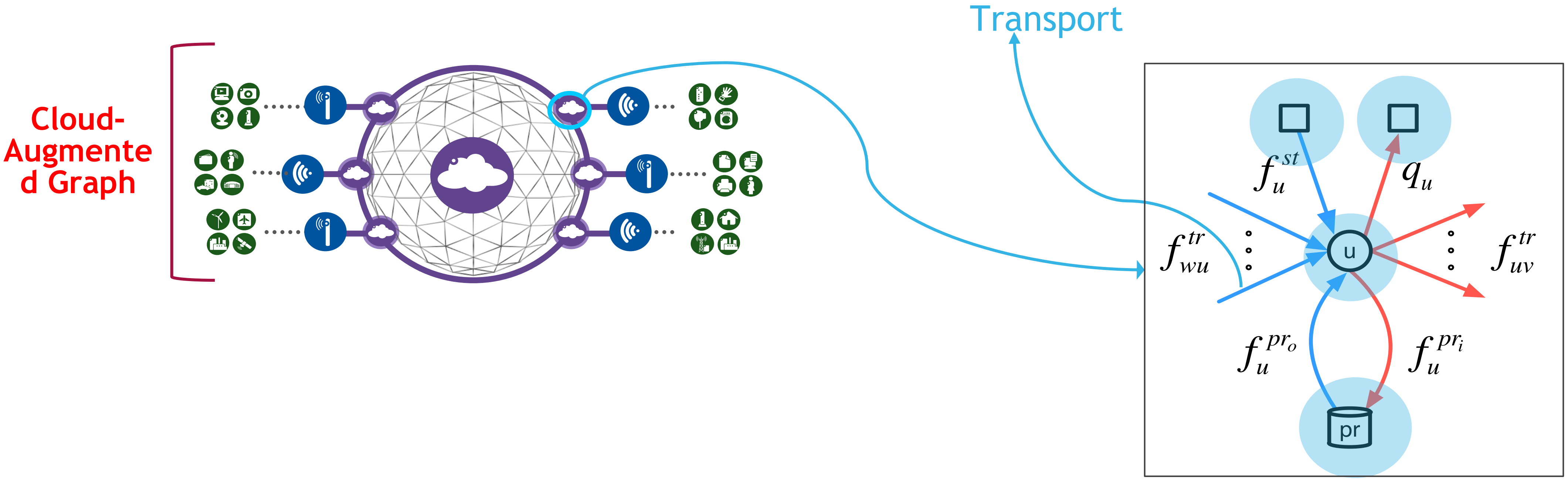

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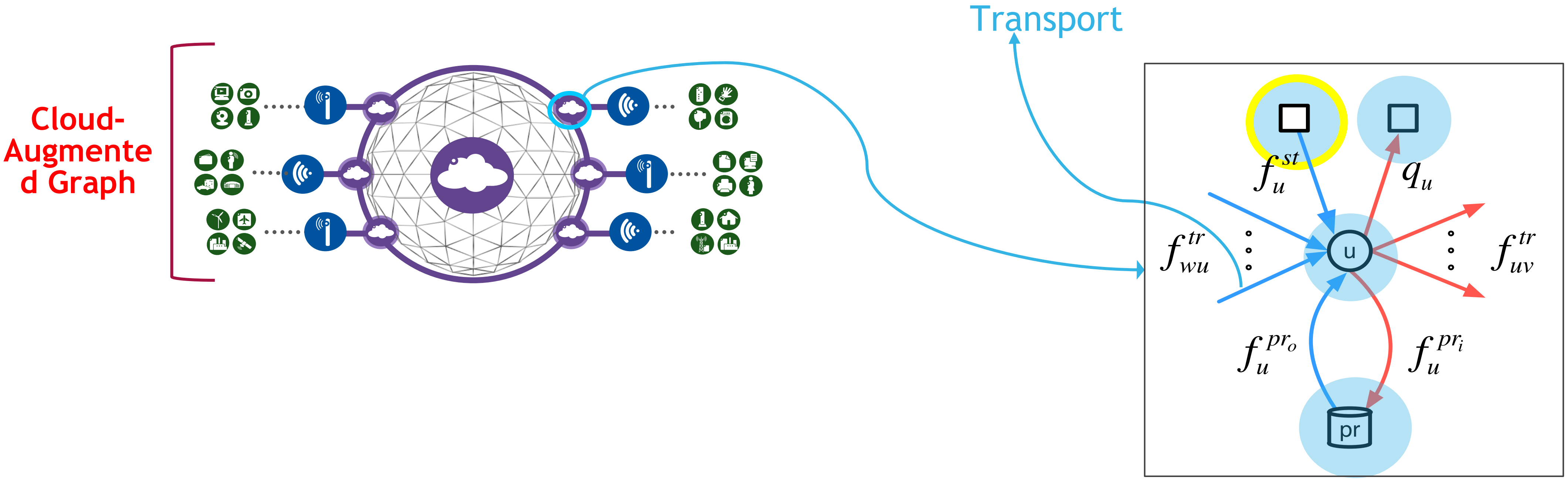

CLOUD NETWORK FLOW

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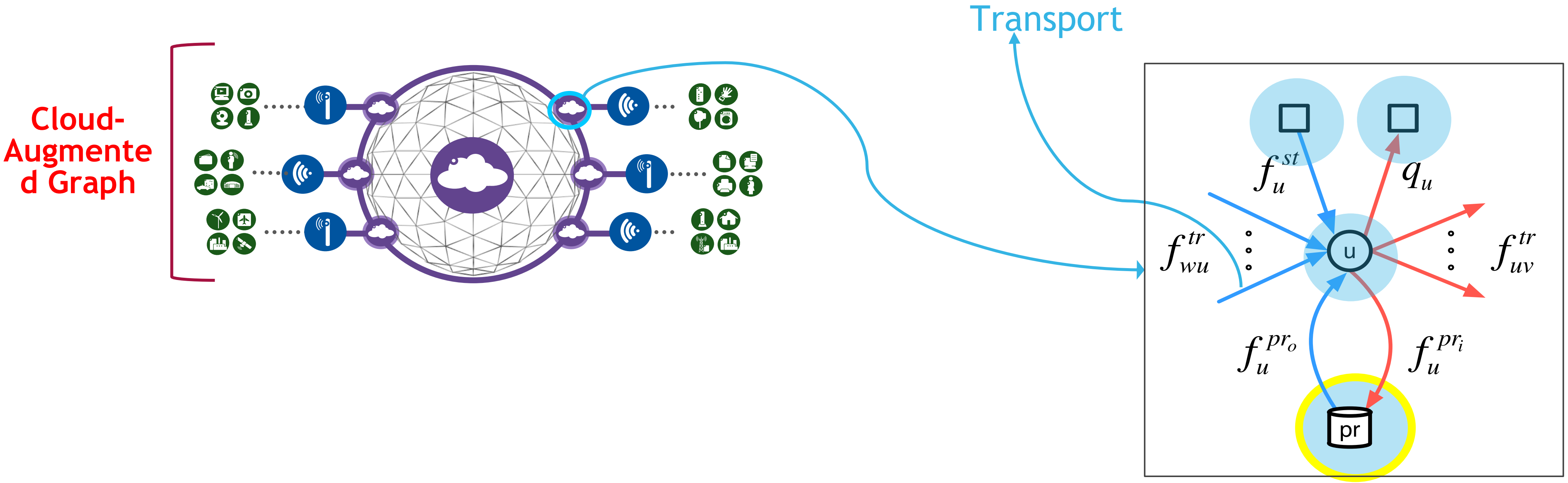
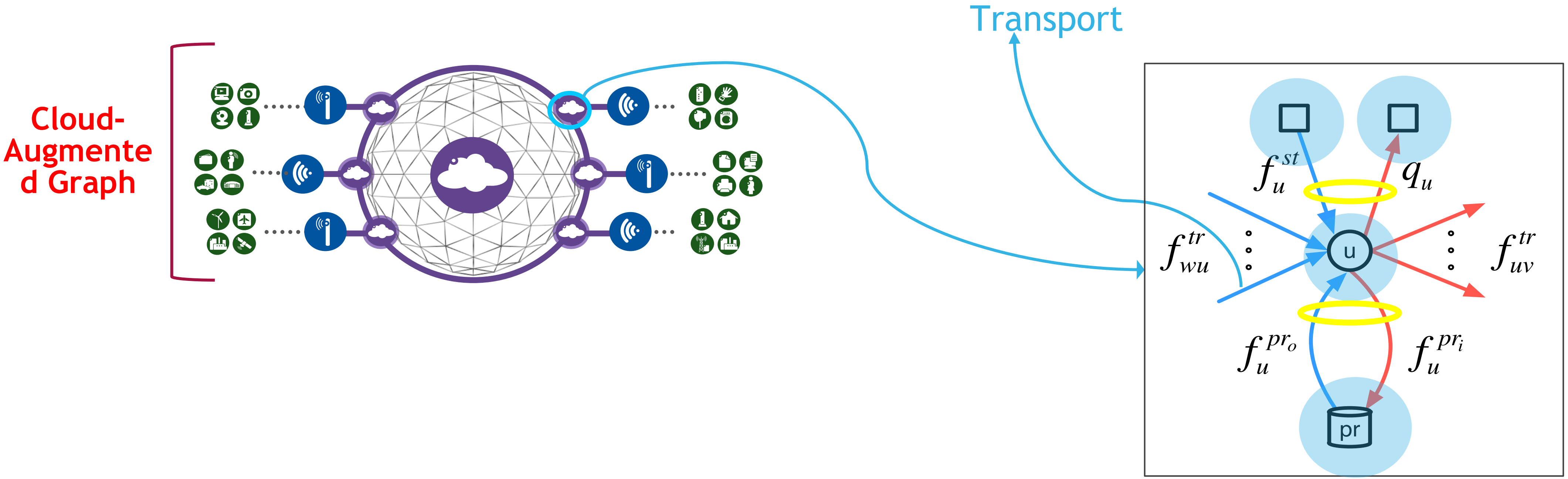


