



**Distributed Cloud/Edge-AI  
for Connected Robotics**

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ELEKTRONIKU I TELEKOMUNIKACIJE**



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**ICONIC:** Centre for intelligent communications,  
networking and information processing

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Editor – IEEE Transactions on Communications

IEEE P.1955 standard – 6G connected robotics

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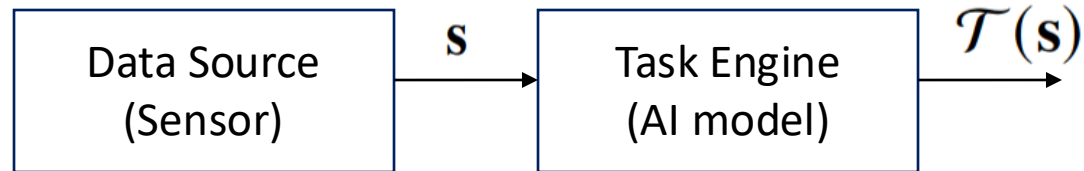
# **Outline of the Talk**

## **Edge/Cloud-AI and Task-Oriented Communications**

### **Task-Oriented Communications in 6G Connected Robotics**

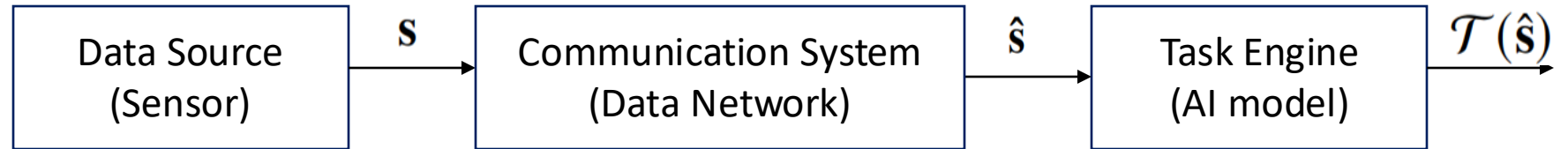
# Task-Oriented Communications

Data source and task engine collocated



Task engine trained to minimize task-specific expected loss function

Data source and task engine separated



Traditional Shannon-theory communications

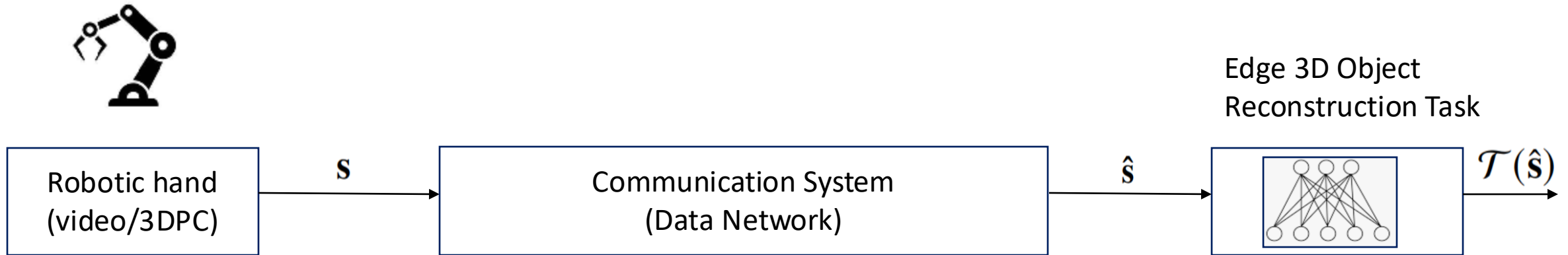
Design Communication System with the goal of  $\hat{\mathbf{s}}$  being equal to  $\mathbf{s}$

Task-oriented (goal-oriented) communications

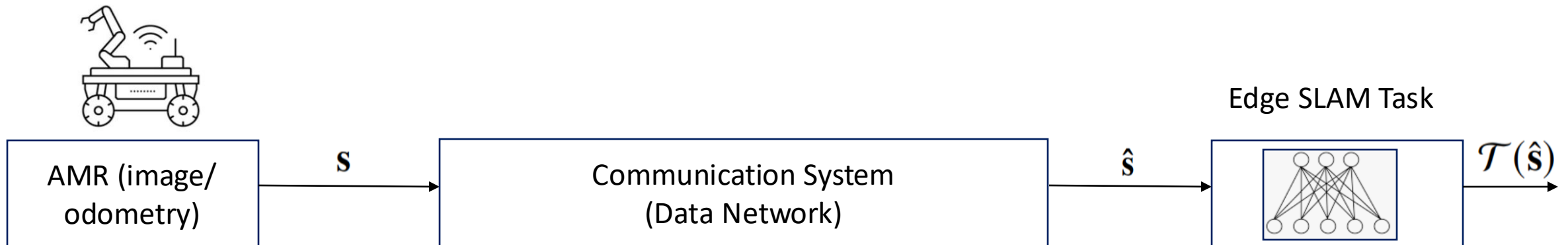
Design Communication System with the goal of  $\mathcal{T}(\hat{\mathbf{s}})$  being equal to  $\mathcal{T}(\mathbf{s})$

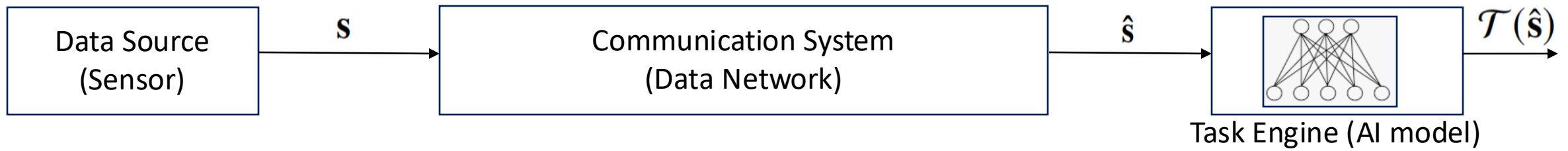
# Task-Oriented Communications in Robotics

## Example 1 (static): Robotic Working Cell



## Example 2 (mobile): Edge SLAM





**Traditional Approach:** Transmit raw sensor data to the edge/cloud

**Problem:** The amount of data easily saturates uplink connection, data transfer delay could be prohibitively high. Motivates relocation of AI models from cloud to edge.

