JOINT COMMUNICATION AND COMPUTING
A PATH TOWARDS SUSTAINABLE IOT

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SOLIDUM PETIT IN PROFUNDIS · UNIVERSITAS ARHUSIENSIS

QI ZHANG

Assoc. Professor, Department of Electrical and Computer Engineering, AU

- MSc and PhD from DTU in Telecommunications
- Leading IoT WP in DIGIT research centre at AU
  - Senor data compression, efficient transmission and storage, as well as approximate, real-time data analytics on compressed data
  - Mobile Edge Computing and Edge Intelligence for time-sensitive IoT applications
  - Lightweight sensor data encryption and privacy preserving schemes for IoT
- Currently leading three DFF projects "**AgileIoT**: Agile Edge Intelligence for Delay Sensitive IoT", "**Light-IoT**: Analytics Straight on Compressed IoT Data", "**eTouch**: Edge Intelligence for Immersive Telerobotics in Touch-enabled Tactile Internet", and Horizon Europe MSCA-DN **TOAST** project.
- Participating in DFF **Growlean** project and H2020 ITN **IoTAlentum** project.

OUTLINE

Motivation: why bridging communication with computing?

How to bridge communication with computing?

- Joint compression and encryption
  - Compressive sensing-based data encryption
- Joint compression and analytics
  - Analytics over GD compressed data

Conclusion and outlook

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MOTIVATION

Enable a sustainable growth in IoT through a holistic design: Joint communication with computing


Wind turbine system

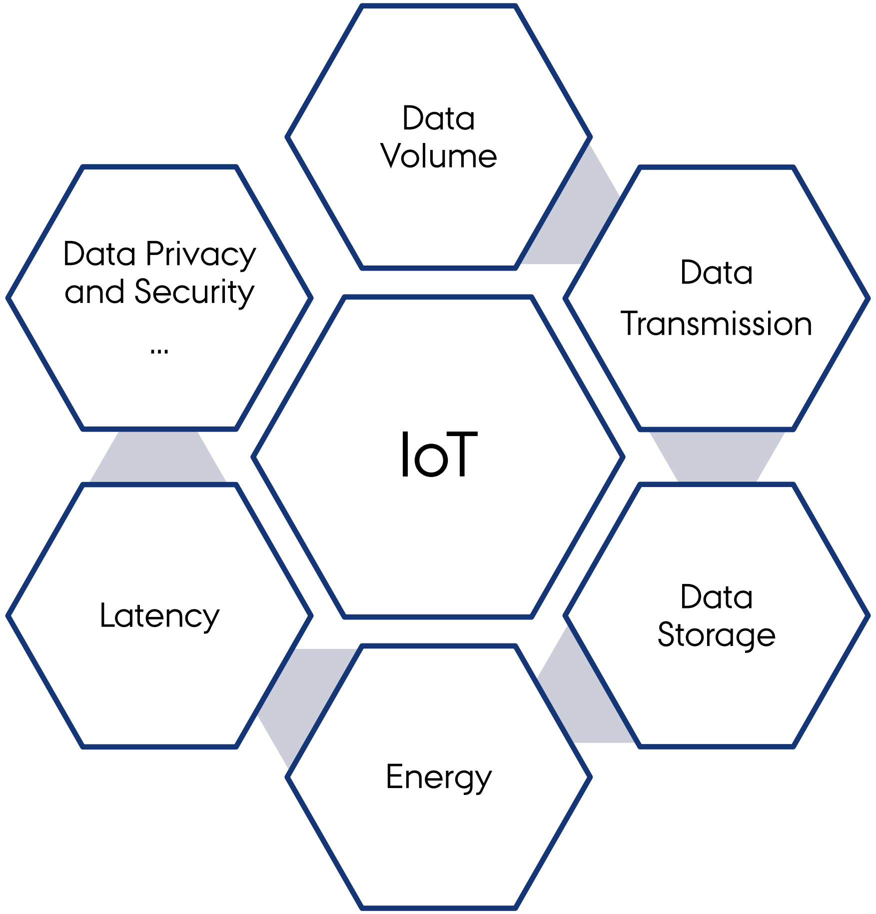

Autonomous vehicles

Industry 4.0


E-health


Smart agriculture


Smart city



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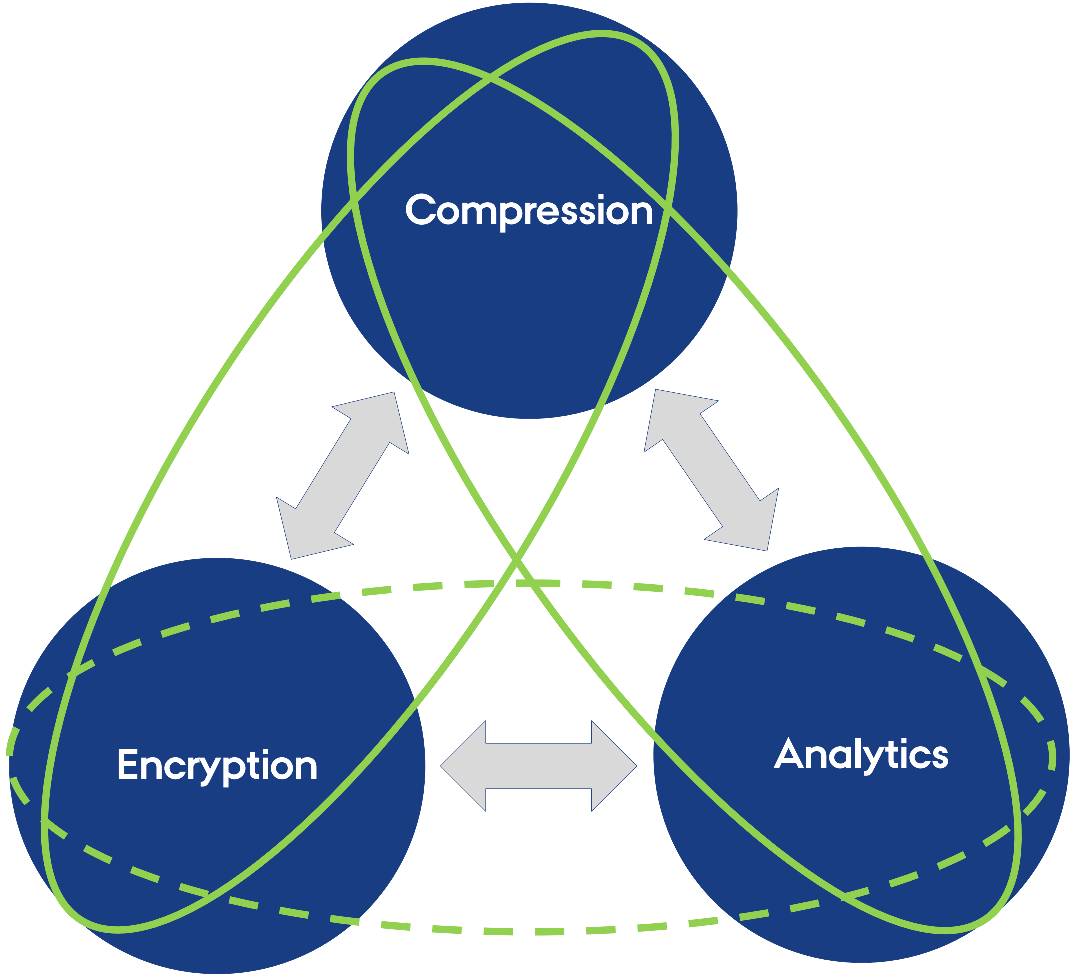

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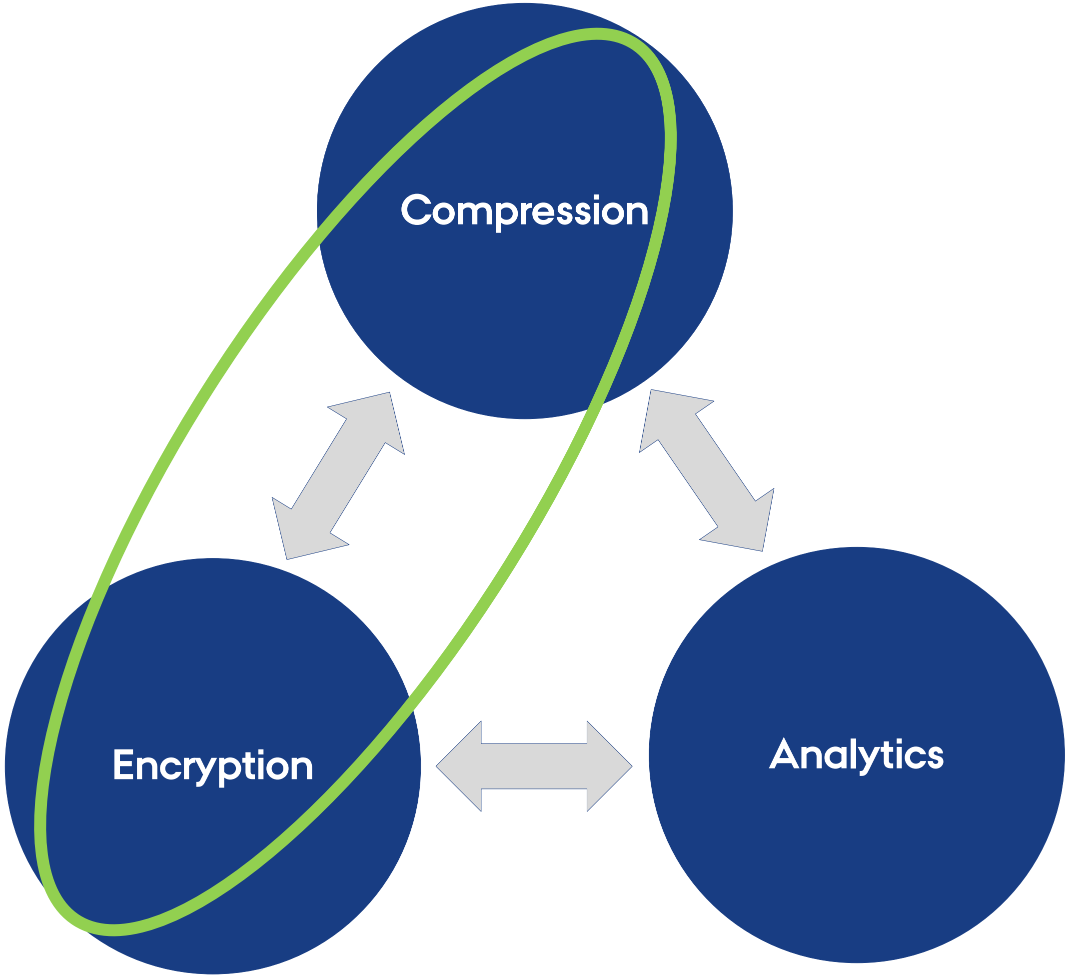