CLOUD NETWORK FLOW

2. Cloud-augmented graph

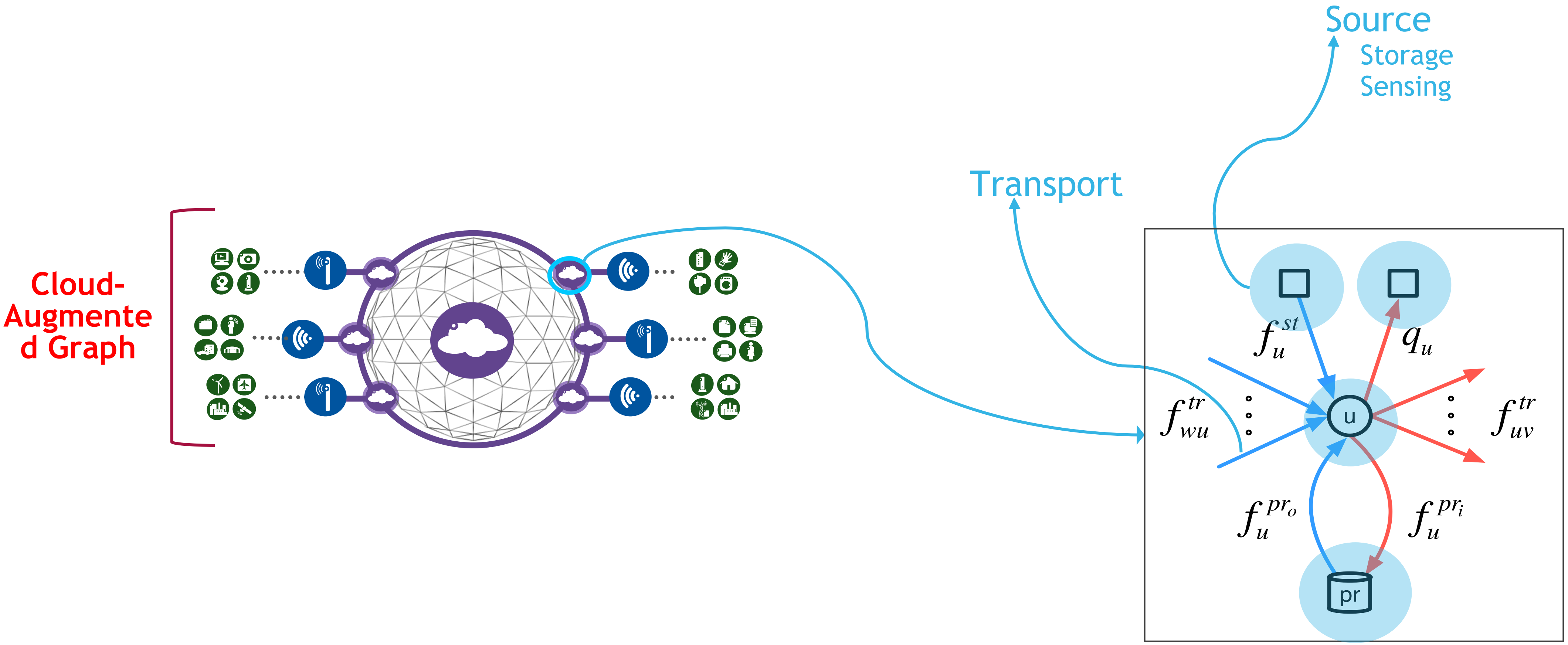


Cloud-Augmented Graph

Transport

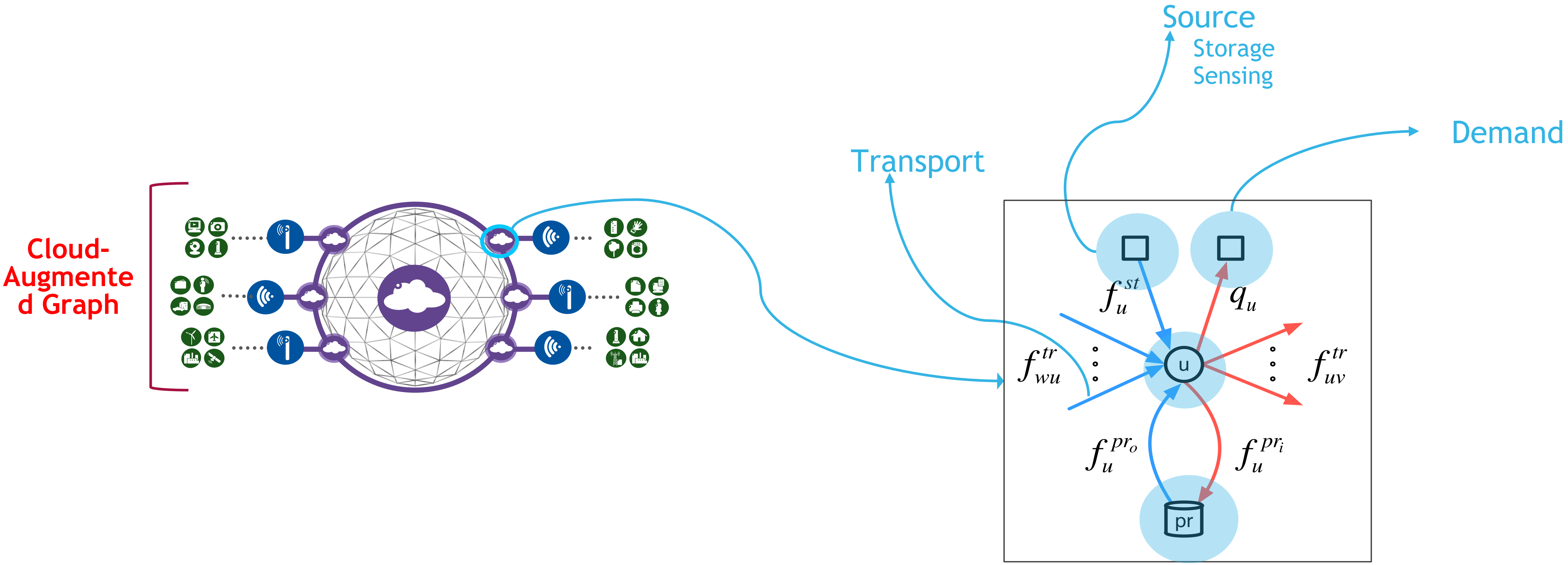
CLOUD NETWORK FLOW

2. Cloud-augmented graph



CLOUD NETWORK FLOW

2. Cloud-augmented graph



CLOUD NETWORK FLOW

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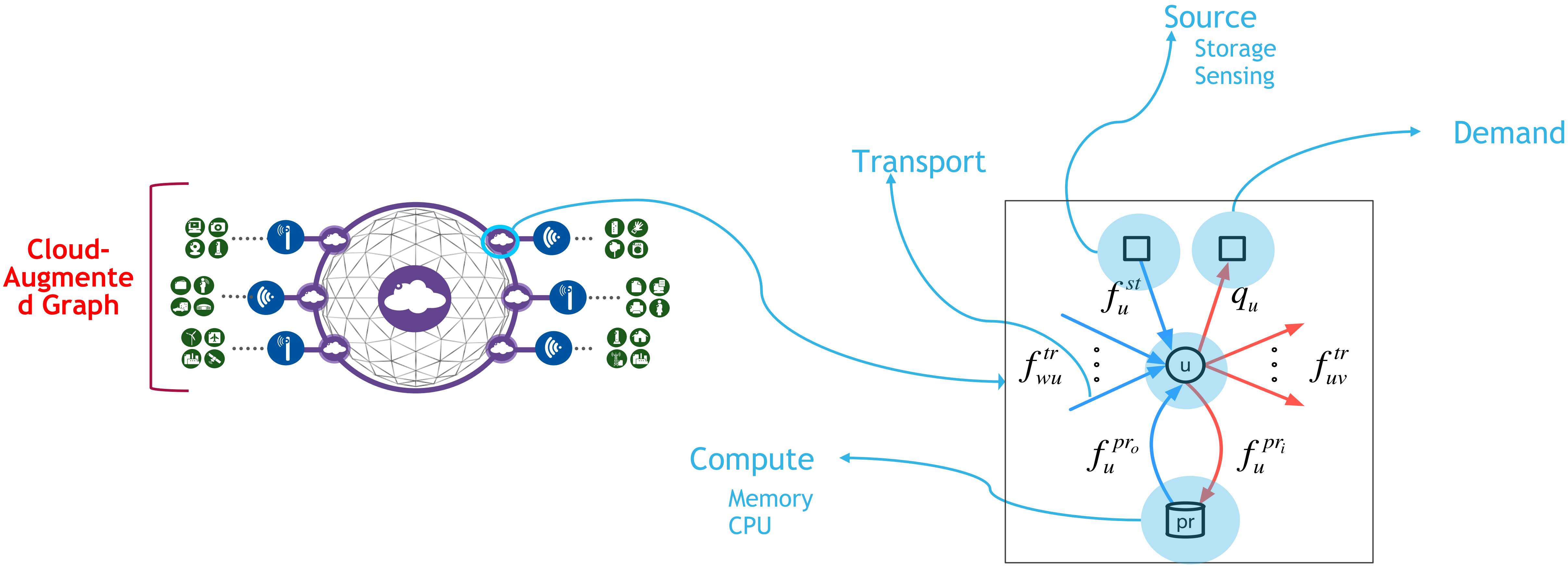