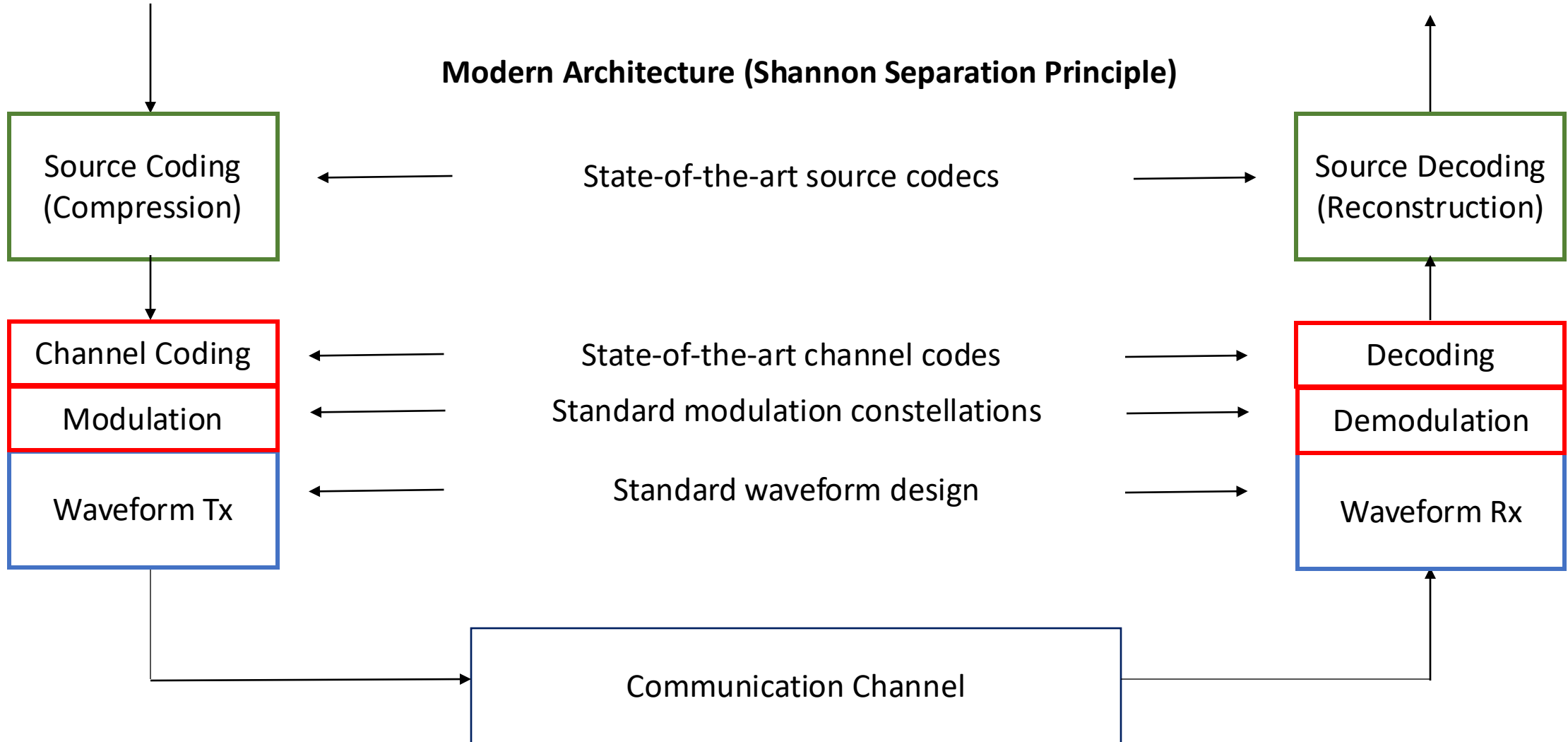
**Potential Traditional Relaxation:** Compress and transmit

**Problem:** Reduces the amount of data to be transmitted and consequently the data transfer delay. Introduces compression/reconstruction delay and processing costs.

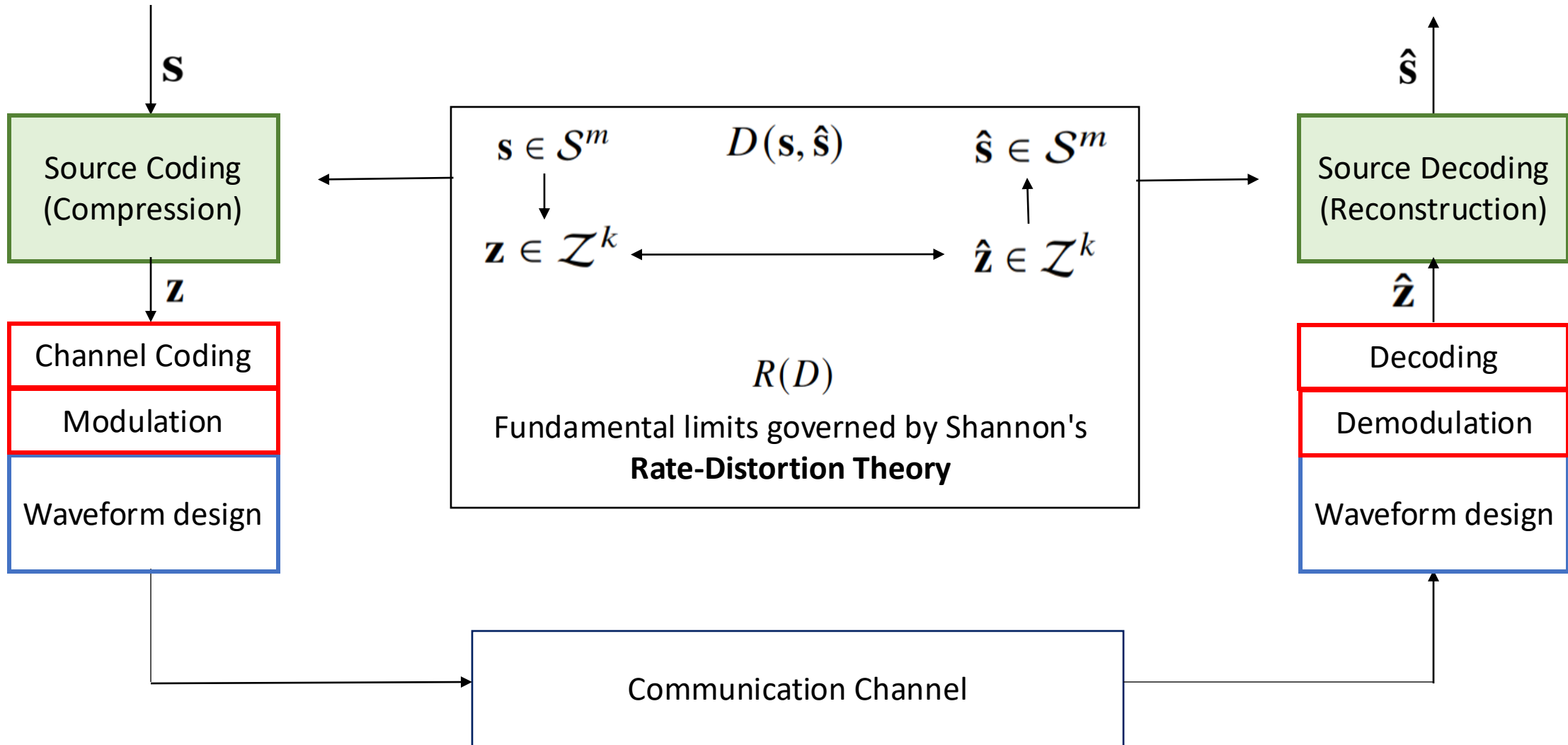
**Overall Goal:** Replicate source data at the receiver side (Shannon technical communication problem) potentially trading-off rate vs distortion (compression). Note that compression might affect AI model (task) performance.