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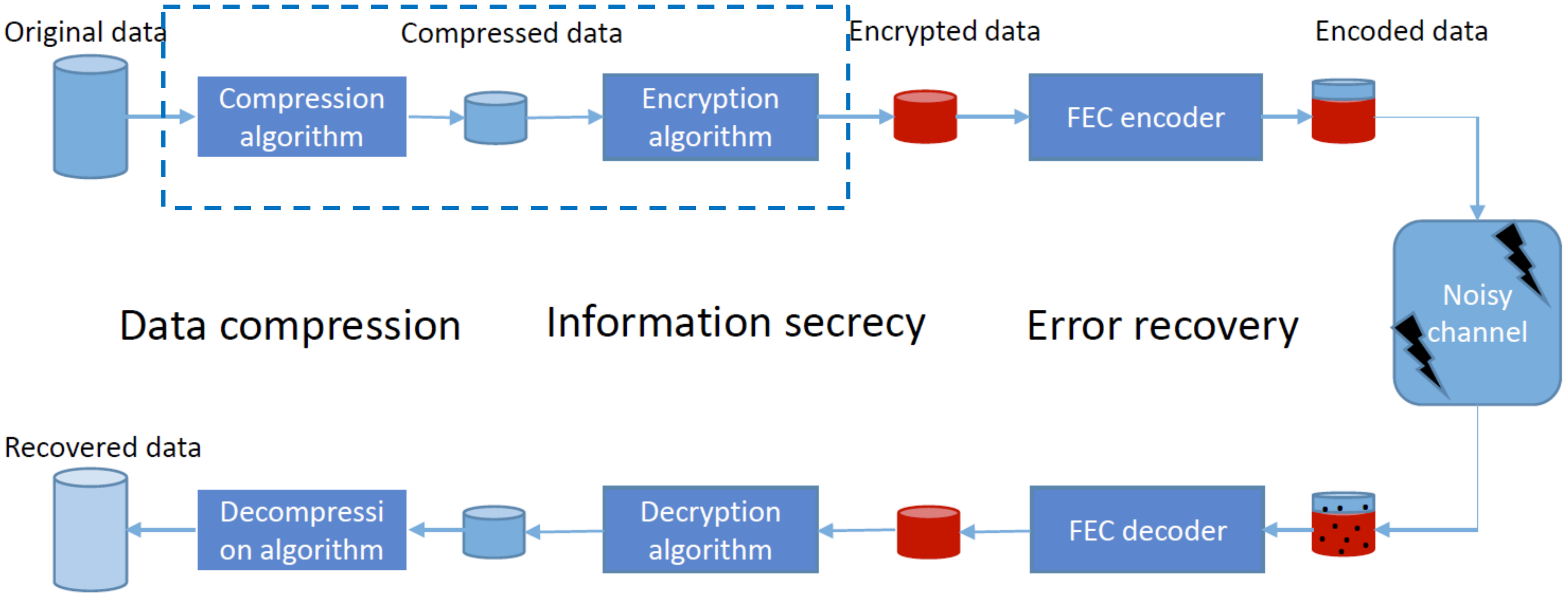
JOINT COMPRESSION AND ENCRYPTION

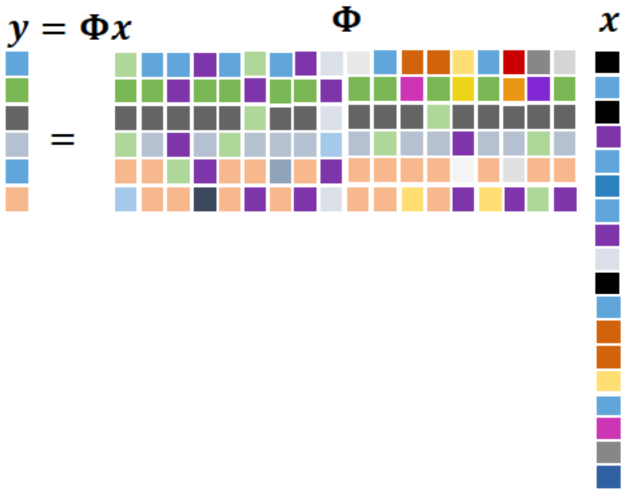


COMPRESSIVE SENSING AND ENCRYPTION

Input signal: $\boldsymbol{x} \in \boldsymbol{R}^{N}$

Sensing matrix: $\boldsymbol{\Phi} \in \boldsymbol{R}^{M\times N}, M < N$

Measurement vector: $\boldsymbol{y}=\boldsymbol{\Phi x}$



Requirements for signal recovery

- Signal sparsity
- Design of the sensing matrix

Information secrecy

- Plaintex: $\boldsymbol{x}$
- Ciphertext: $\boldsymbol{y}$
- Gaussian one-time sensing

Computational secrecy

$$\boldsymbol{y}_i = \boldsymbol{\Phi}_i \boldsymbol{x}_i$$

Perfect secrecy

Mutual information:

$$I(\boldsymbol{x}_i, \boldsymbol{y}_i) = I\left(E_{\boldsymbol{x}_i}, E_{\boldsymbol{y}_i}\right)$$

$E_{\boldsymbol{x}_i}$ is energy of $\boldsymbol{x}_i$ and $E_{\boldsymbol{y}_i}$ is energy of $\boldsymbol{y}_i$.

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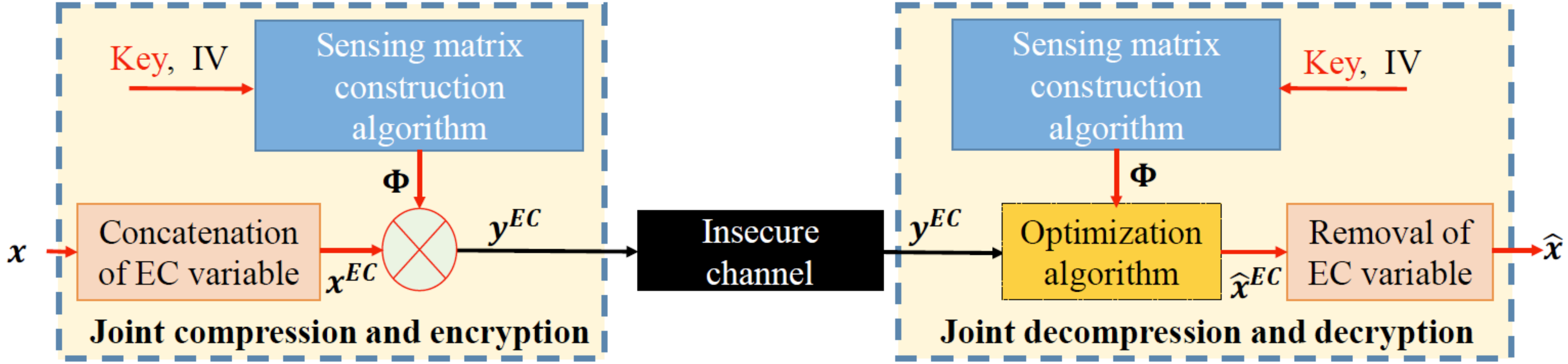
ENERGY CONCEALMENT ENCRYPTION SCHEME

Objective: To tackle the weaknesses of the state-of-the-art CS-based encryption systems

- CS ciphertext leaks energy
- Plaintext are correlated

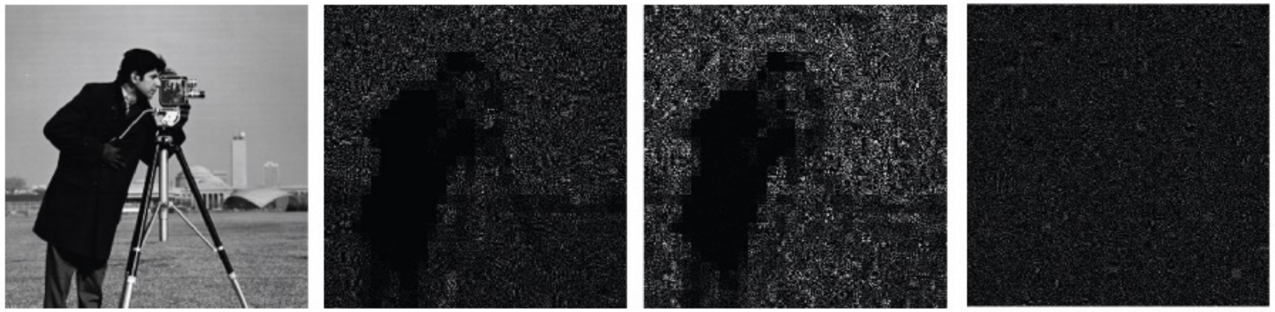
For data $\boldsymbol{x} = [x_1, \; x_2, \dots, x_{N-1}]^T$, construct an energy concealment $\boldsymbol{x}^{EC} = [c, x_1, \; x_2, \dots, x_{N-1}]^T$

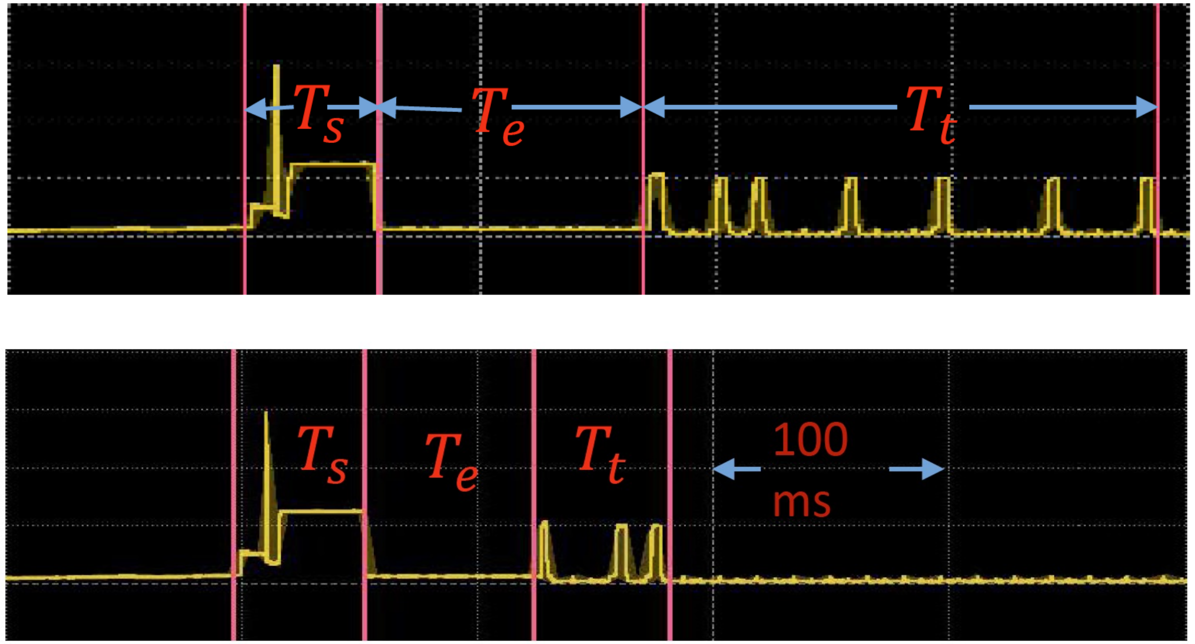
Using Compressive Sensing to compress data $\boldsymbol{x}^{EC} \in R^N$ to $\boldsymbol{y}^{EC} \in R^M$, with CR = M/N