Cloud-Augmented Graph

Transport

Source

Storage

Sensing

Demand

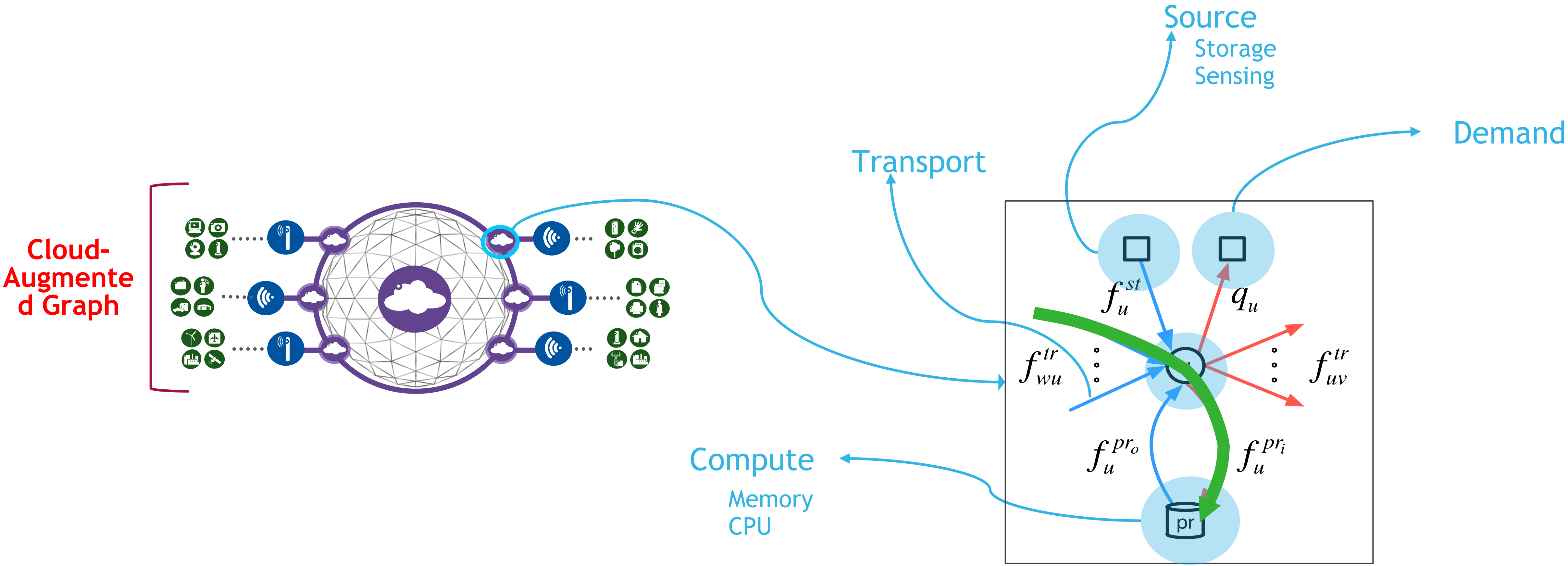
Compute

Memory

CPU

CLOUD NETWORK FLOW

2. Cloud-augmented graph



CLOUD NETWORK FLOW

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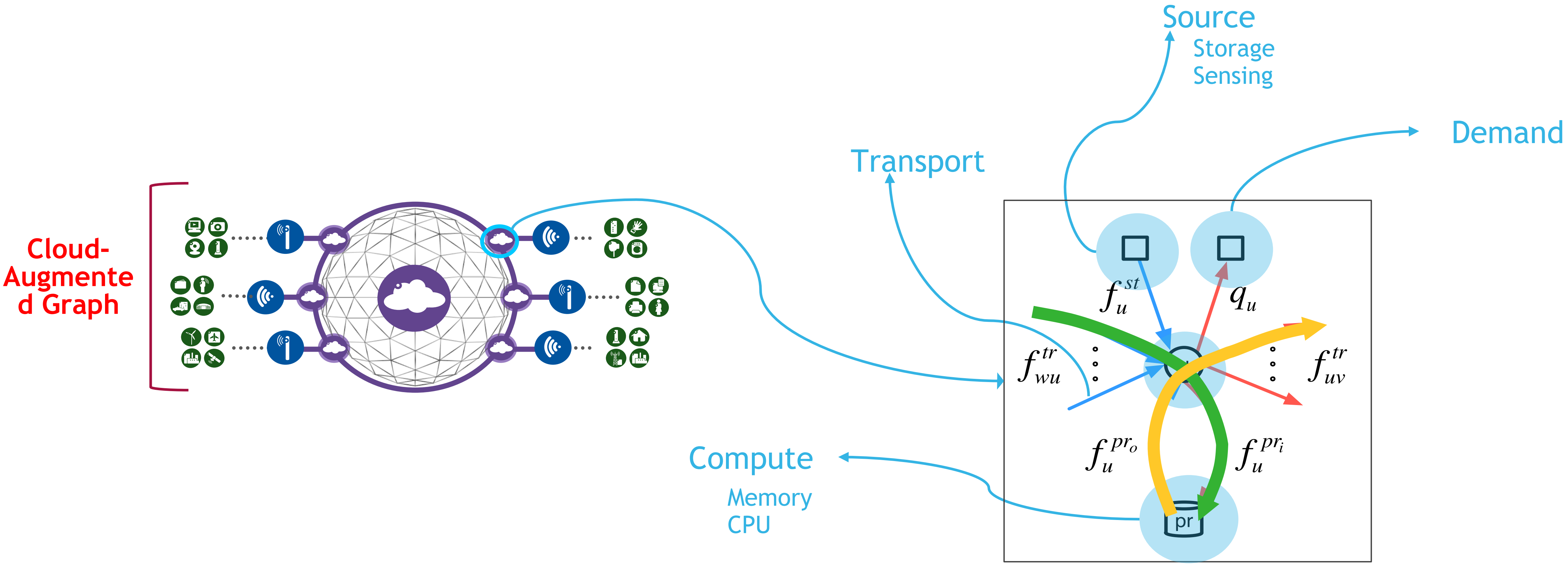
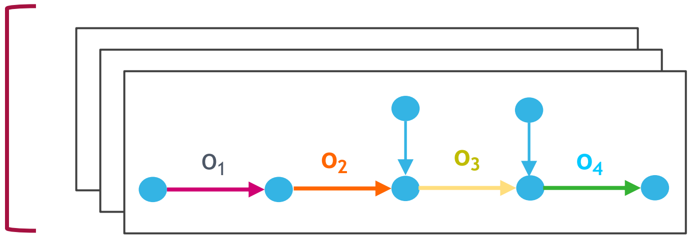
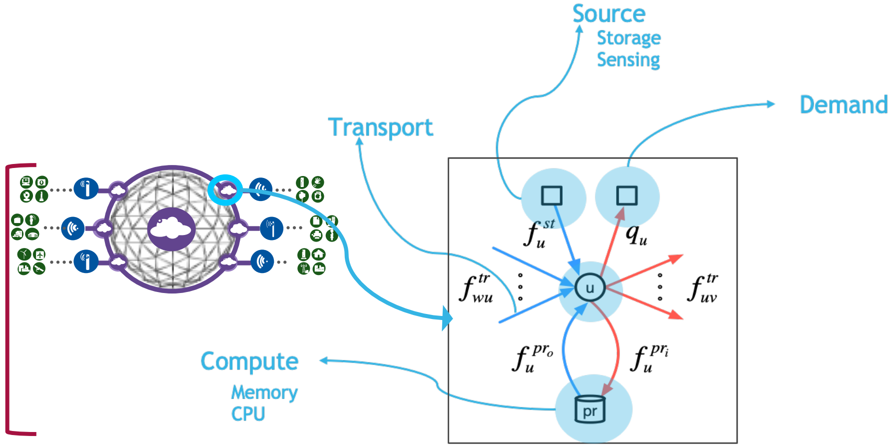