**Traditional Approach:** How does it work?

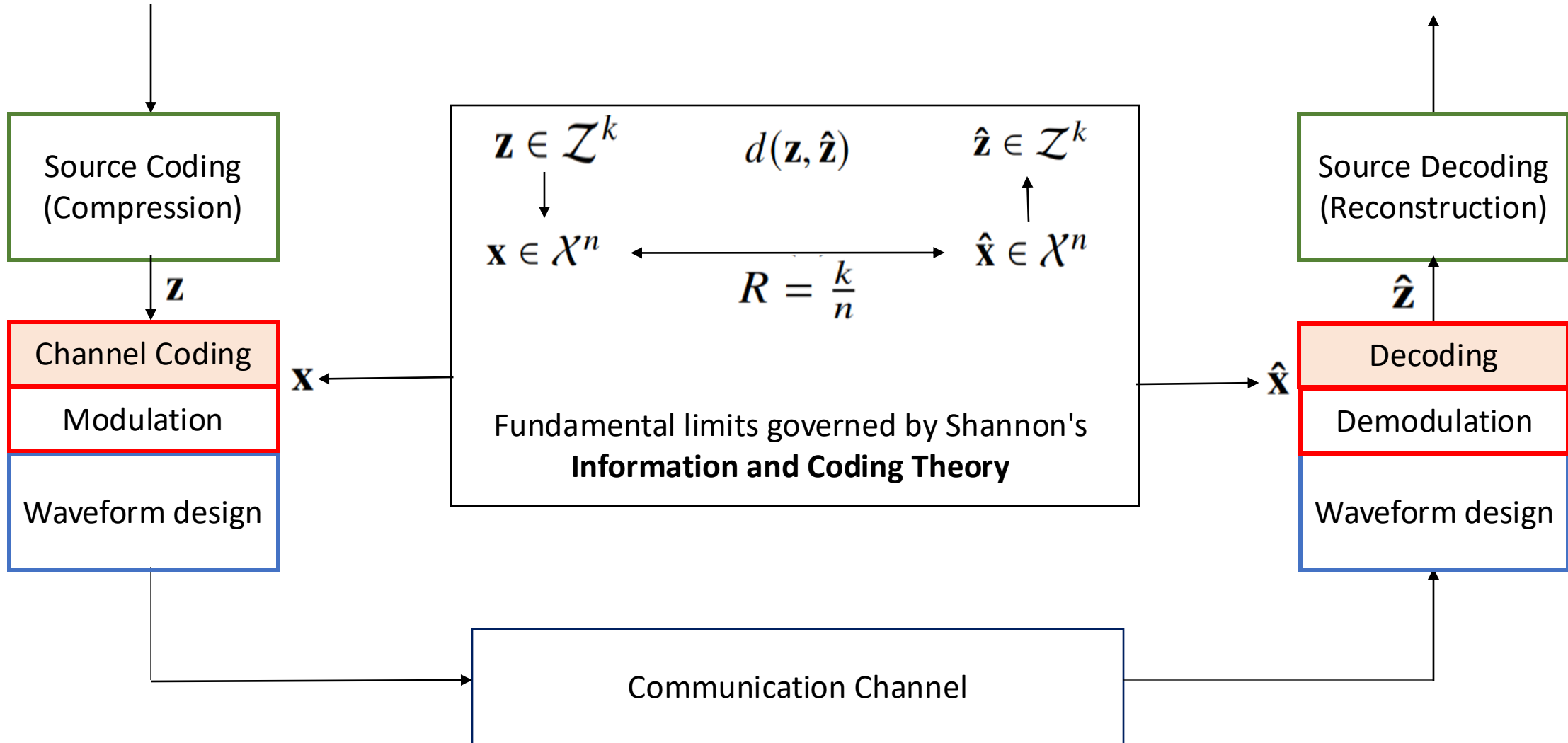
# Traditional (Shannon) Approach



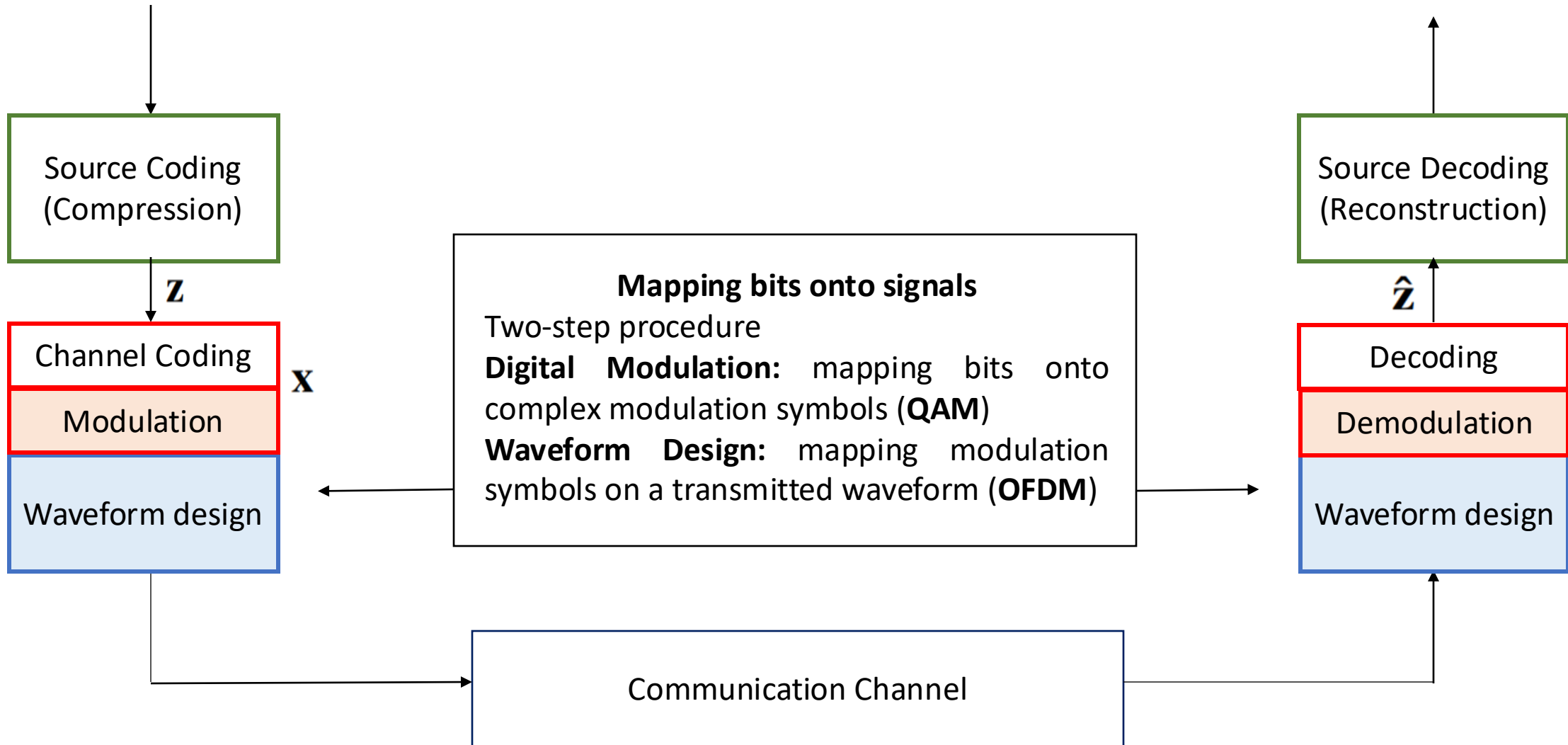
# Solving Classical Shannon Technical Problem