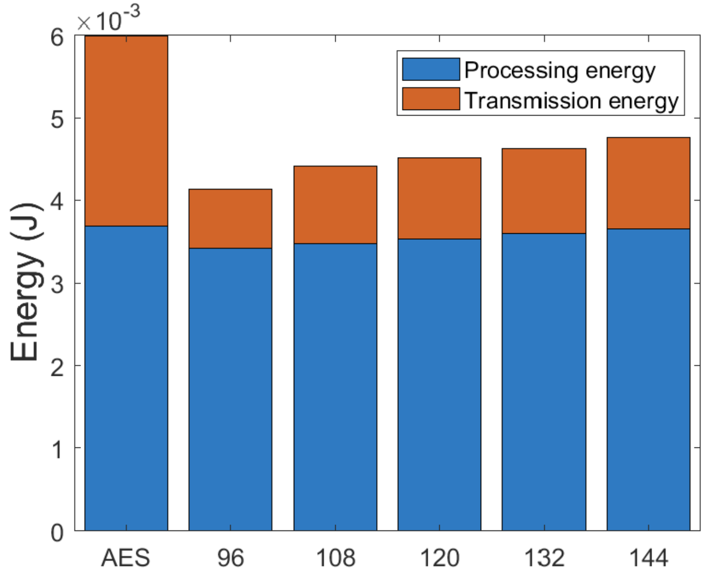


G. Kuldeep and Q. Zhang, “Design Prototype and Security Analysis of a Lightweight Joint Compression and Encryption Scheme for Resource-Constrained IoT Devices," in IEEE Internet of Things Journal, 2022.

EC: PERFORMANCE EVALUATION







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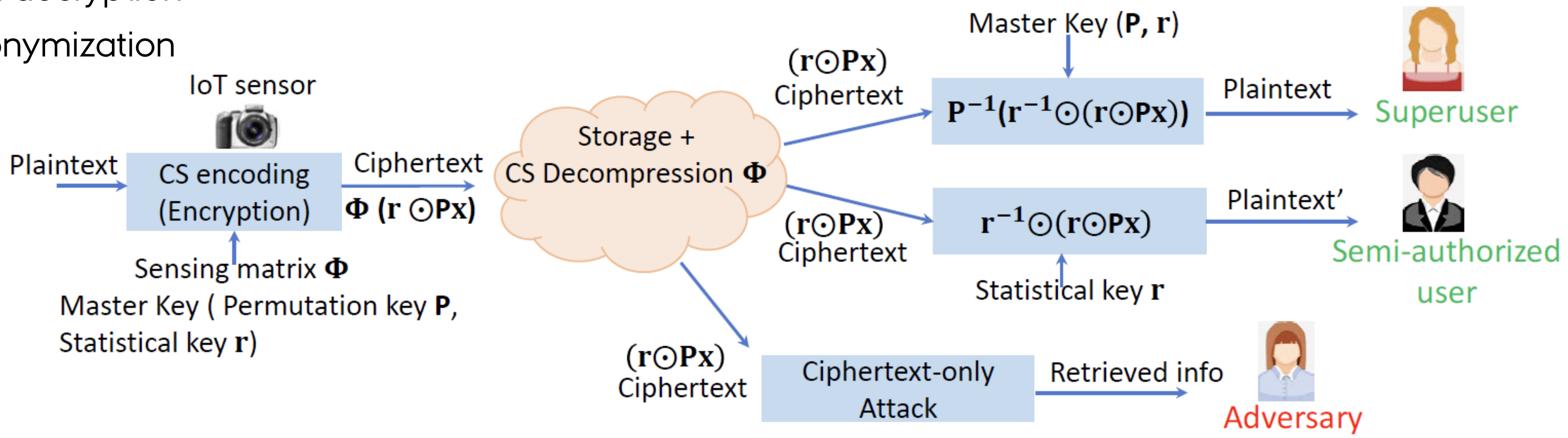
MULTI-CLASS PRIVACY PERSEVERING CLOUD COMPUTING (MPCC)

Objectives:

- Multi-class encryption
- Privacy preserving computation intensive signal recovery at cloud
- Joint compression and information secrecy

MPCC applications:

- Statistical decryption
- Data anonymization



G. Kuldeep and Q. Zhang, “Multi-class Privacy-preserving Cloud Computing based on Compressive Sensing for IoT," Elsevier Journal of Information Security and Applications, 2022.

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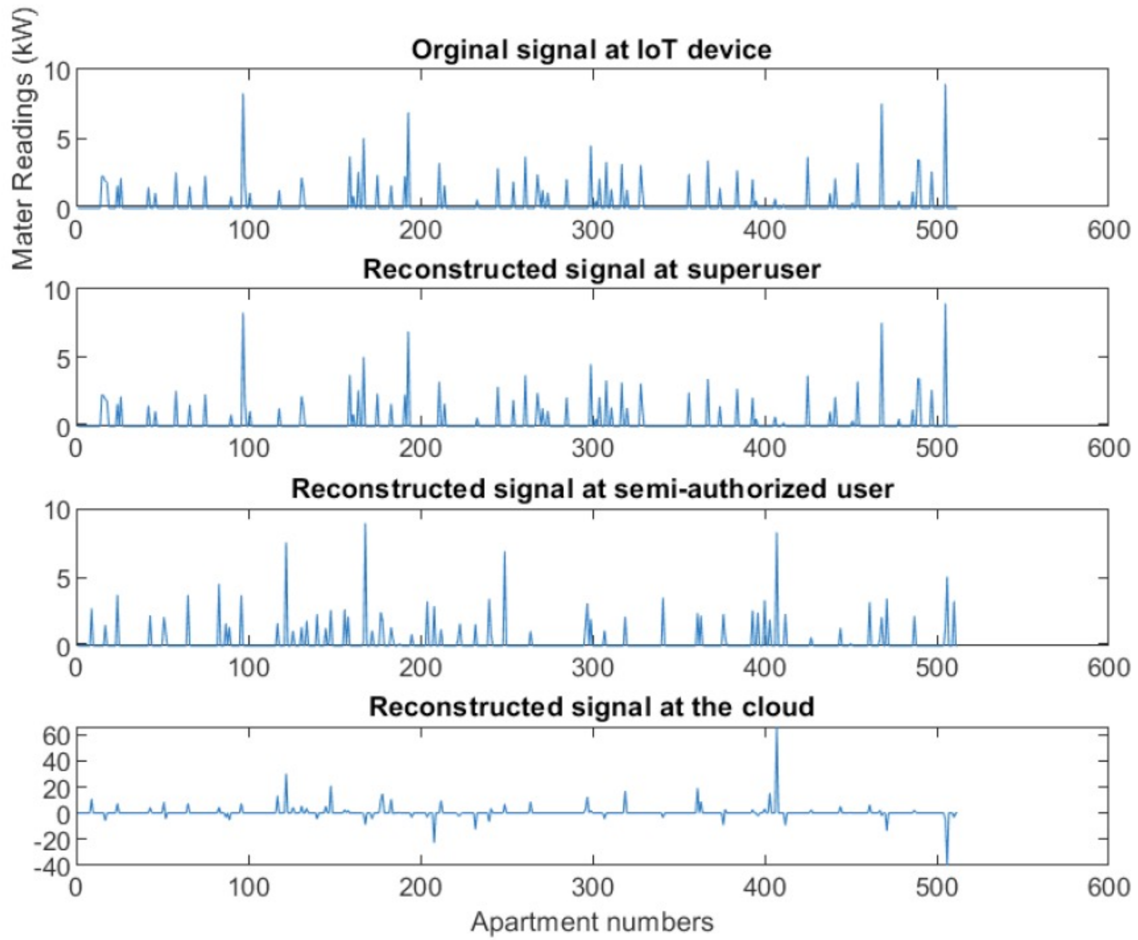
MPCC: STATISTICAL DECRYPTION-1