JOINT END-TO-END SERVICE OPTIMIZATION

Service Graph



Cloud-Augmented Graph



Cloud Network Flow problem: Mixed-cast multi-commodity-chain flow on a cloud-augmented graph

- Includes and generalizes placement and network flow problems
- Captures combined use of compute/storage/transport resources, unicast and multicast flows, and flow/function chaining, scaling, splitting, and replication
- Admits optimal polynomial time solutions under linear costs and splittable flows, and efficient approximations otherwise

SERVICE CLASSIFICATION AND APPROXIMATION ALGORITHMS

	Unicast		Multicast	
	Splittable	Unsplittable	Splittable	Unsplittable
Service Chain	Polynomial FPTAS	NP-Hard Bicriteria approx.	NP-Hard (no coding)	NP-Hard Bicriteria approx.
Service DAG	NP-Hard (no coding	NP-Hard Bicriteria approx.	NP-Hard (no coding)	NP-Hard Bicriteria approx.

5G Slices

Cloud network flow admits optimal polynomial time solutions under linear costs and splittable flows, and efficient approximations otherwise

SERVICE CLASSIFICATION AND APPROXIMATION ALGORITHMS

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5G Slices

- Barcelo, Llorca, Tulino, Raman, “The Cloud Service Distribution Problem in Distributed Cloud Networks,” IEEE ICC, 2015.
- Feng, Llorca, Tulino, Raz, Molisch “Approximation Algorithms for the NFV Service Distribution Problem,” IEEE INFOCOM, 2017.
- Zhang, Sinha, Llorca, Tulino, Modiano, “Optimal Control of Distributed Computing Networks with Mixed-Cast Traffic Flows,” IEEE INFOCOM, 2018.
- Feng, Llorca, Tulino, Molisch, “Optimal Dynamic Cloud Network Control,” IEEE/ACM Transactions on Networking, 2018.
- Feng, Llorca, Tulino, Molisch, “Optimal Control of Wireless Computing Networks,” IEEE Transactions on Wireless Communications, 2018.

SERVICE CLASSIFICATION AND APPROXIMATION ALGORITHMS

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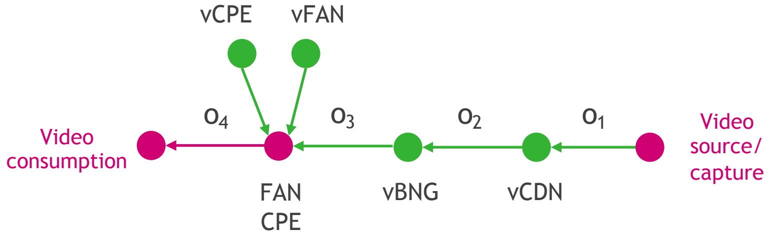
5G Slices

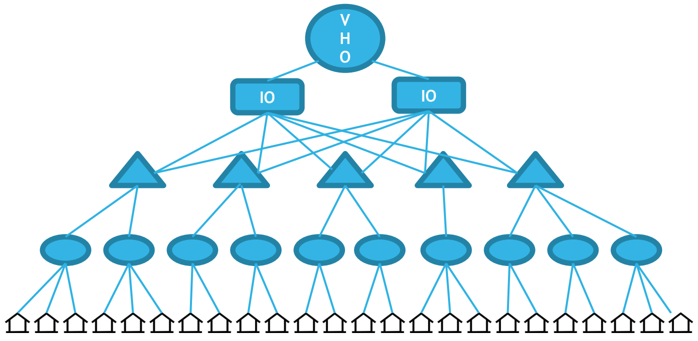
RTA

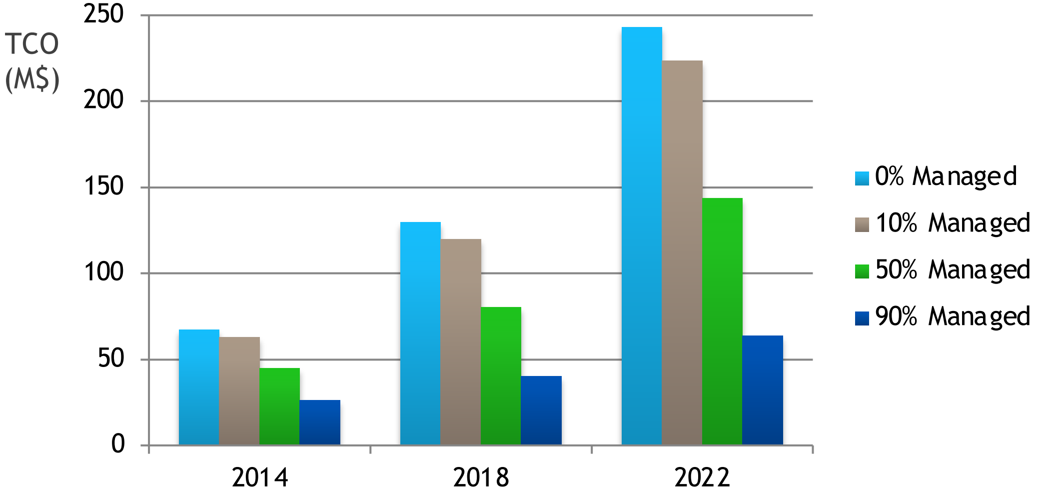
- Barcelo, Llorca, Tulino, Morell, Vicario, "IoT-Cloud Service Optimization in Smart Environments," IEEE JSAC 2016
- Michael, Llorca, Tulino, "Approximation Algorithms for the Optimal Distribution of Real-time Stream-Processing Services," IEEE ICC, 2019.
- Poularakis, Llorca, Tulino, Tassiulas, "Service Placement and Request Routing in MEC Networks With Storage, Computation, and Communication Constraints," IEEE Trans. on Networking, 2020.
- Poularakis, Llorca, Tulino, Tassiulas, "Approximation Algorithms for Data-Intensive Service Chain Embedding," ACM MOBIHOC, 2020.