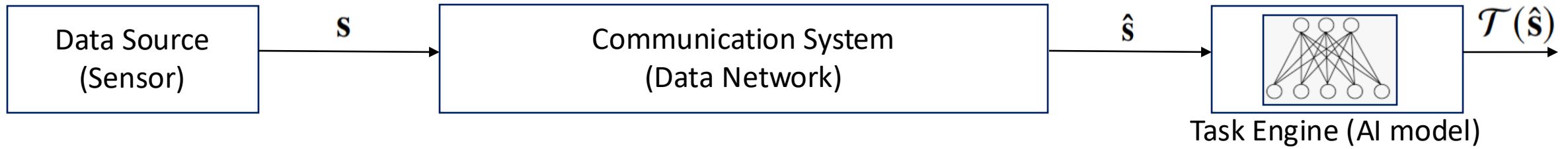


# Solving Classical Shannon Technical Problem



# Solving Classical Shannon Technical Problem





## Task Engine (AI Model)

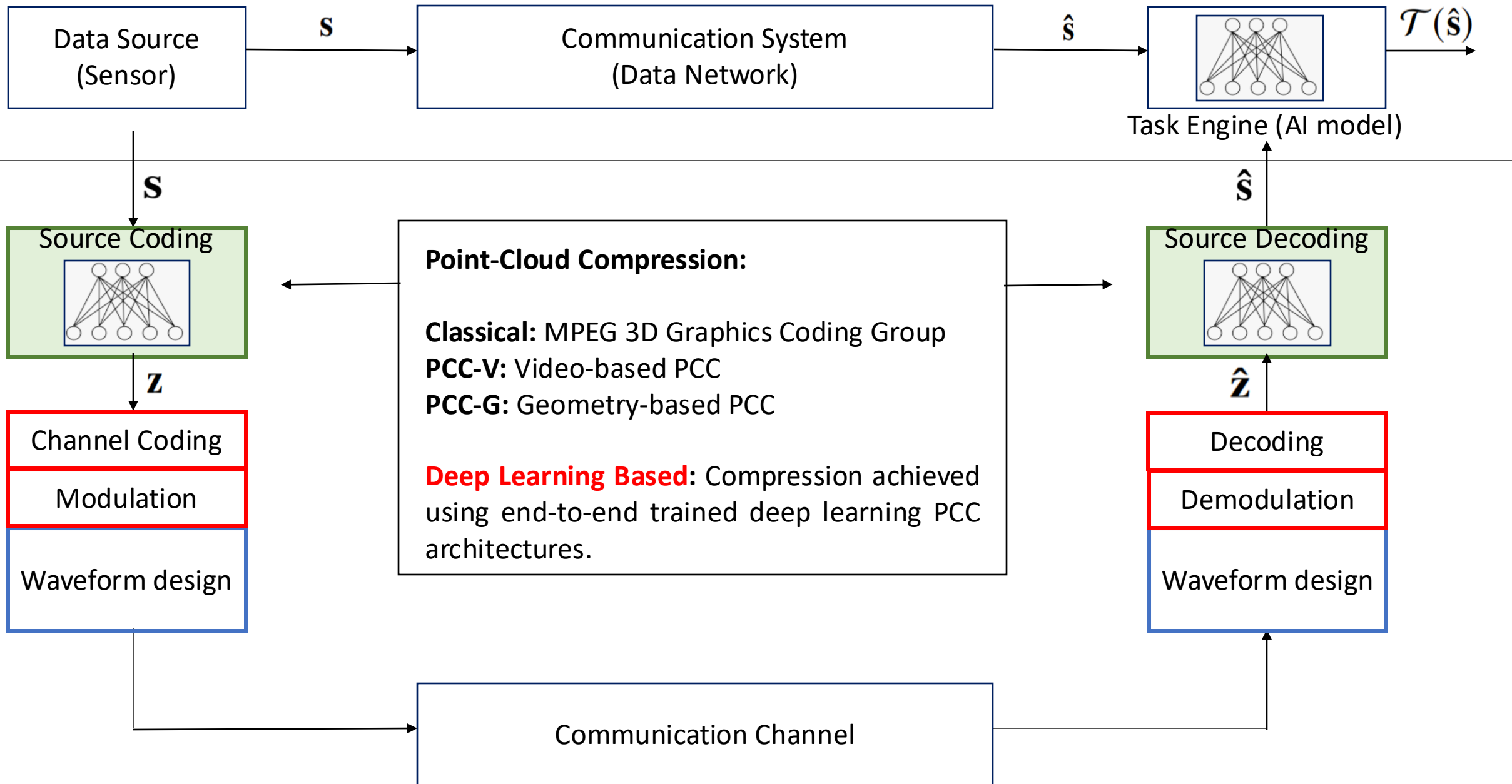
- Based on modern deep learning architectures

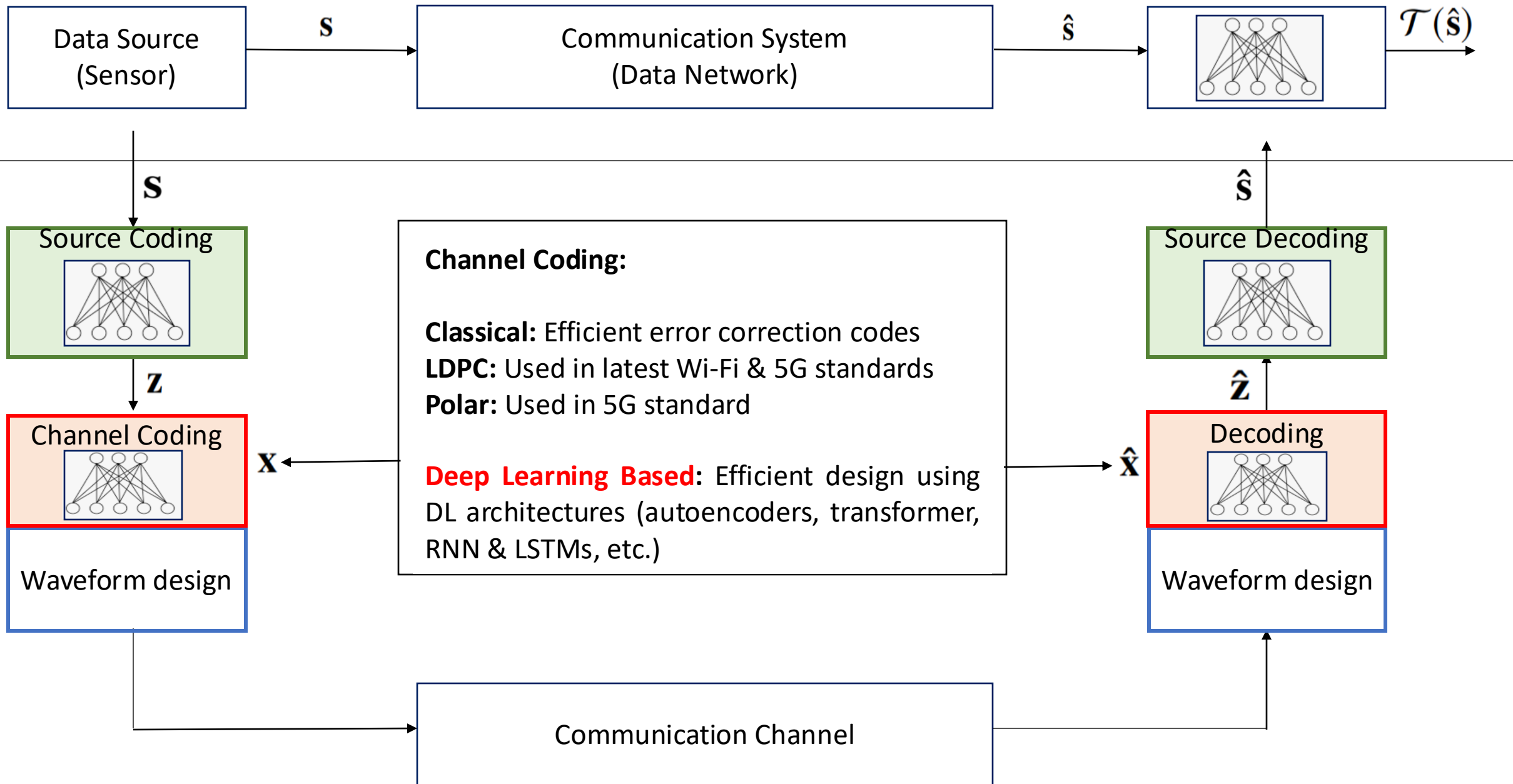
## Traditional Shannon Communication System Approach