Access point: joint compression and encryption of smart meter readings

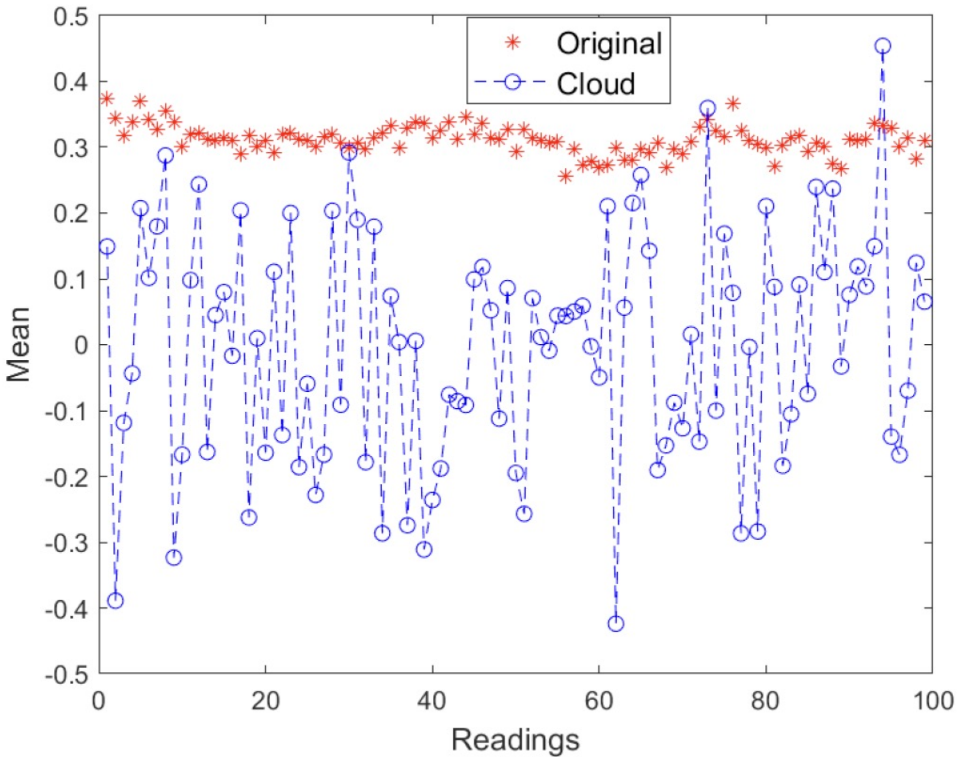
Cloud: storage and decompression

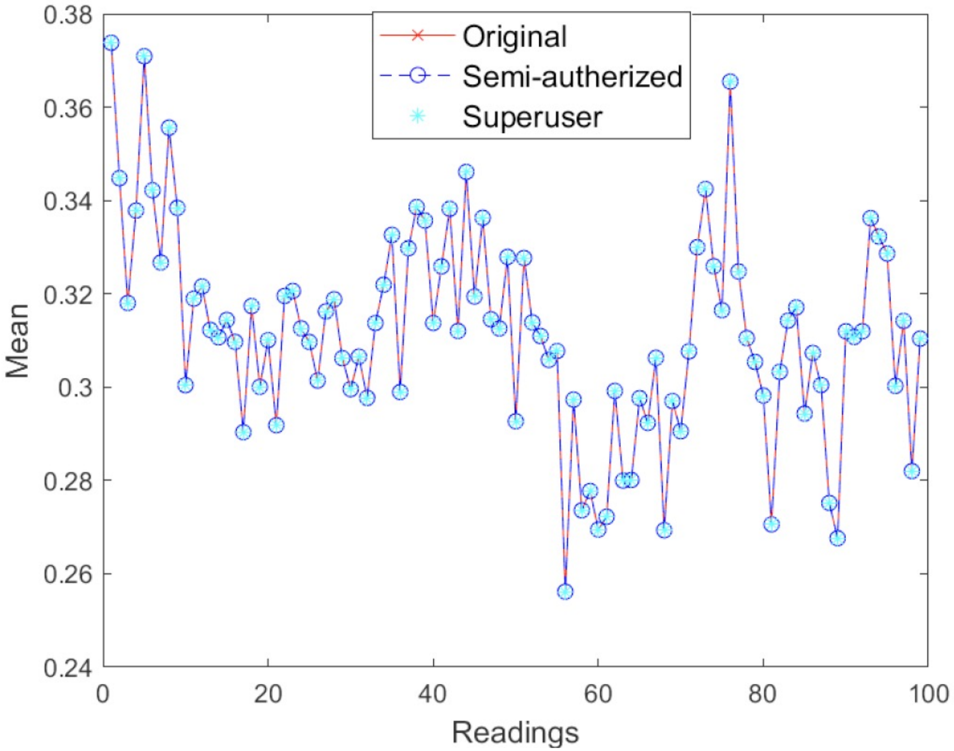
Superuser: exact meter readings

Semi-authorized user: only statistical information



MPCC: STATISTICAL DECRYPTION-2





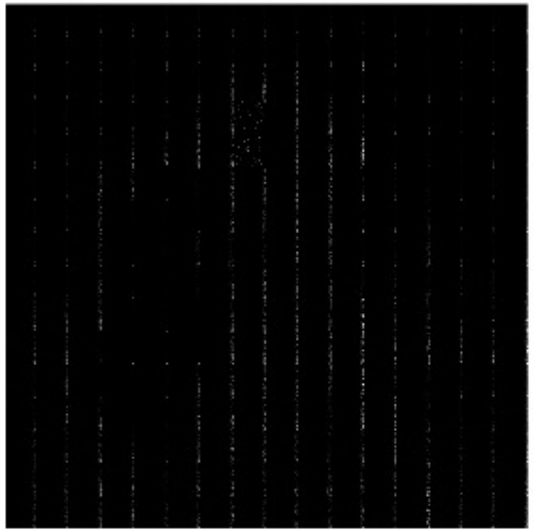
MPCC: DATA ANONYMIZATION

IoT device: joint compression and encryption of images

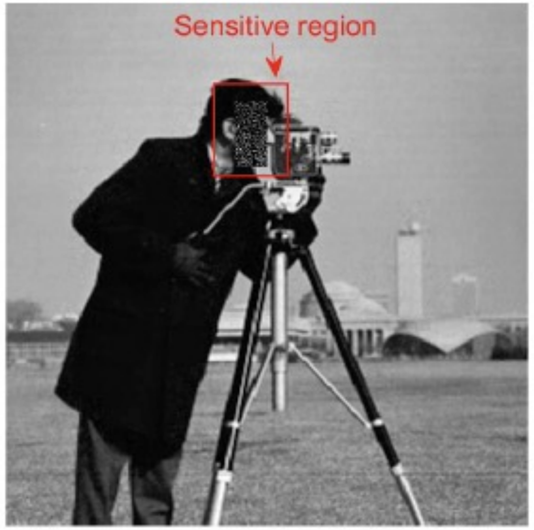
Cloud: storage and decompression

Superuser: complete image

Semi-authorized user: non-sensitive part of the image



Reconstructed image at the cloud



At semi-authorized user

At super-user

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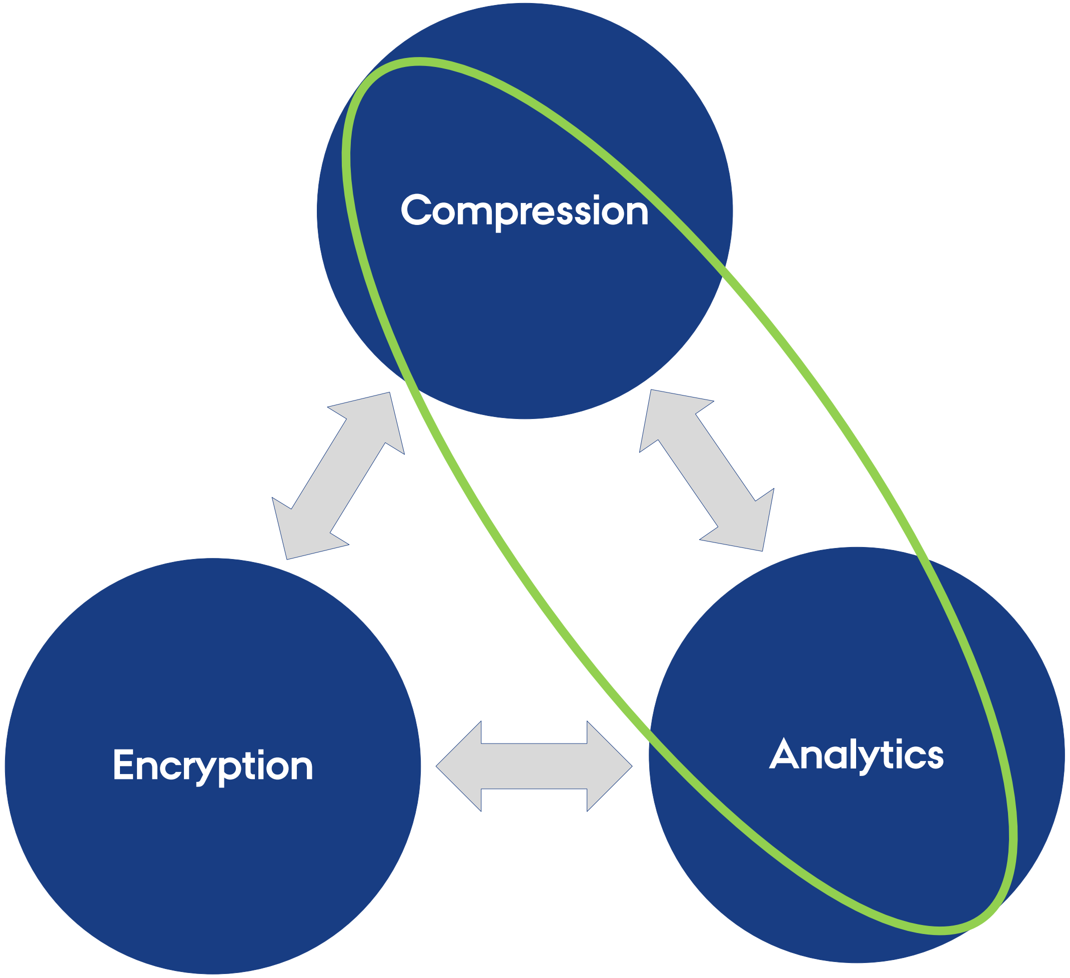
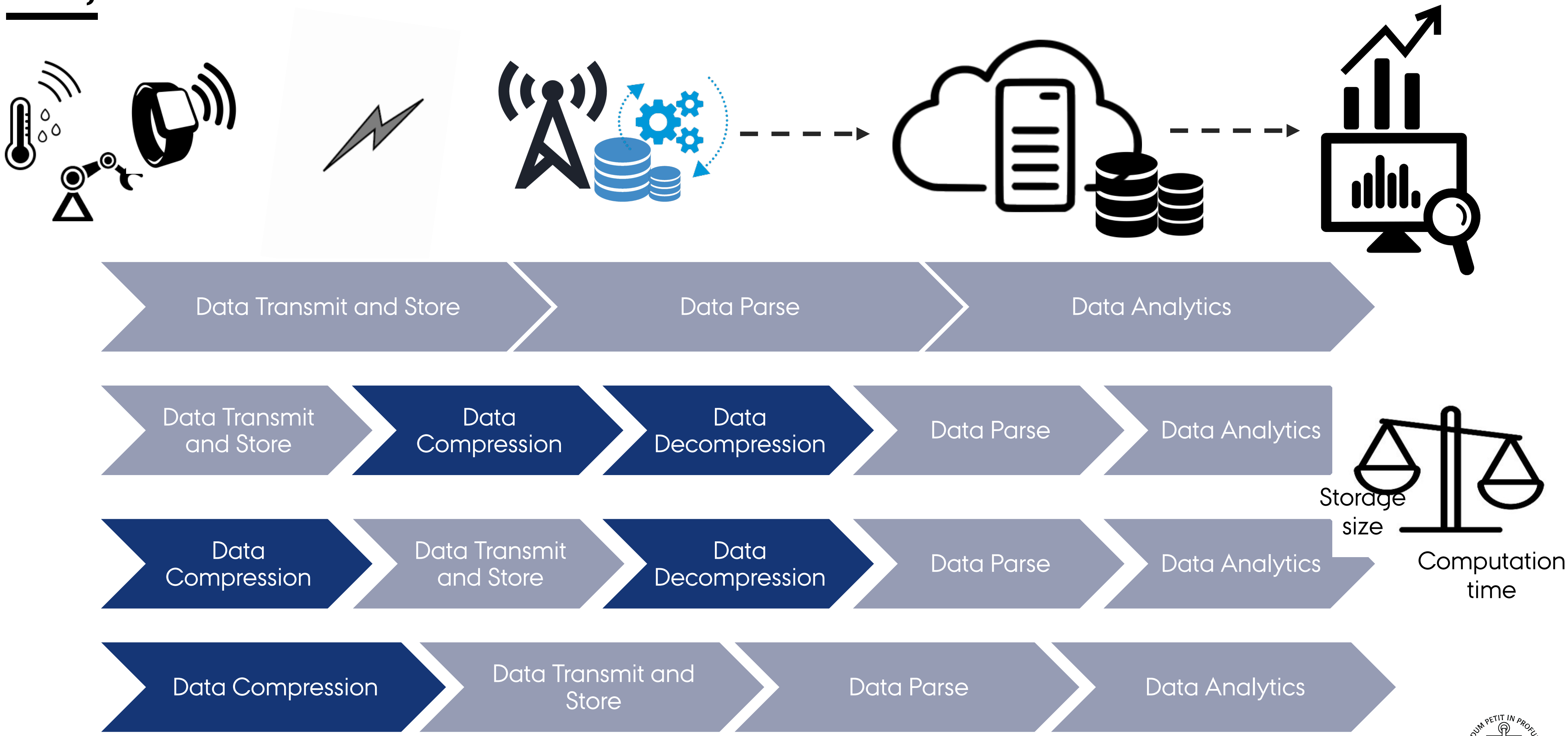