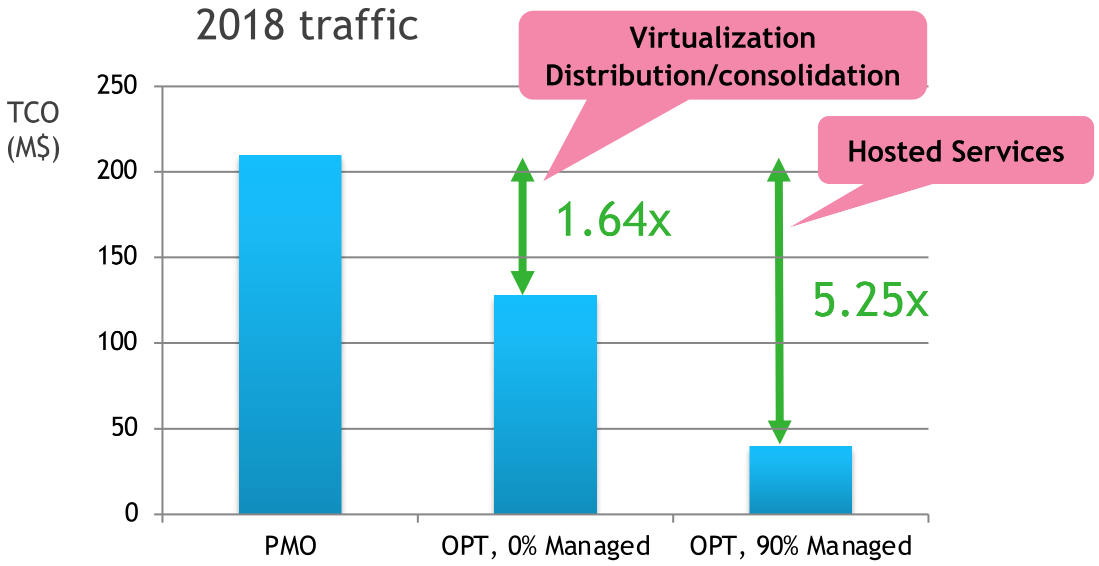
NETWORK SERVICE CHAINS

- Network: Generic US Metro
  - 4 Metro PoP, 12 Metro Agg, 60 Metro Edge
  - 10G links, CloudBand compute nodes
- Service: Fixed Residential Video
  - Data plane: vCDN, vBNG, FAN, CPE
  - Control Plane: vCDN, vBNG, vFAN, vCPE
- Demand:
  - 2014, 2018, 2022 video traffic
  - 50% VoD, 40% VS, 10% IPTV









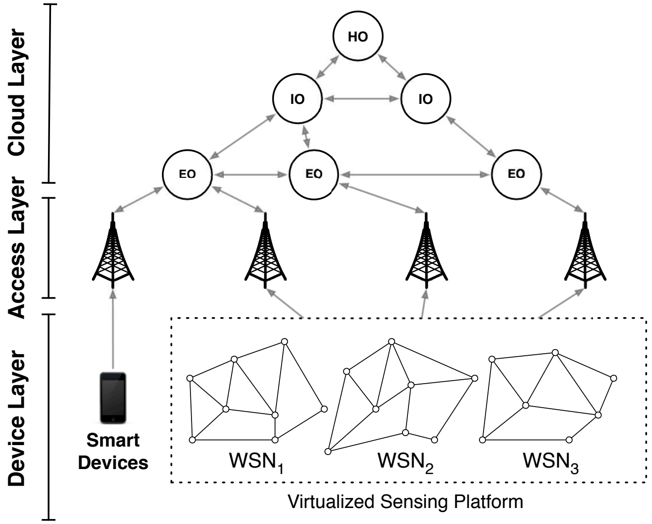
Virtualization Distribution/consolidation

Hosted Services

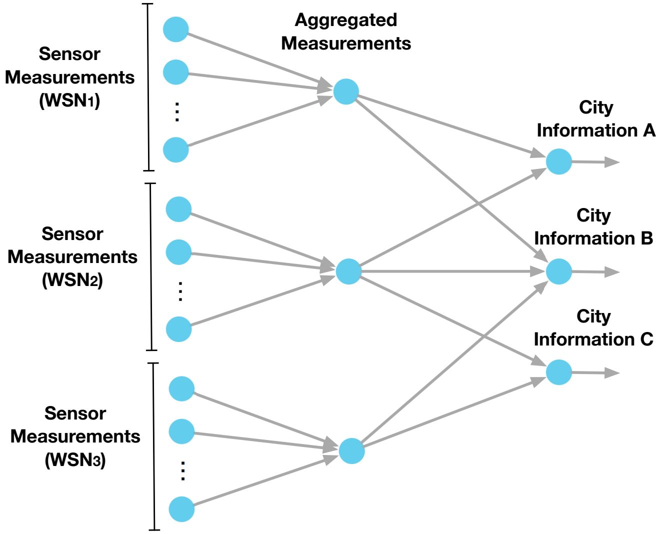
- Barcelo, Llorca, Tulino, Raman, “The Cloud Service Distribution Problem in Distributed Cloud Networks,” IEEE ICC 2015.

SMART CITY SERVICES

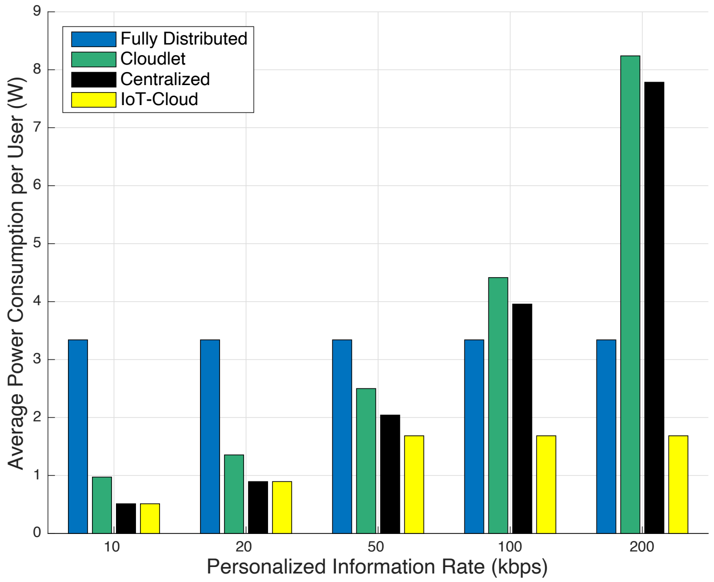
- IoT-Cloud Network:
  - Cloud layer (core, metro, edge)
  - Access layer
  - Device layer



- City Streams Service:
  - Deliver contextually relevant personalized city streams



- Operational cost as a function of personalized stream data rate



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RECONFIGURATION-AWARE DYNAMIC CLOUD NETWORK CONTROL

- Centralized online-competitive algorithm to smooth resource allocation in distributed cloud networks with reconfiguration cost
- Distributed throughput-optimal flow scheduling and resource allocation algorithms under reconfiguration delay and cost

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IN SUMMARY

- Next generation services will be deployed in the form virtual **cloud network slices** that can be elastically configured to meet user demands while minimizing the use of the shared physical infrastructure

- The proposed **cloud network flow model** allows jointly optimizing the allocation of cloud and network resources to services with arbitrary function relationships and mix of unicast/multicast flows

- Significant efficiency improvements can be obtained via the **end-to-end optimization** of next generation services over cloud-integrated networks

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Developing And Applying Signal Processing and Machine Learning Methodologies For Metagenomics and Human Microbiome Applications

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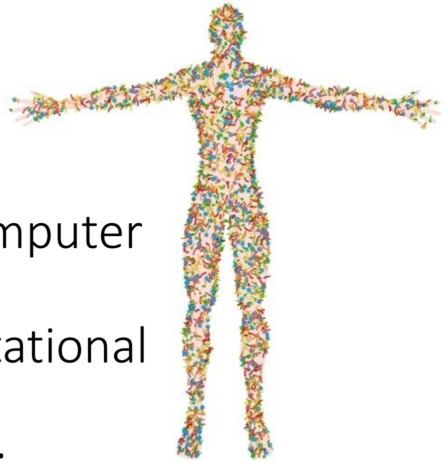
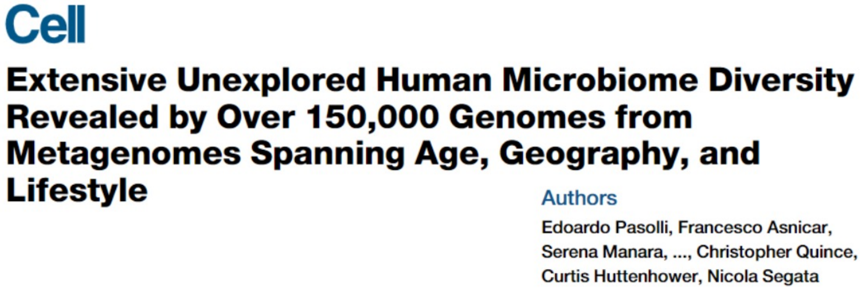