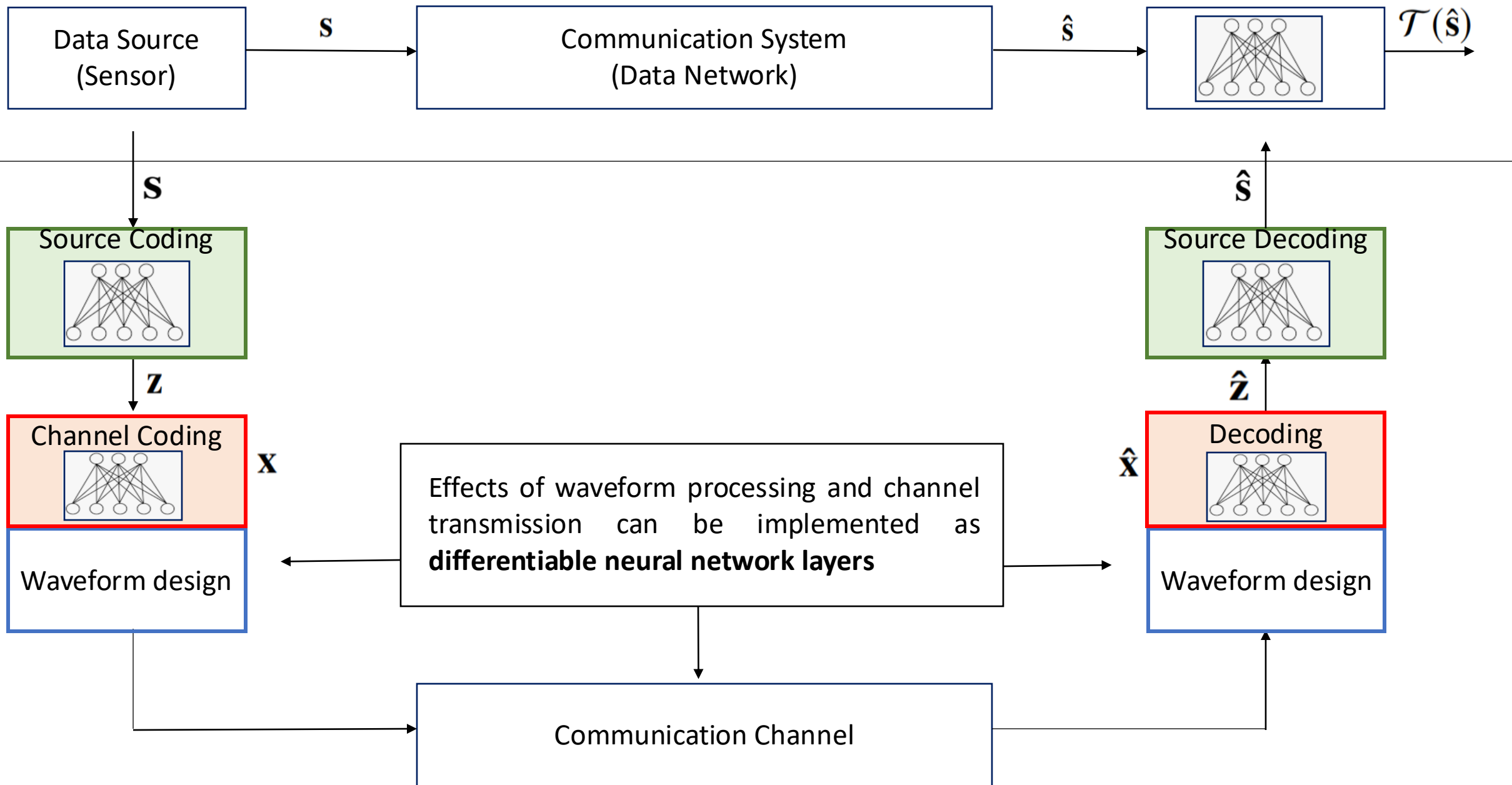
- Based on classical model-based signal processing and optimization methods
- Represents current state of the art
- Supported by established theoretical results (information theory, signal processing)

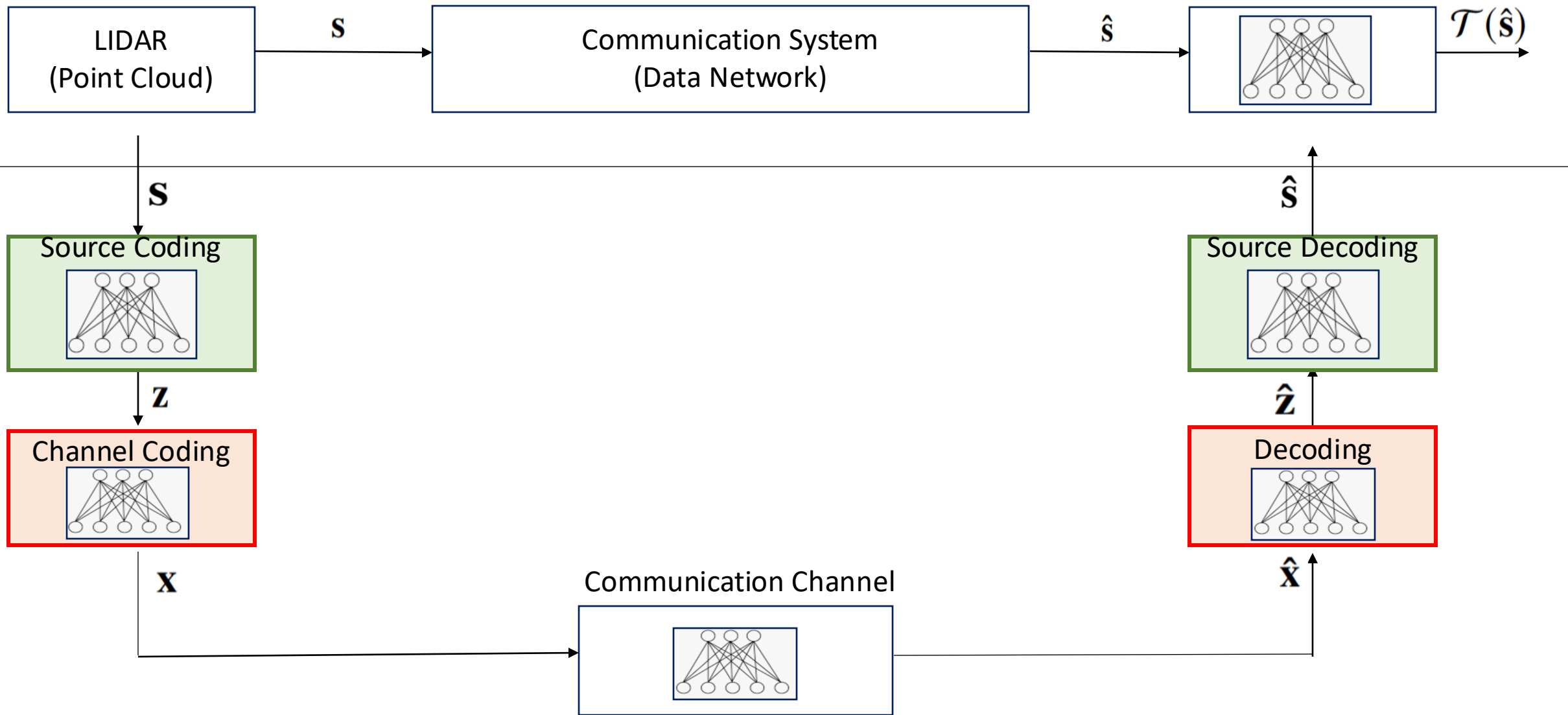
## Modern AI-Based Communication System Approach