IOT FRAMEWORK FOR DATA ACQUISITION, TRANSMISSION, STORE, AND ANALYTICS



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FOR IOT DATA ACQUISITION, TRANSMISSION, STORE, AND ANALYTICS

Goal: to create a sustainable IoT solution through a holistic, end-to-end framework to address the challenges,

- Minimize IoT data traffic and storage;
- Save energy in IoT devices, communication and storage infrastructure, as well as in computing;
- Accelerate data analysis, striking a balance between accuracy and efficiency;

Solution:

- New lossless data compression algorithm, **Generalized Deduplication**, enables
  - random data access;
  - direct data analytics;
  - and could provide an opportunity for privacy-preserving analytics.

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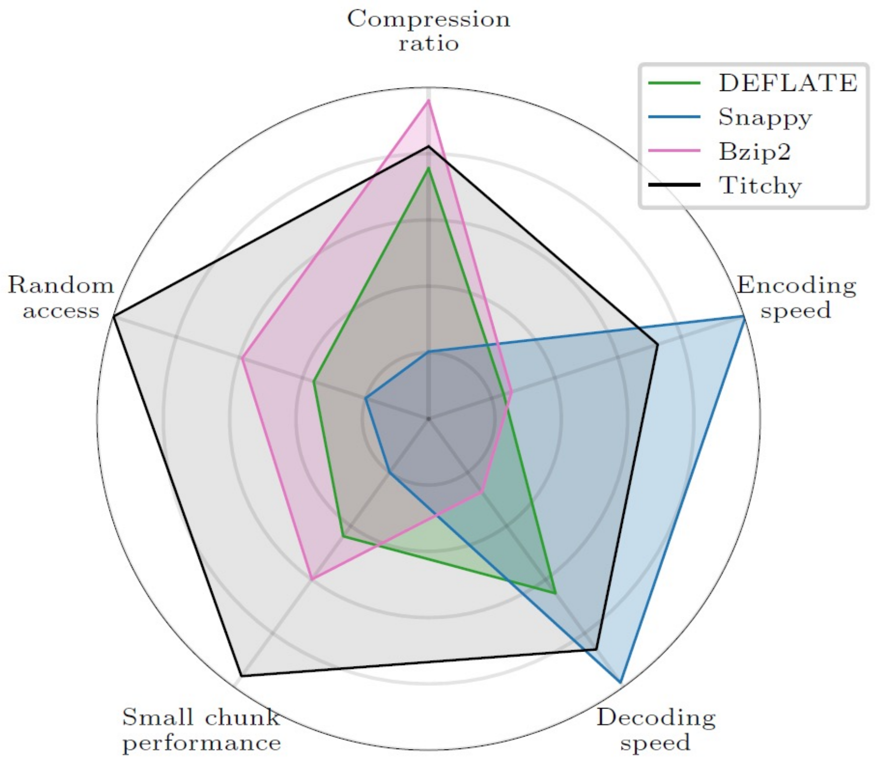
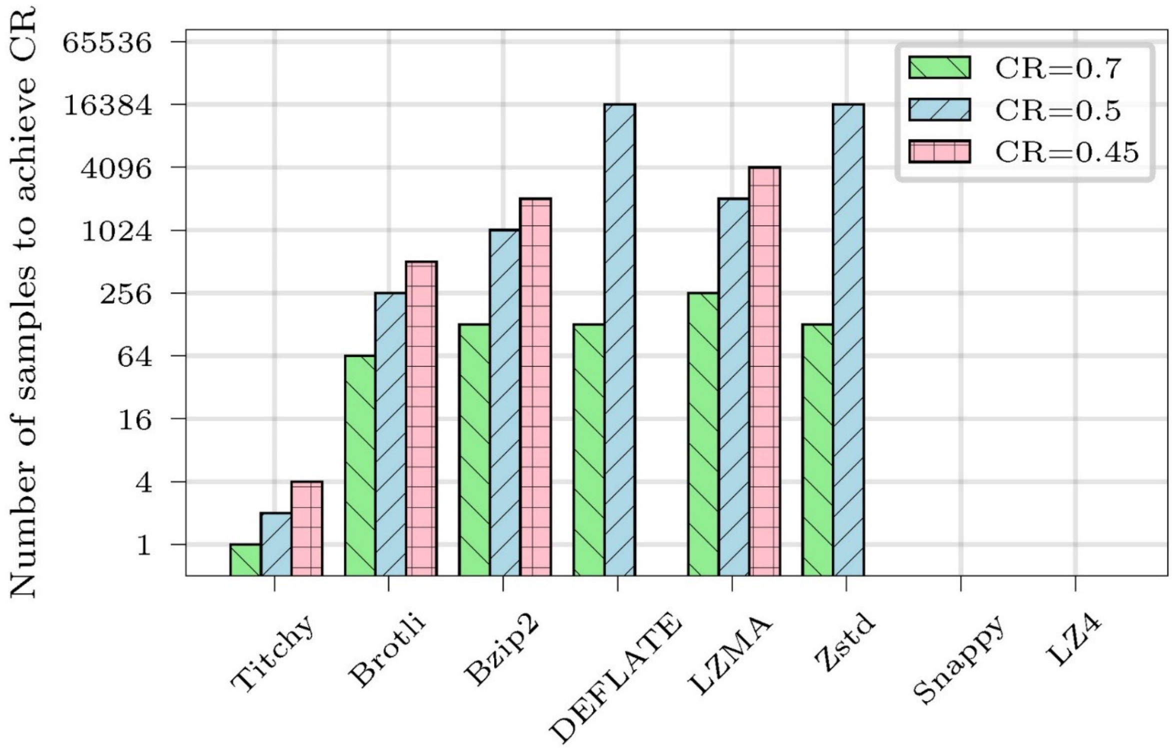
GENERALIZED DEDUPLICATION
TITCHY: TIME-SERIES COMPRESSION WITH RANDOM ACCESS

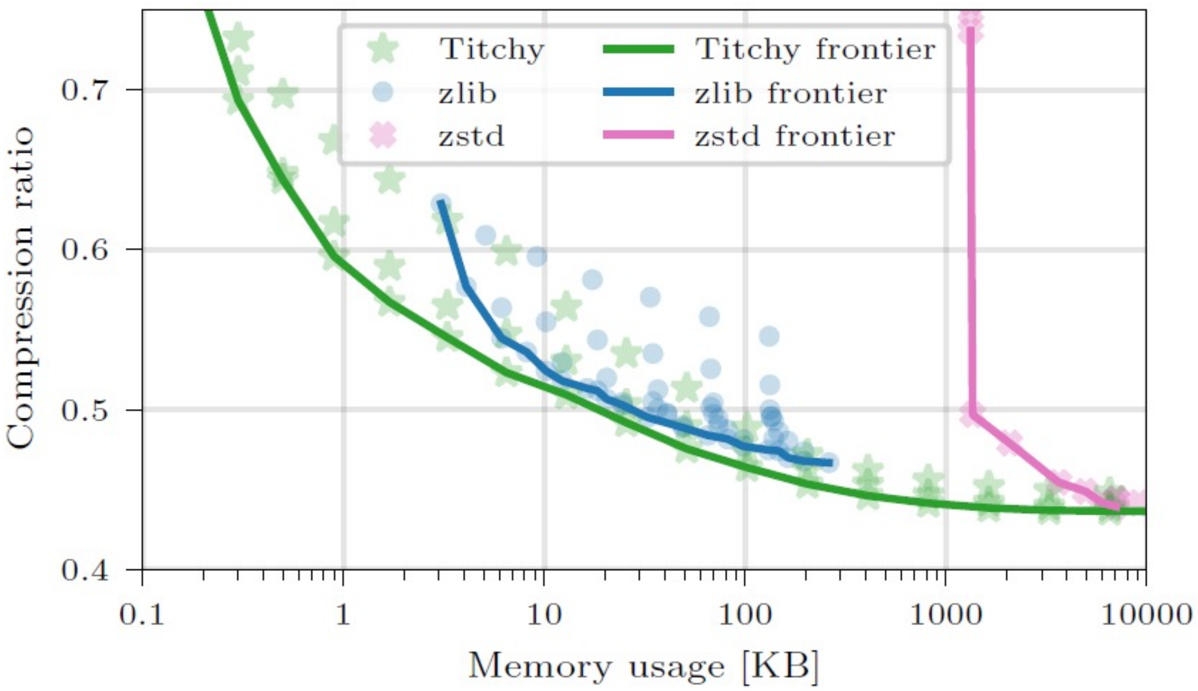
- Data Compression at resource-constrained IoT devices
- To realize end-to-end compression, with good overall performance in
  - Compression ratio
  - Encoding speed
  - Decoding speed
  - Small chunk performance
  - Random access capability