- **Human microbiome** is a hot topic in **biomedical research**
- It is **highly multidisciplinary** and involves clinicians, microbiologists, bioinformaticians, computer scientists, engineers, etc.
- High demand of **methodological developments** including bioinformatic software, computational tools, machine learning strategies, etc.
- We are active in developing and applying methods in this field. Some recent publications:



Cell

Extensive Unexplored Human Microbiome Diversity Revealed by Over 150,000 Genomes from Metagenomes Spanning Age, Geography, and Lifestyle

Authors

Edoardo Pasolli, Francesco Asnicar, Serena Manara, ..., Christopher Quince, Curtis Huttenhower, Nicola Segata

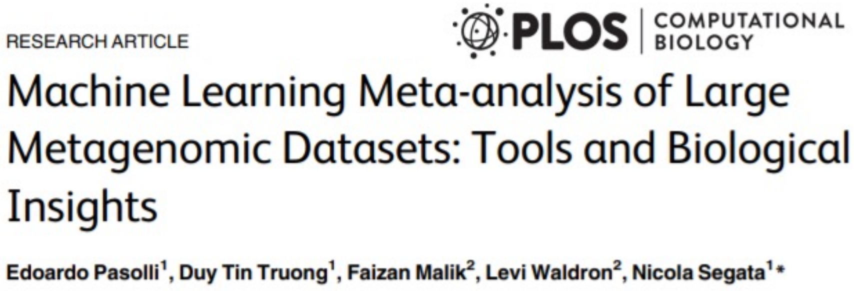
ARTICLE

https://doi.org/10.1038/s41467-020-16438-8 OPEN

nature COMMUNICATIONS

Large-scale genome-wide analysis links lactic acid bacteria from food with the gut microbiome

Edoardo Pasolli^{1,2}, Francesca De Filippis^{1,2}, Italia E. Mauriello^{1}, Fabio Cumbo^{3}, Aaron M. Walsh^{4,5}, John Leech^{4,5}, Paul D. Cotter^{4,5}, Nicola Segata^{3} & Danilo Ercolini^{1,2}✉

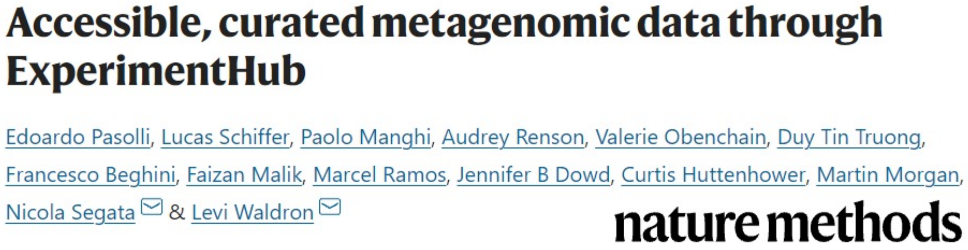


RESEARCH ARTICLE

PLOS | COMPUTATIONAL BIOLOGY

Machine Learning Meta-analysis of Large Metagenomic Datasets: Tools and Biological Insights

Edoardo Pasolli[1], Duy Tin Truong[1], Faizan Malik[2], Levi Waldron[2], Nicola Segata[1]*



Accessible, curated metagenomic data through ExperimentHub

Edoardo Pasolli, Lucas Schiffer, Paolo Manghi, Audrey Renson, Valerie Obenchain, Duy Tin Truong, Francesco Beghini, Faizan Malik, Marcel Ramos, Jennifer B Dowd, Curtis Huttenhower, Martin Morgan, Nicola Segata ✉ & Levi Waldron ✉

nature methods

Reflected-power communications: from half-wave to sub-wavelength sizes

Giacinto Gelli and Francesco Verde

October 20, 2021

The age of Green Internet-of-Things (G-IoT)

- “Things” are equipped with sensing, computing, and communication capabilities to enable them interacting with each other and with the surrounding environment.
- Communication modules are expected to take a significant portion of the overall energy consumption for IoT devices.
- Enabling extremely efficient wireless communications is the main focus of G-IoT.
- **Reflected-power communications**, which do not require active analog components to generate a carrier wave, but leverage dedicated or **ambient sources** (e.g., digital TV broadcasting, cellular systems, local area networks), have emerged as a promising solution to G-IoT, due to their inherent energy-harvesting capability, low power consumption, and low implementation cost.

Reflected-power at sub-wavelength sizes

- Conventional reflected-power communications rely on arrays constituted by $\lambda/2$ size electromagnetic (EM) antennas, where λ denotes the operating wavelength.
- A viable alternative is offered by the recent advent of **EM metamaterials**, which possess unique EM properties that are hard or even impossible to be achieved using natural materials.
- Arrays of uniform or nonuniform elements, whose dimension is smaller than λ by more than one order of magnitude (subwavelength size) exhibit unique properties, such as anomalous reflection/refraction for beamforming/beamsteering and transmissive/reflective focusing for high directivity.
- **Reconfigurable and programmable metasurfaces** can be implemented to obtain dynamically switching EM functions, thus yielding more freedom and flexibility with respect to conventional phased antenna arrays.

Our research activity on G-IoT

- Many existing works exploit only the spatial dimension of EM metamaterials, by overlooking their temporal properties.
- Our study shows that **joint exploitation of space and time dimensions** of EM metamaterials offers additional degrees of freedom that can be exploited for different purposes:
  - Improved information rates
  - Channel estimation
  - Physical-layer security
  - Sensing and data fusion
  - Wireless E-health

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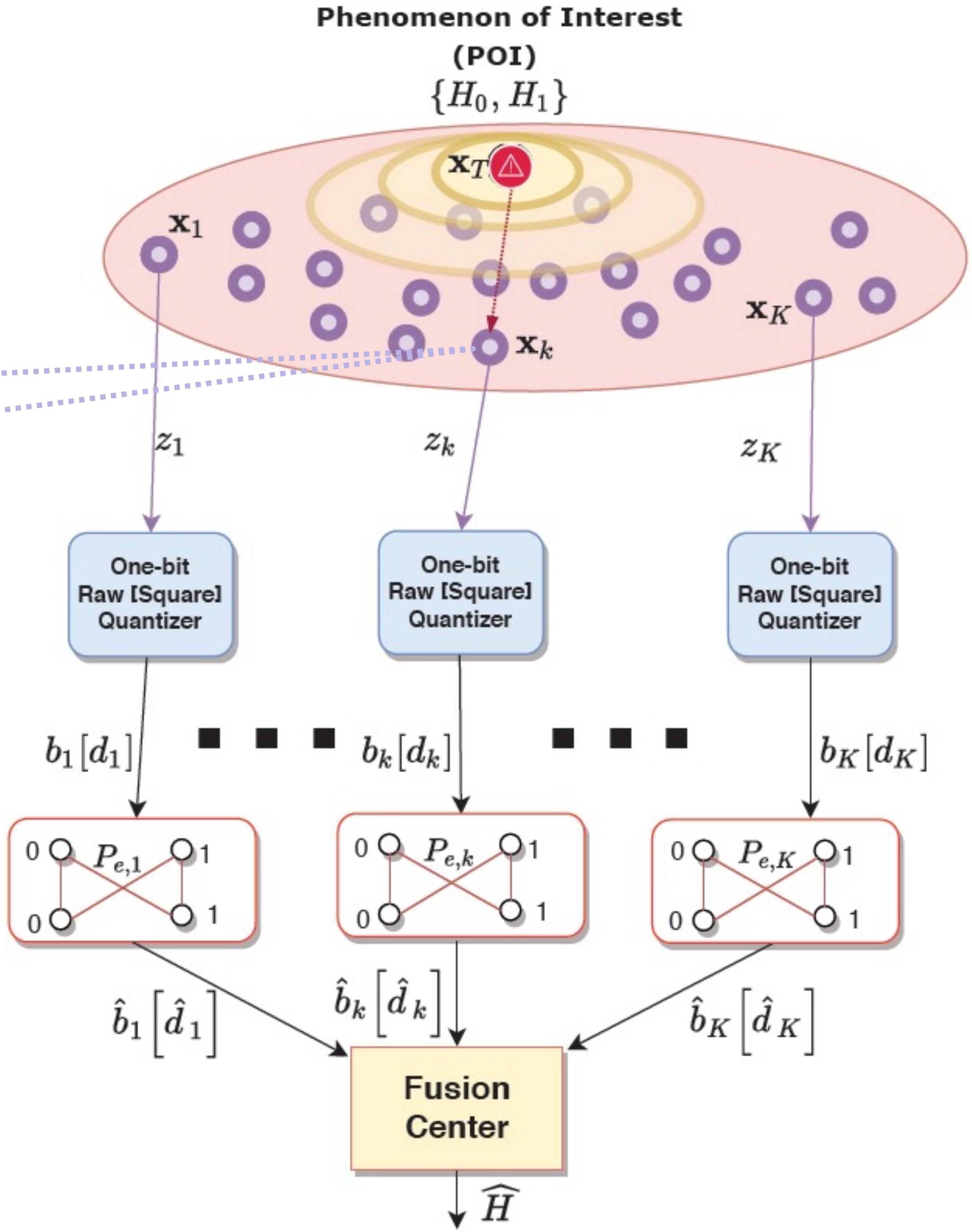
Decentralized Inference with sensing uncertainty