- Replaces model-based system design with data-based deep learning models
- Achieves state-of-the-art performance across communication system blocks
- **Transforms data transmission/processing pipeline into an end-to-end AI model**

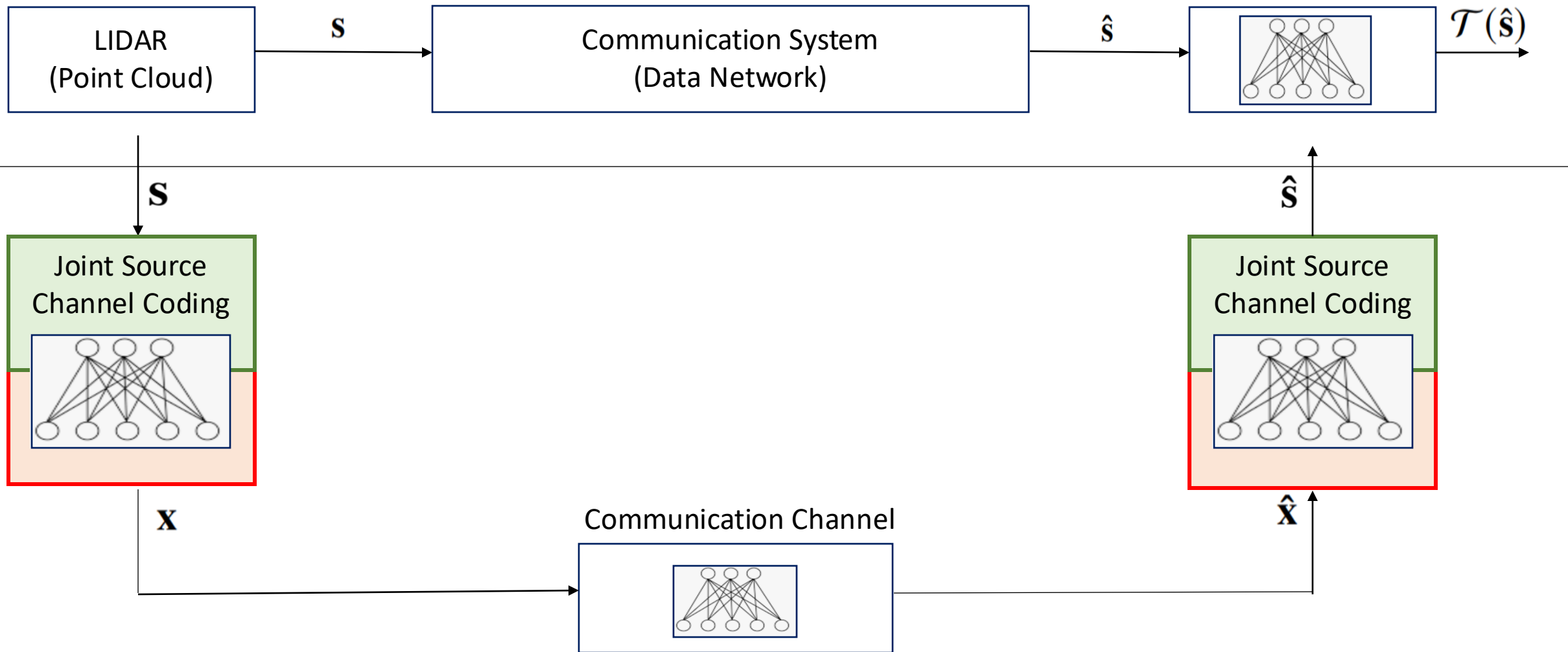






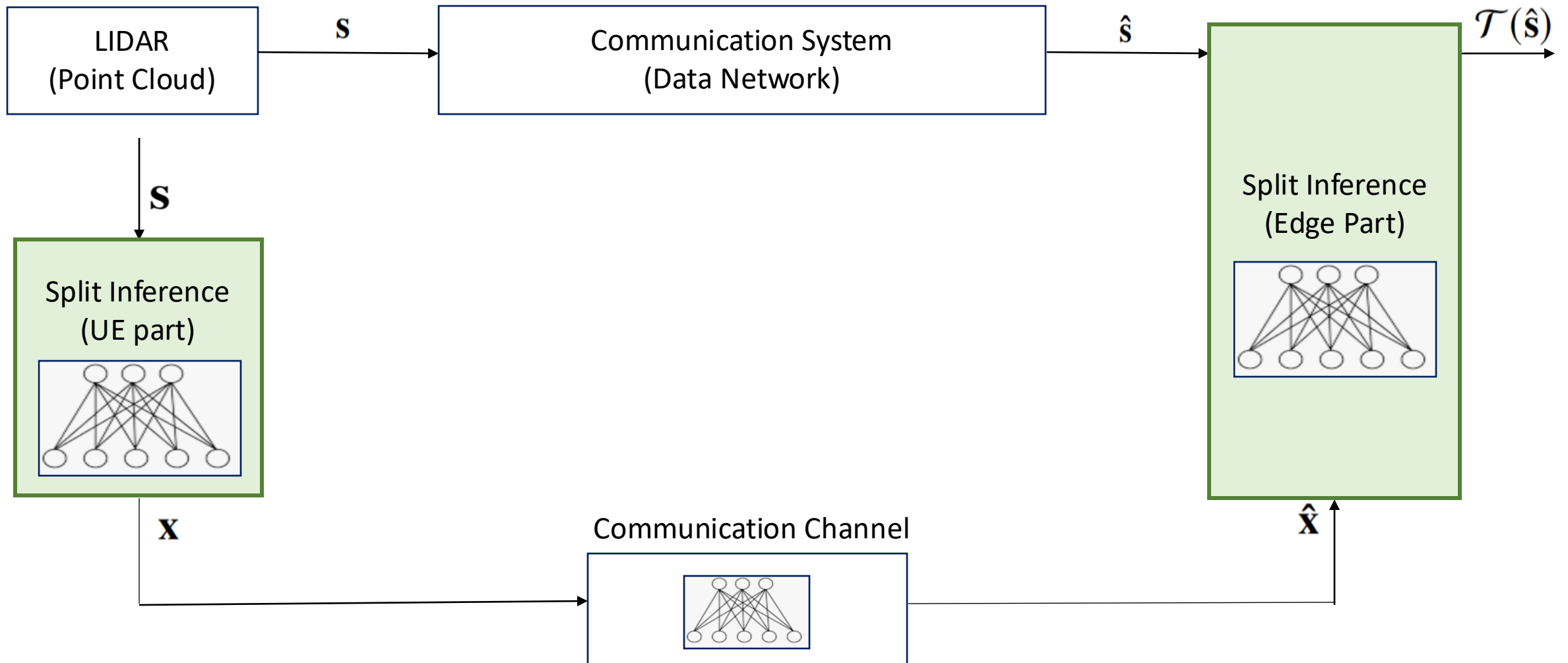


**The whole communication and edge-AI setup is an end-to-end neural network**  
Can we learn it through appropriate architecture design and end-to-end training?