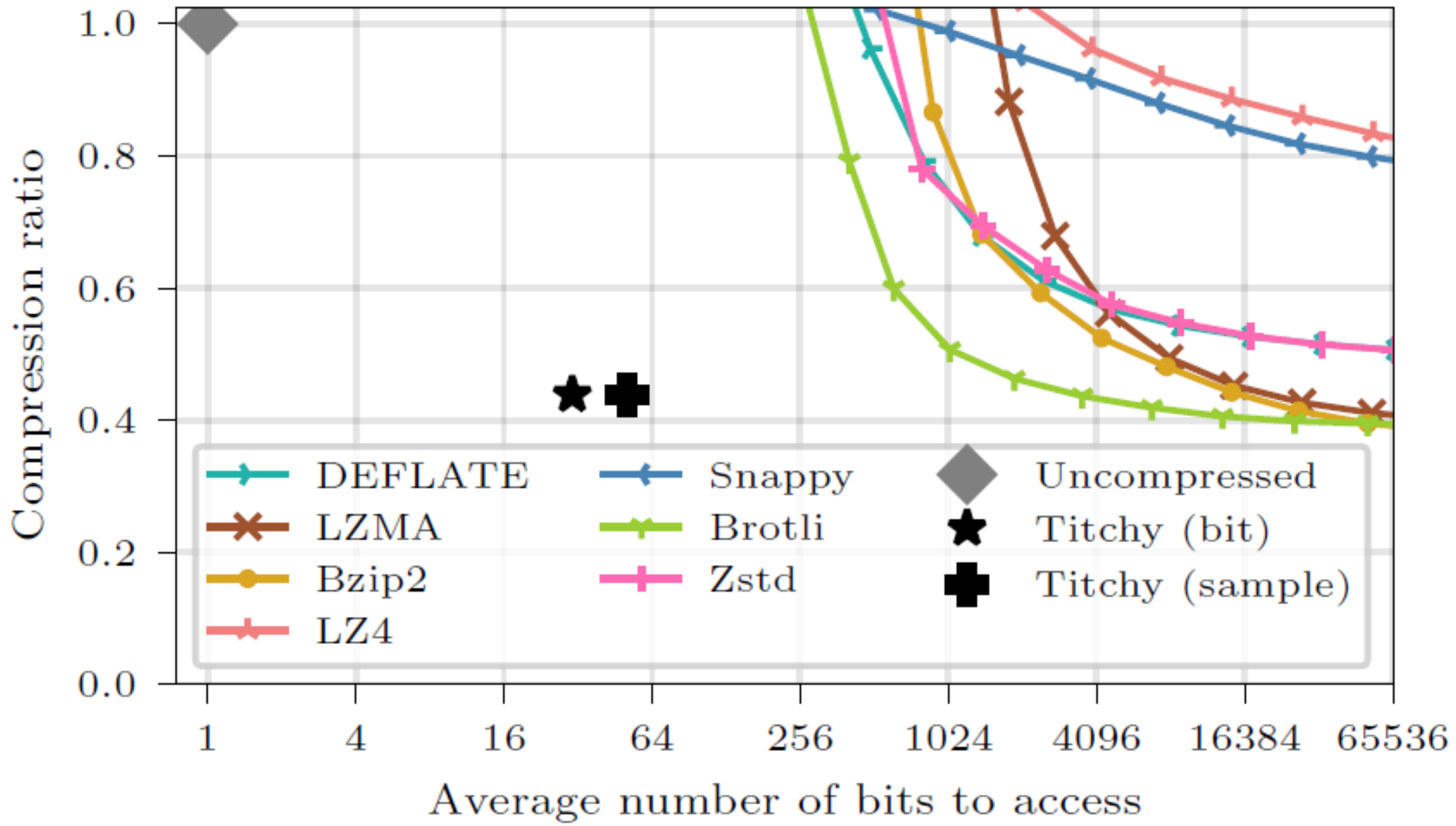
- R. Vestergaard, D. E. Lucani Rötter; Q. Zhang. A Randomly Accessible Lossless Compression Scheme for Time-Series Data. IEEE INFOCOM 2020. s. 2145-2154.
- R. Vestergaard, Q. Zhang, M. Sipos, D. E. Lucani Rötter, "Titchy: Online Time-series Compression with Random Access for the Internet of Things", IEEE Internet of Things Journal, 05.2021.

COMPRESSION RATIO VS. BLOCK SIZE & MEMORY USAGE



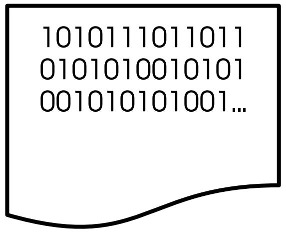


RANDOM ACCESS COST



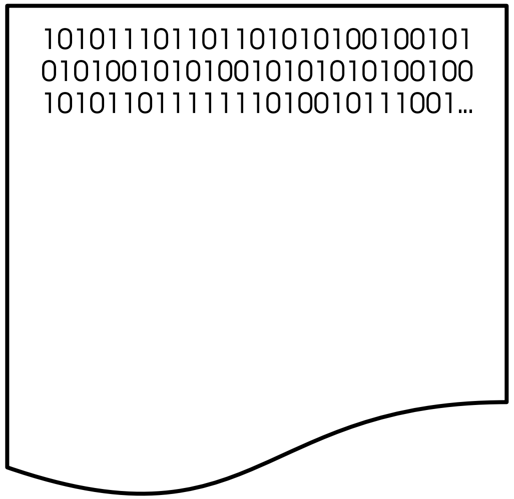
Can we perform data query processing and analytics directly on the GD compressed data?

Bases

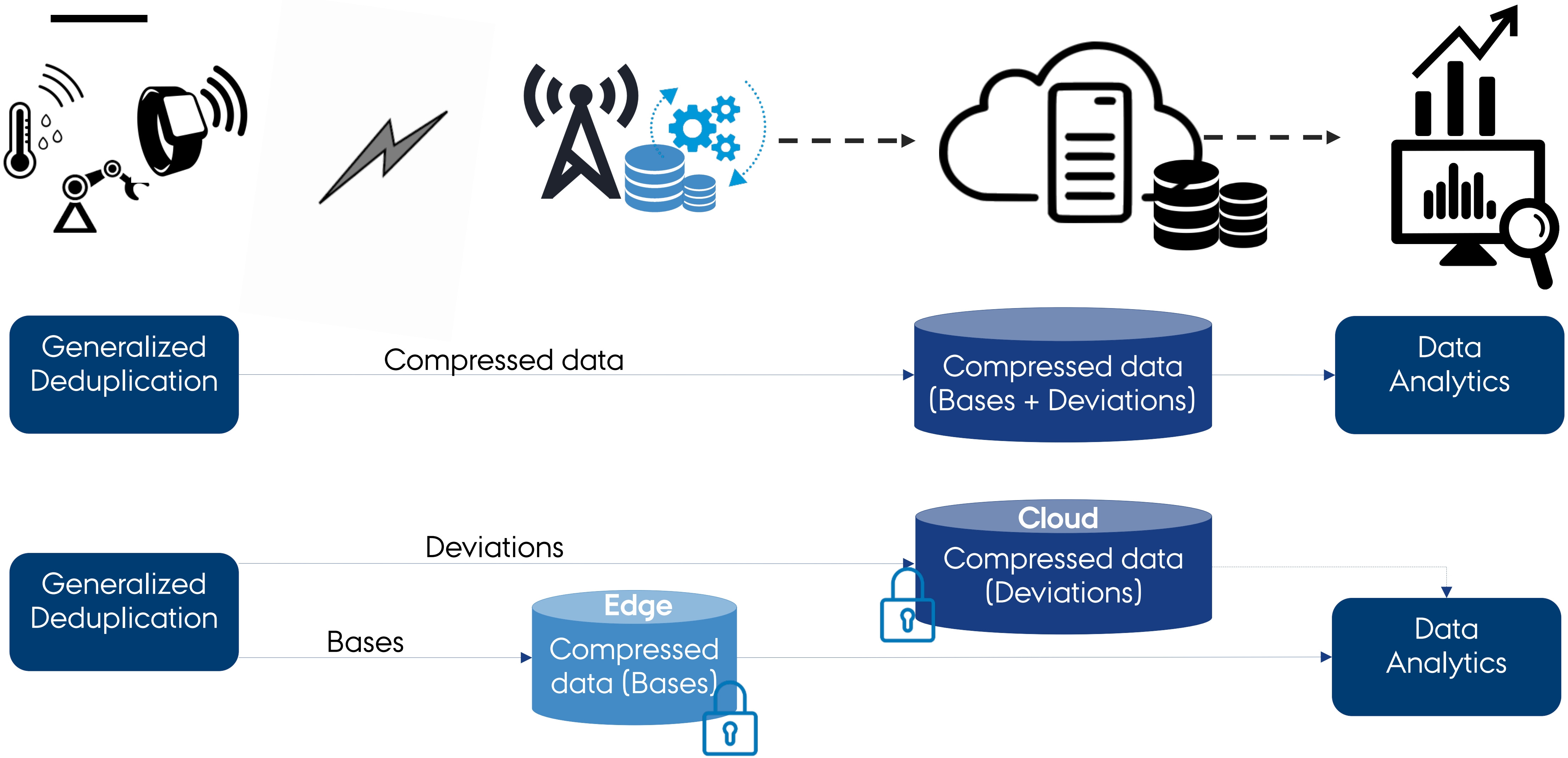


The bases act like a **summary** of the data.

Deviations



A JOINT COMMUNICATION AND COMPUTING IOT FRAMEWORK



CLUSTERING ON GD COMPRESSED DATA

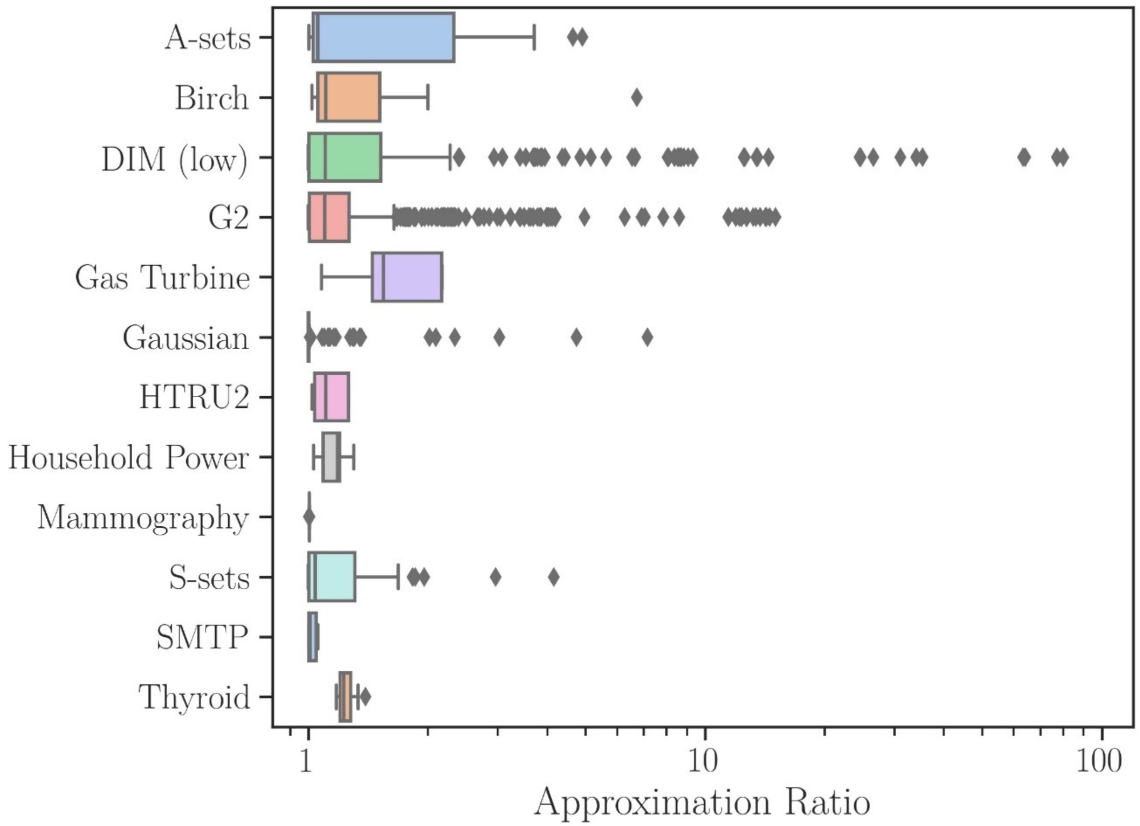
	Dataset Group	Description	# Datasets	n	d	k	Mean Size (kB)	Type	Comp. Configs Total	Comp. Configs Mean
SYNTHETIC	A-sets [40]	Varied k	3	3,000–7,500	2	20–50	42.1	int	24	8
	Birch [40]	Varied structure	2	100,000	2	100	800.1	int	21	11
	DIM (low) [40], [41]	Varied d	14	1,351–10,126	2–15	9	239.1	int	292	21
	G2 [40]	Varied d & overlap	60	2,048	2–64	2	172.2	int	924	16
	S-sets [40]	Varied overlap	4	5,000	2	15	40.1	int	32	8
	Gaussian [28]	Well-defined clusters	10	100,000	2	5	800.1	float	100	10
REAL	Gas turbine [42]	Hourly emissions	1	36,733	11	5	1,616.4	float	22	22
	Power consumption [43]	Single household	5	10,000–400,000	7	4	4,213.2	float	35	7
	HTRU2 [44]	Pulsar emissions	1	17,898	8	5	572.9	float	10	10
	Mammography [45]	Calcification scans		11,183	6	6	268.5	float	10	10
	SMTP [45]	Network attack attempts	1	95,156	3	5	1,142.0	float	10	10
	Thyroid [45]	Patient data	1	3,772	6	7	90.7	float	10	10
	Total		**103**						**1,490**	**14.5**