- How to detect localized Phenomenon of Interests via WSNs?

$$\begin{cases}\mathcal{H}_0 : & z_k = w_k \\ \mathcal{H}_1 : & z_k = \boxed{g(\boldsymbol{x}_k, \boldsymbol{x}_T)} h_k \boxed{\theta} + w_k\end{cases}$$

- Sensing model is incompletely specified
- Rician sensing model

$$h_k \sim \mathcal{N}(\mu_{h,k}, \sigma^2_{h,k})$$



Decentralized Inference with sensing uncertainty

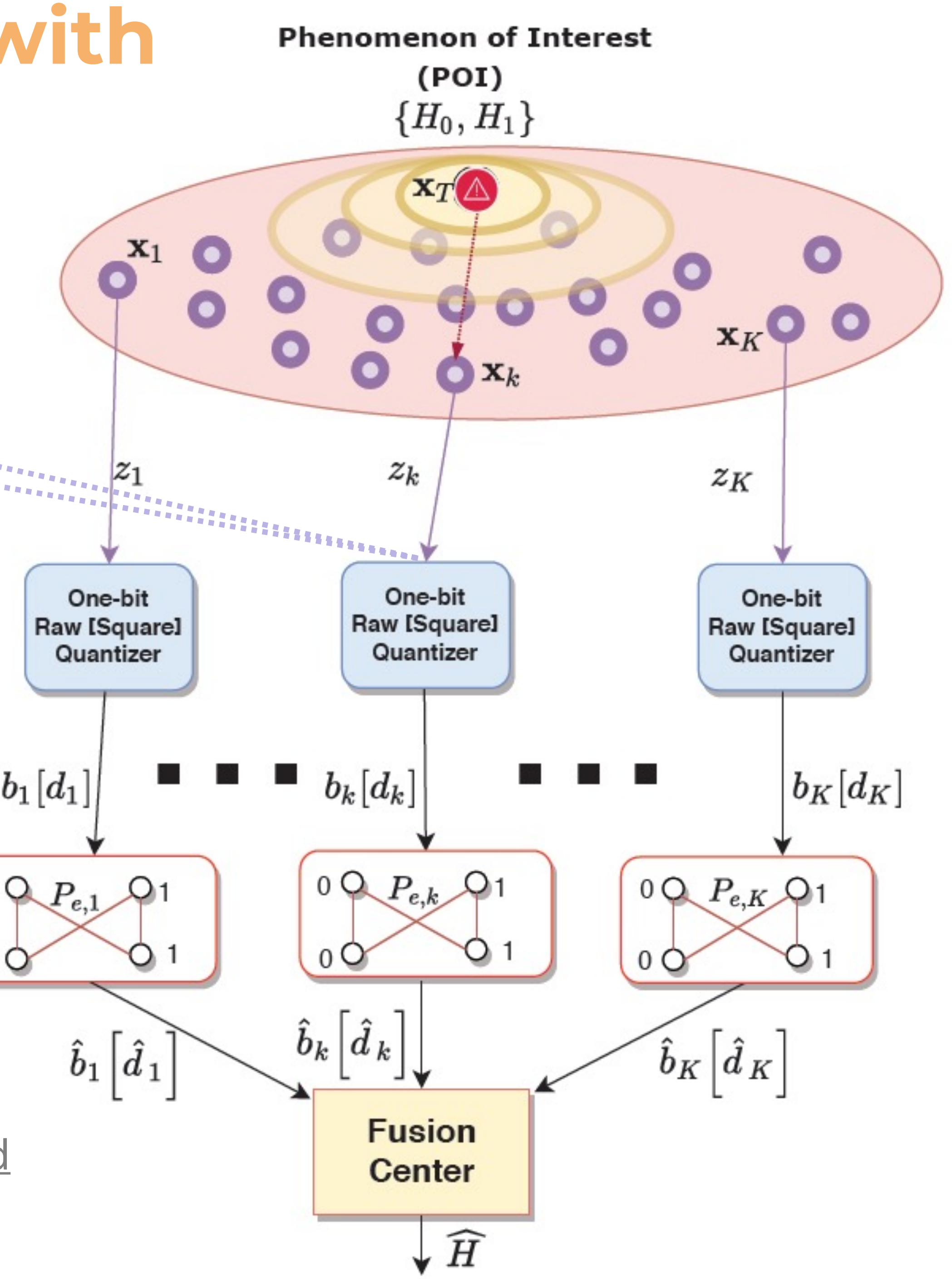
$b_k \triangleq u\left(z_k - \tau_k\right)$ **Vs.** $d_k \triangleq u(z_k^2 - \gamma_k)$

Raw quantization

Square quantization

$$\beta_k(\theta, x_T) \triangleq \mathcal{Q}\left([\tau_k - g_k\, \mu_{h,k}\, \theta] \,/\, \sqrt{\sigma^2_{\mathrm{eq},k}(\theta)}\right)$$

$$\rho_k(\theta, x_T) \triangleq \mathcal{Q}\left([\sqrt{\gamma_k} - g_k\, \mu_{h,k}\, \theta] \,/\, \sqrt{\sigma^2_{\mathrm{eq},k}(\theta)}\right) + \mathcal{Q}\left([\sqrt{\gamma_k} + g_k\, \mu_{h,k}\, \theta] \,/\, \sqrt{\sigma^2_{\mathrm{eq},k}(\theta)}\right) ,$$



- Local sensor performance are not known
- Standard fusion techniques cannot be applied