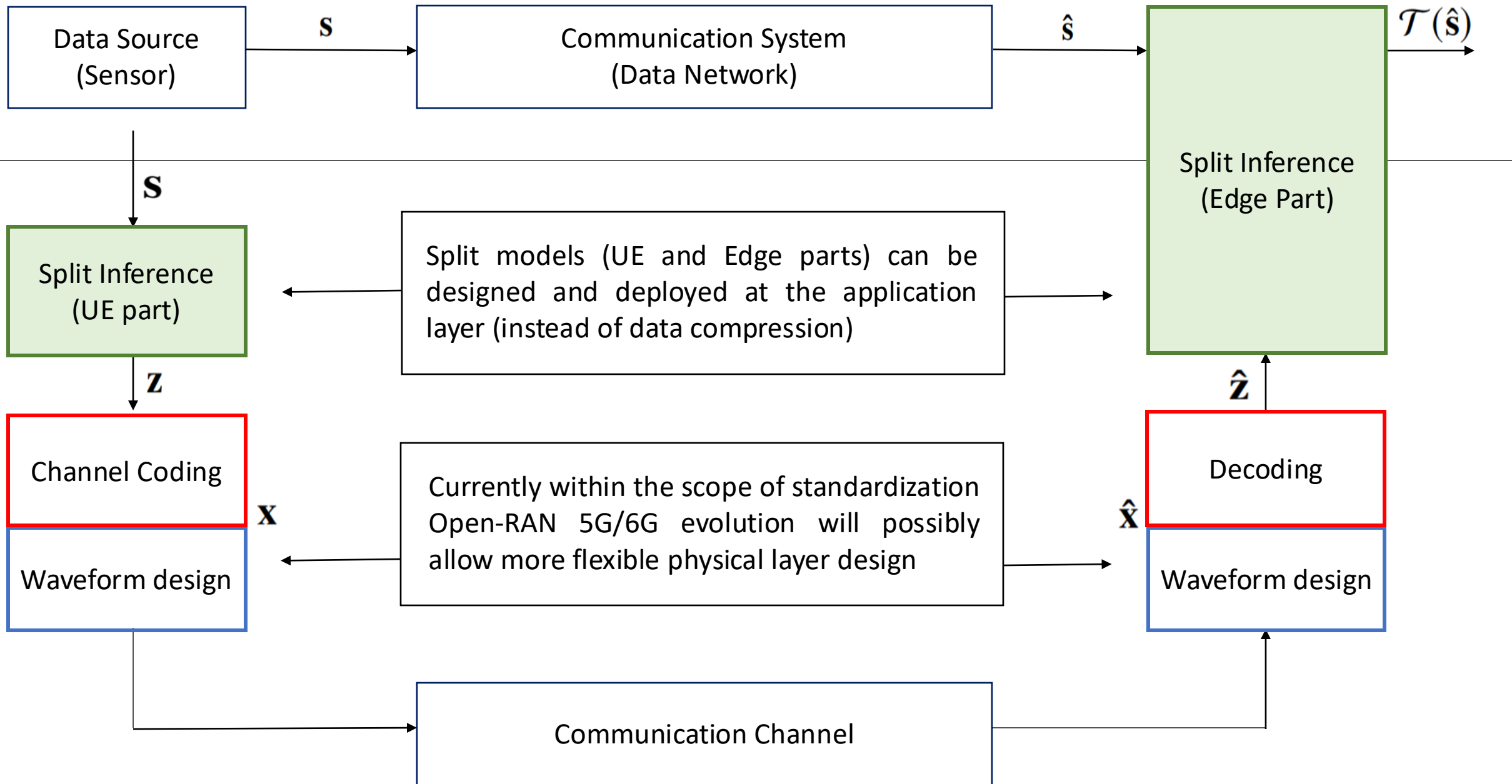


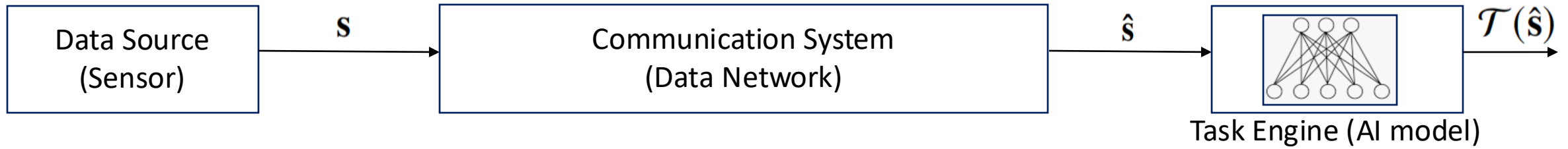
**Deep Joint Source-Channel Coding (DJSCC) demonstrates improved performance**

However, DJSCC still aims to replicate the source message at the receiver



**Deep Learning models could be end-to-end trained and split into UE and Edge parts**  
The source message is converted in semantic representation and never reconstructed