A. Hurst, D. E. Lucani, I. Assent and Q. Zhang, “GLEAN: Generalized Deduplication Enabled Approximate Edge Analytics”, IEEE Internet of Things Journal, 2022

DATA CLUSTERING QUALITY ON COMPRESSED DATA WITH DIFFERENT GD CONFIGURATIONS

Only access the bases of GD compressed data

Approximation Ratio = sum of squared errors (basis) /sum of squared errors (x)



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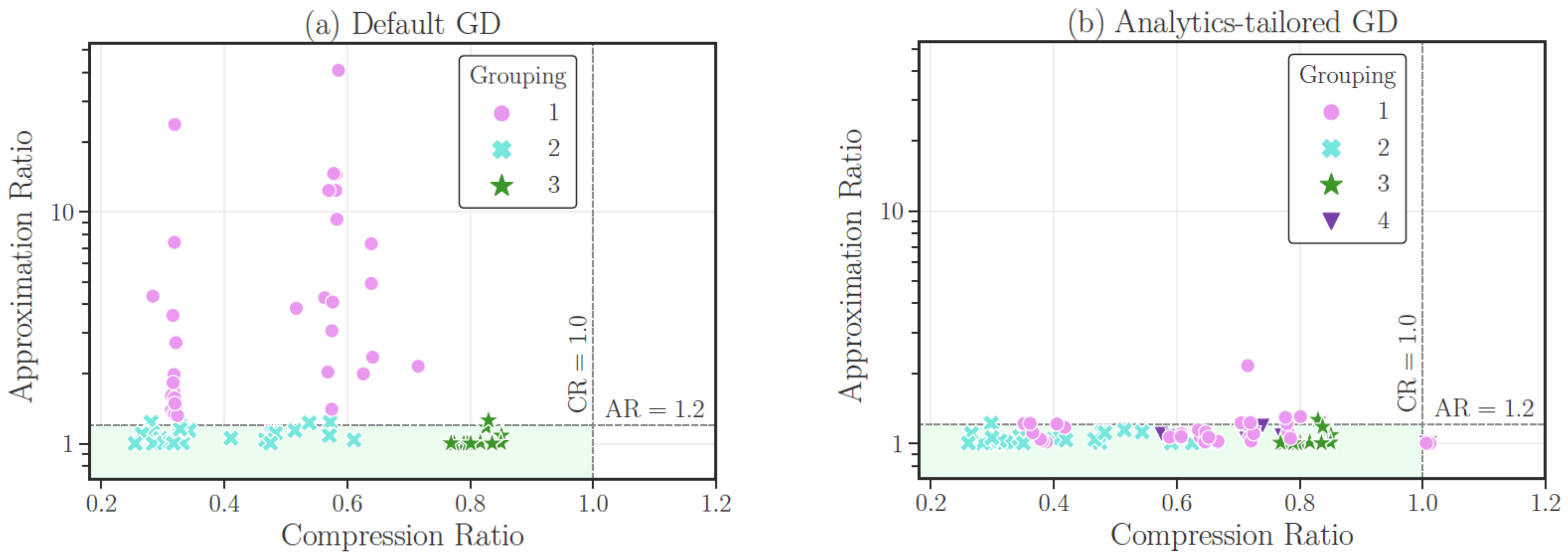
OPTIMIZE GD TO IMPROVE CLUSTERING QUALITY

Optimizing GD

- Design a heuristic approach
- Improve data clustering quality at the expense of compression ratio



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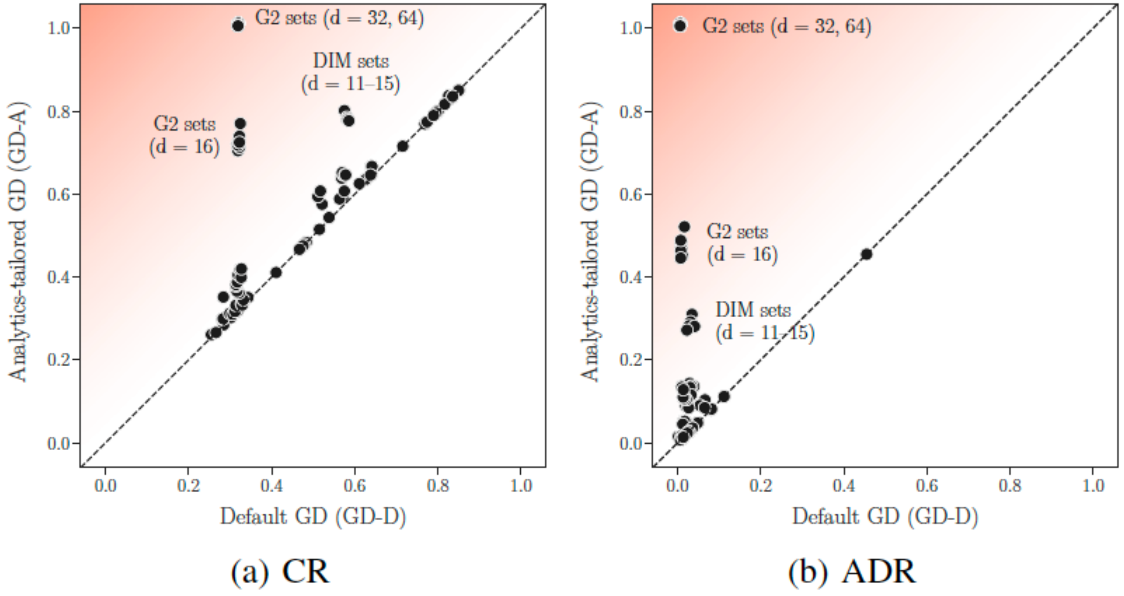
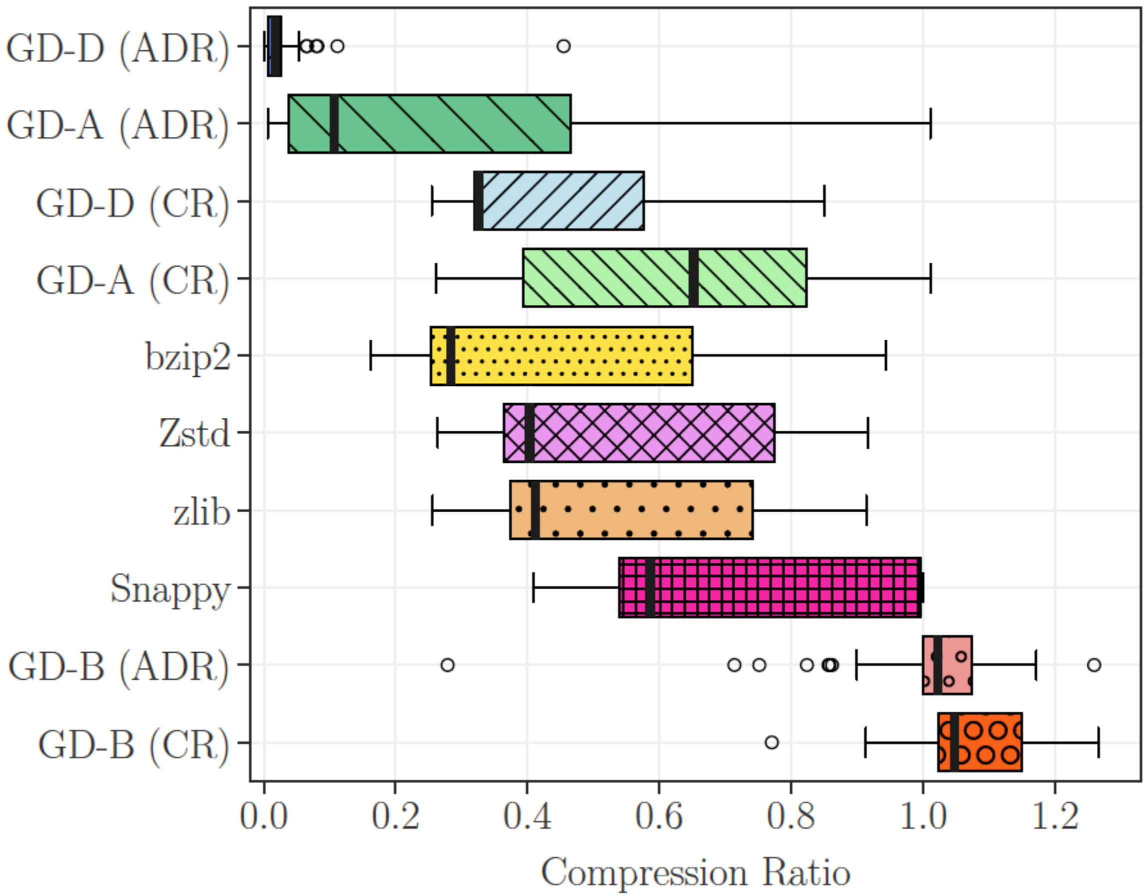
ANALYTICS DATA RATIO AND COMRESSION RATIO