Decentralized Inference with sensing uncertainty

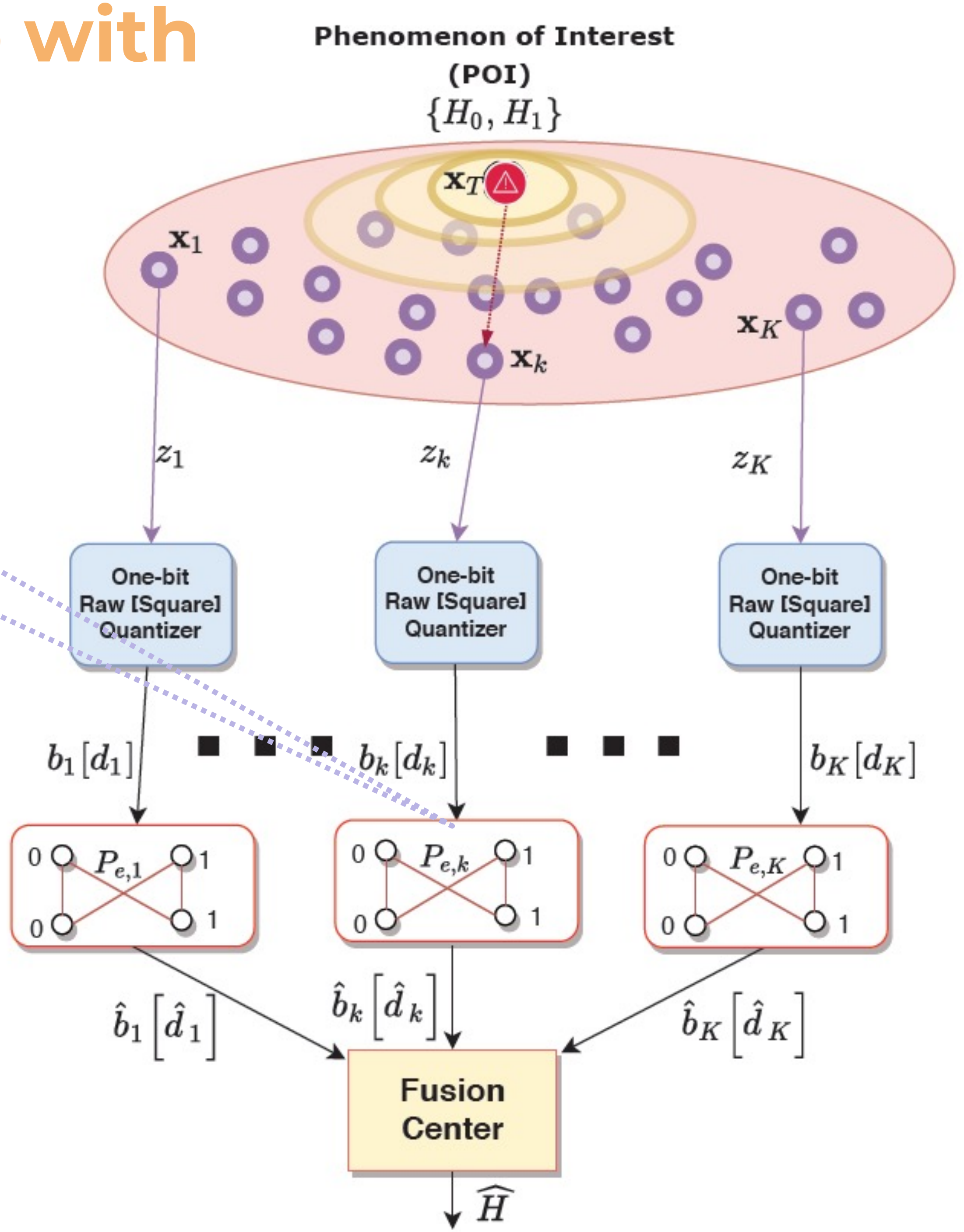
Issue:

Low-energy and lossy reporting

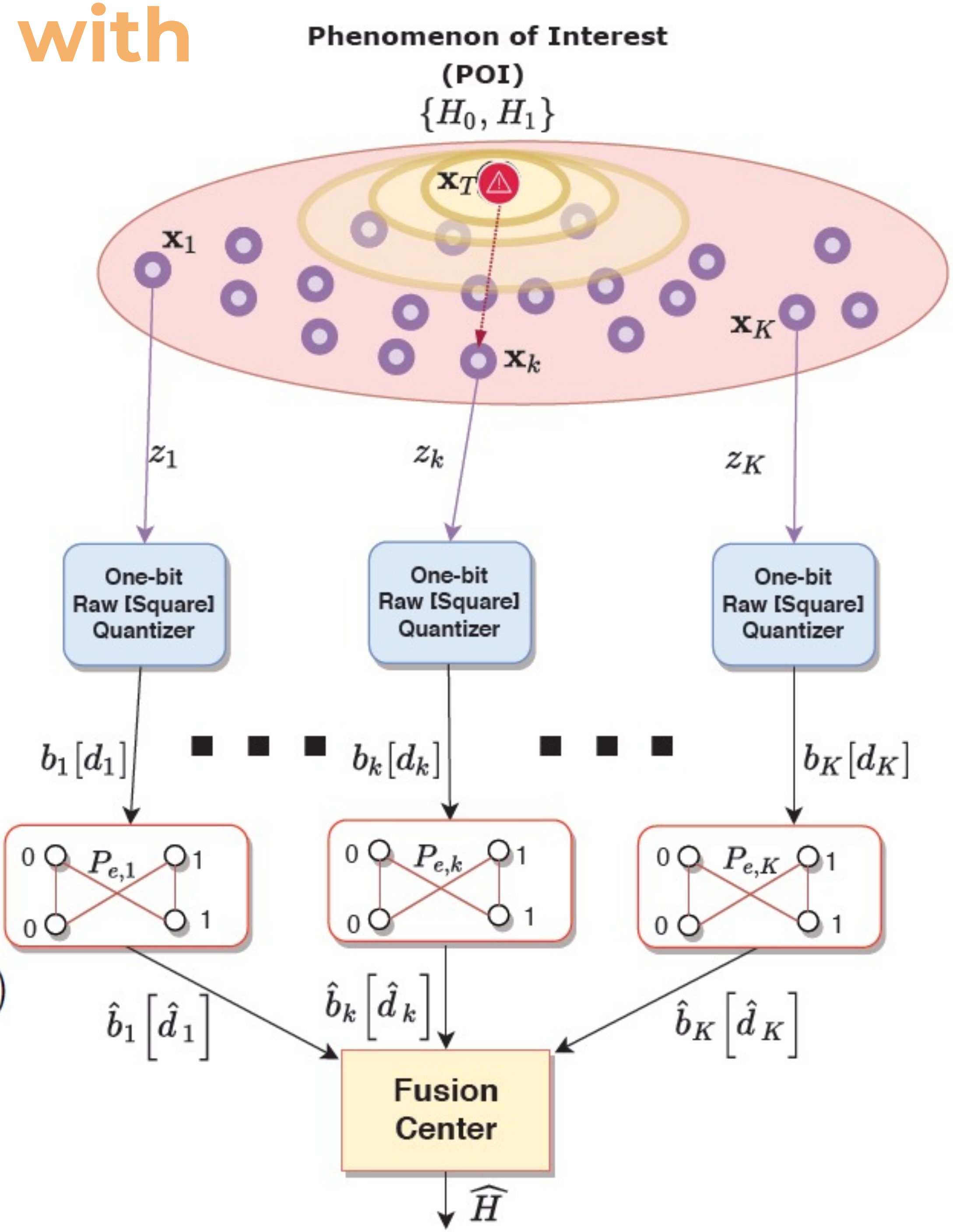
Hp: independent BSCs to emulate the modulation-decoding process

Common operational mode of **NB-IoT uplink**:

- low-order modulation schemes (e.g. BPSK)
- single-carrier frequency division multiple access
- connectivity to a large number of sensors with low data rate requirements



Decentralized Inference with sensing uncertainty



Bit probability for RQ:

$$\alpha_k^{\mathrm{sq}}(\theta, \boldsymbol{x}_T) \triangleq$$

$$(1 - P_{e,k})\rho_k(\theta, \boldsymbol{x}_T) + P_{e,k}(1 - \rho_k(\theta, \boldsymbol{x}_T))$$

Bit probability for SQ:

$$\alpha_k^{\mathrm{rq}}(\theta, \boldsymbol{x}_T) \triangleq$$

$$(1 - P_{e,k})\beta_k(\theta, \boldsymbol{x}_T) + P_{e,k}(1 - \beta_k(\theta, \boldsymbol{x}_T))$$

Decentralized Inference with sensing uncertainty

Log-likelihood of decisions received at FC

$$\log P(\hat{\boldsymbol{b}};\theta,\boldsymbol{x}_T)$$

$$=$$

$$\sum_{k=1}^{K}\{\hat{b}_k\log[\alpha_k^{\mathrm{rq}}(\theta,\boldsymbol{x}_T)]+(1-\hat{b}_k)\log[1-\alpha_k^{\mathrm{rq}}(\theta,\boldsymbol{x}_T)]\}$$

(a similar expression holds also for SQ)

POI parameters are not known!

$$(\theta,\boldsymbol{x}_T)$$

(Composite) Test of hypotheses:

SQ: $\{\mathcal{H}_0,\mathcal{H}_1\}\rightarrow\{\theta=\theta_0,\theta\neq\theta_0\}$

RQ: $\{\mathcal{H}_0,\mathcal{H}_1\}\rightarrow\{P_\theta=P_{\theta_0},P_\theta>P_{\theta_0}\}$

$\boxed{(\boldsymbol{x}_T)\text{ identifiable only under }\mathcal{H}_1}$