Compression ratio and Analytics data ratio

- GD vs. SoTA universal data compressors





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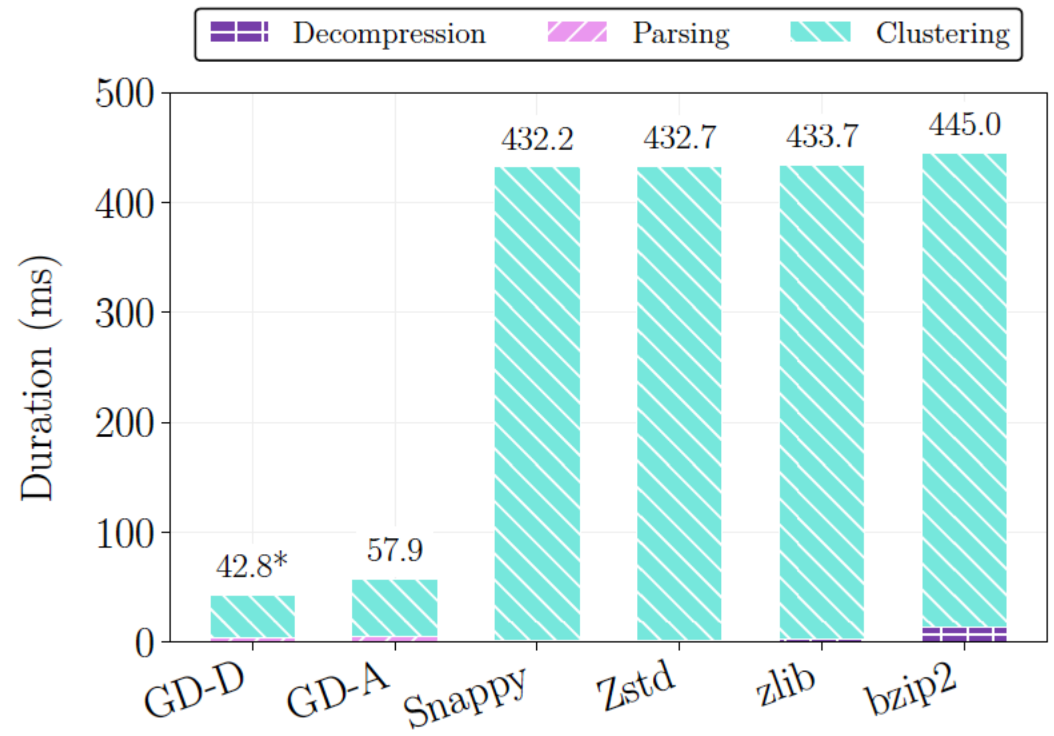
RUNTIME COMPARISON



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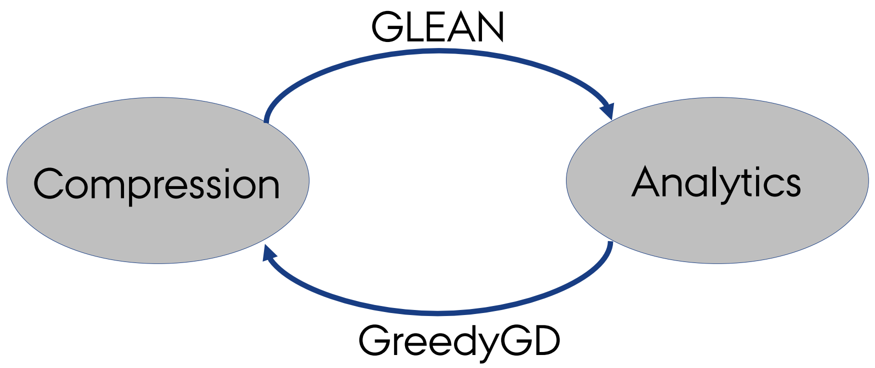
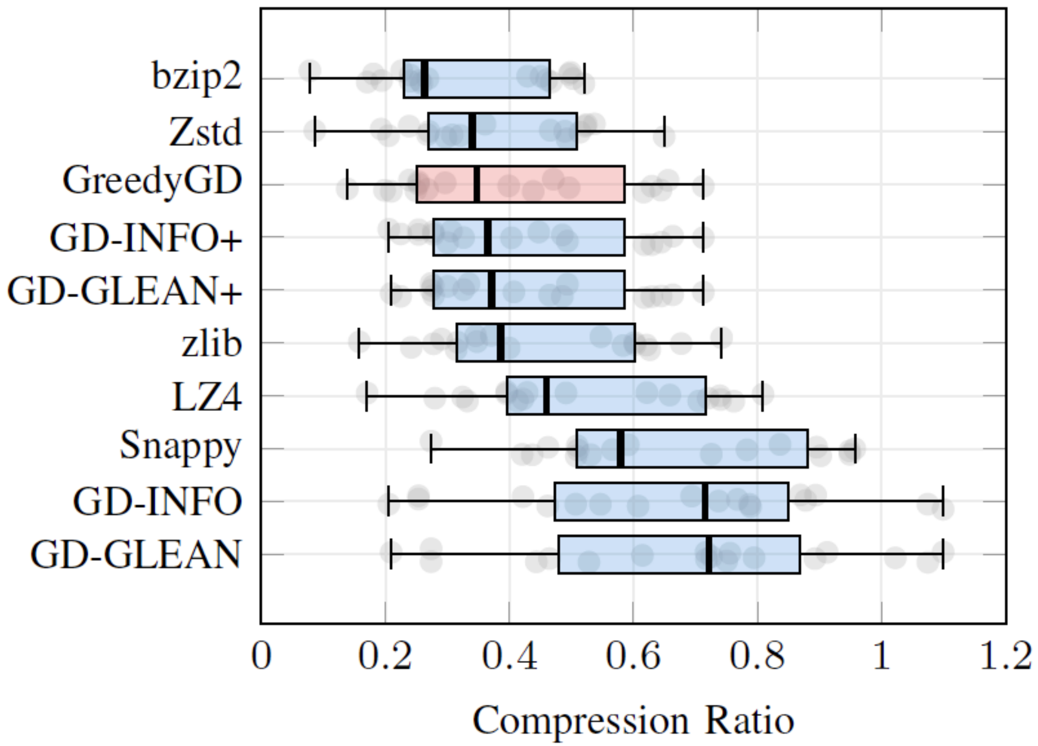
GREEDYGD

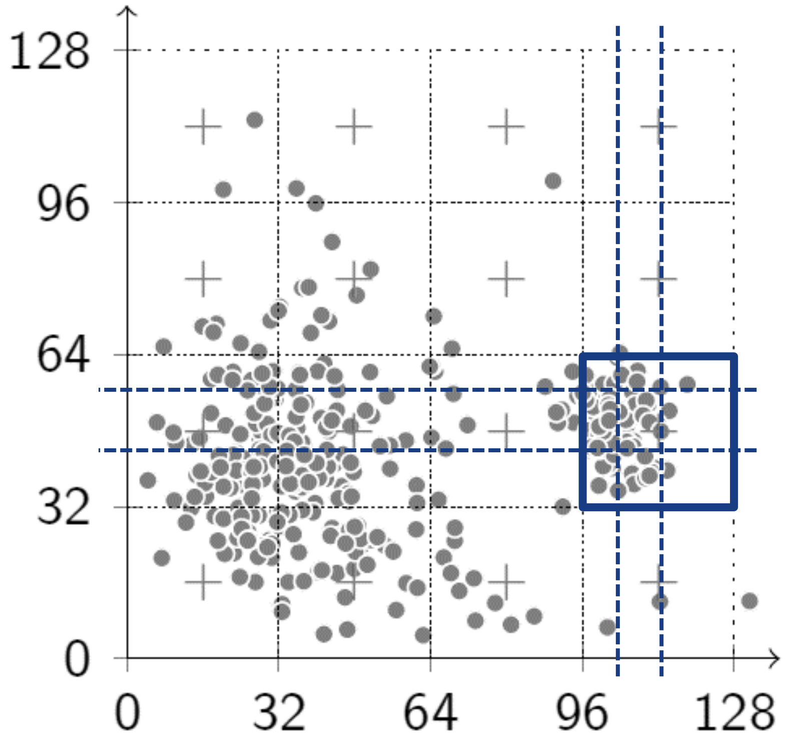
Dataset	Precision	n	d	Size (kB)
Aarhus weather [19]	single	26,387	4	422
Aarhus pollution #172156 [21]	single	17,568	5	351
Aarhus pollution #204273 [21]	single	17,568	5	351
Chicago beach water [22]	single	39,829	5	797
Chicago beach water (w/depth) [22]	single	10,034	6	241
Chicago beach weather (float) [23]	single	86,694	9	3,121
Chicago beach weather (integer) [23]	single	86,763	5	1,735
Chicago taxi trips [24]	double	3,466,498	10	277,320
CMU IMU (accelerometer) [25]	single	134,435	3	1,613
CMU IMU (angular velocity) [25]	single	134,435	3	1,613
CMU IMU (magnetometer) [25]	single	134,435	3	1,613
CMU IMU (position) [25]	single	134,435	4	2,151
CMU IMU (all) [25]	single	134,435	13	6,991
COMBED Mains power [26]	double	82,888	3	995
COMBED UPS power [26]	double	86,199	3	1,035
Melbourne city environment [27]	single	56,570	3	679
Gas turbine emissions [28]	single	36,733	11	1,616
Household power consumption [29]	single	2,049,280	7	57,380





APPROXIMATE QUERY PROCESSING

Compute additional metadata to support analytics: **multi-dimensional histograms**



Query median percentage error
(MEAN queries)

Query aggregated on column…

Query predicate on column…

	1	2	3	4	5	6	7
1	.08	.17	.00	.10	.67	.29	.76
2	.12	.21	.00	.14	.40	.27	.13
3	.27	.14	.00	.25	.99	.56	.32
4	.10	.05	.00	.02	.12	.06	.01
5	.04	.02	.00	.03	.00	.00	.00
6	.04	.06	.00	.05	.00	.00	.00
7	.06	.04	.00	.05	.00	.00	.00

Overall median error: **0.02%**
95^{th} percentile error: **0.54%**
Amount of data accessed: **2.3%**

50 X

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CONCLUSION AND OUTLOOK

- IoT has many challenges but also opportunities.

- A sustainable IoT system requires a holistic design in data- acquisition, compression, encryption, communication, storage and analytics.
  - To bridge Communication with Computing

- Opportunities
  - Time-critical IoT applications also needs joint design of communication and computing
  - It is worth looking into privacy-preserving analytics on compressed data

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THANK YOU

DANMARKS FRIE FORSKNINGSFOND

Innovation Fund Denmark

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