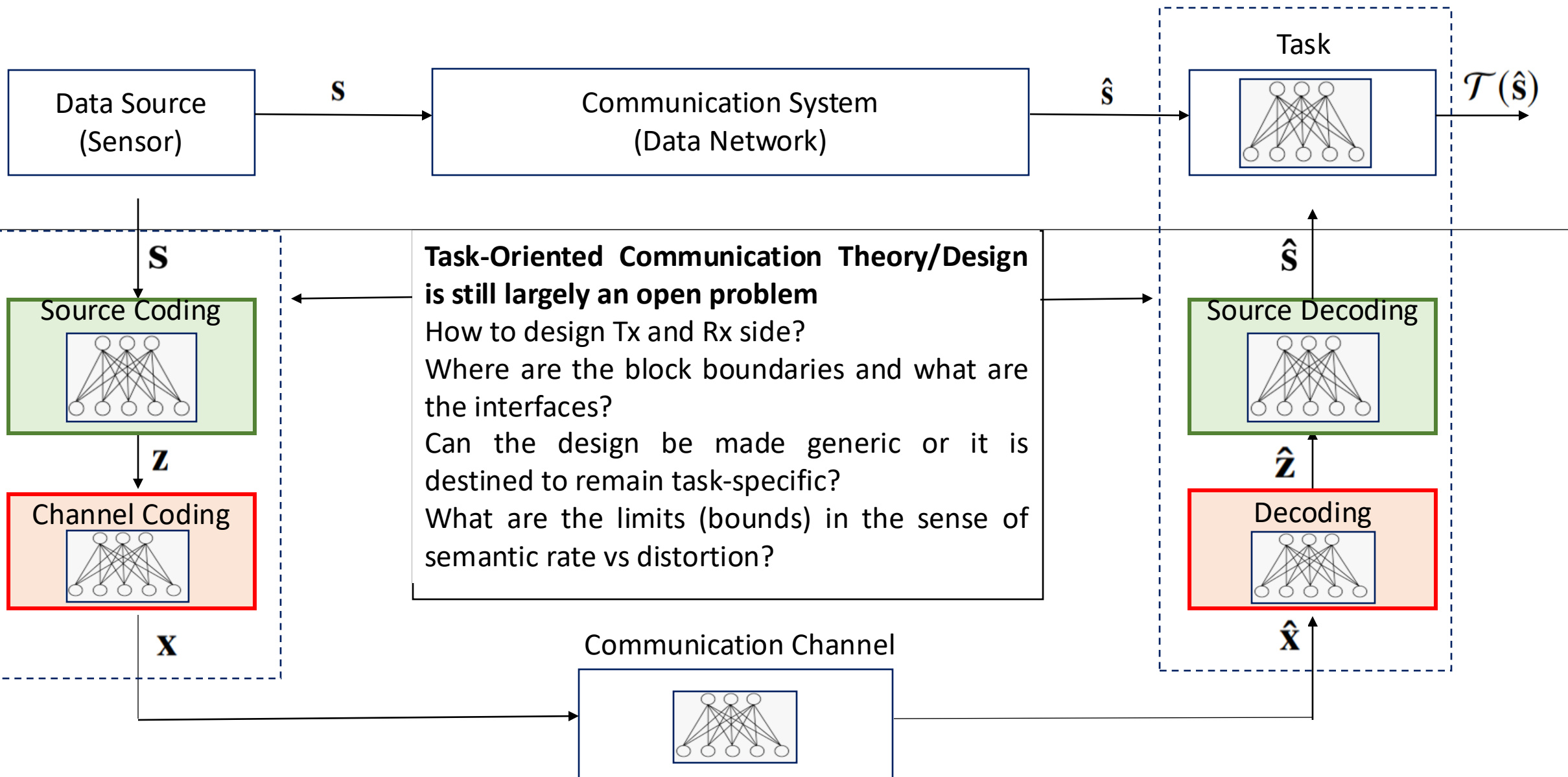
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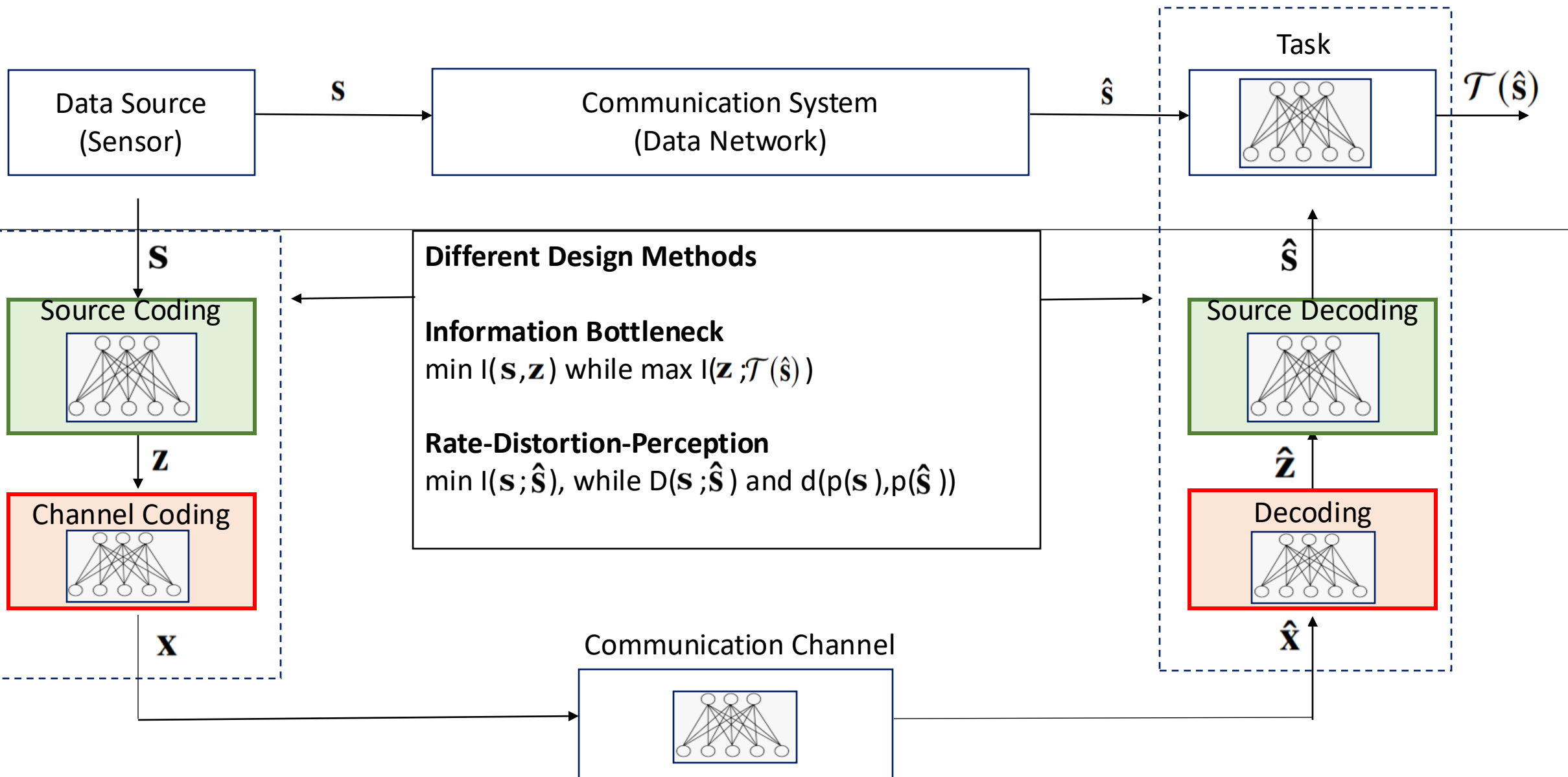
## Summary of the Problem

**Key Question:** How to represent source information  $s$  efficiently in order to achieve the same (or as close) task performance on remotely received data  $\hat{s}$  as it would be achieved if the task is executed on the original data?

**Question?** Is attempting to replicate source data at the receiver side (Shannon technical communication problem) a good strategy?

**Comment:** Efficient source data semantic representations could be task-dependent!





# **Outline of the Talk**

Task-Oriented Communications: High-Level Introduction

**Task-Oriented Communications in 6G Connected Robotics**

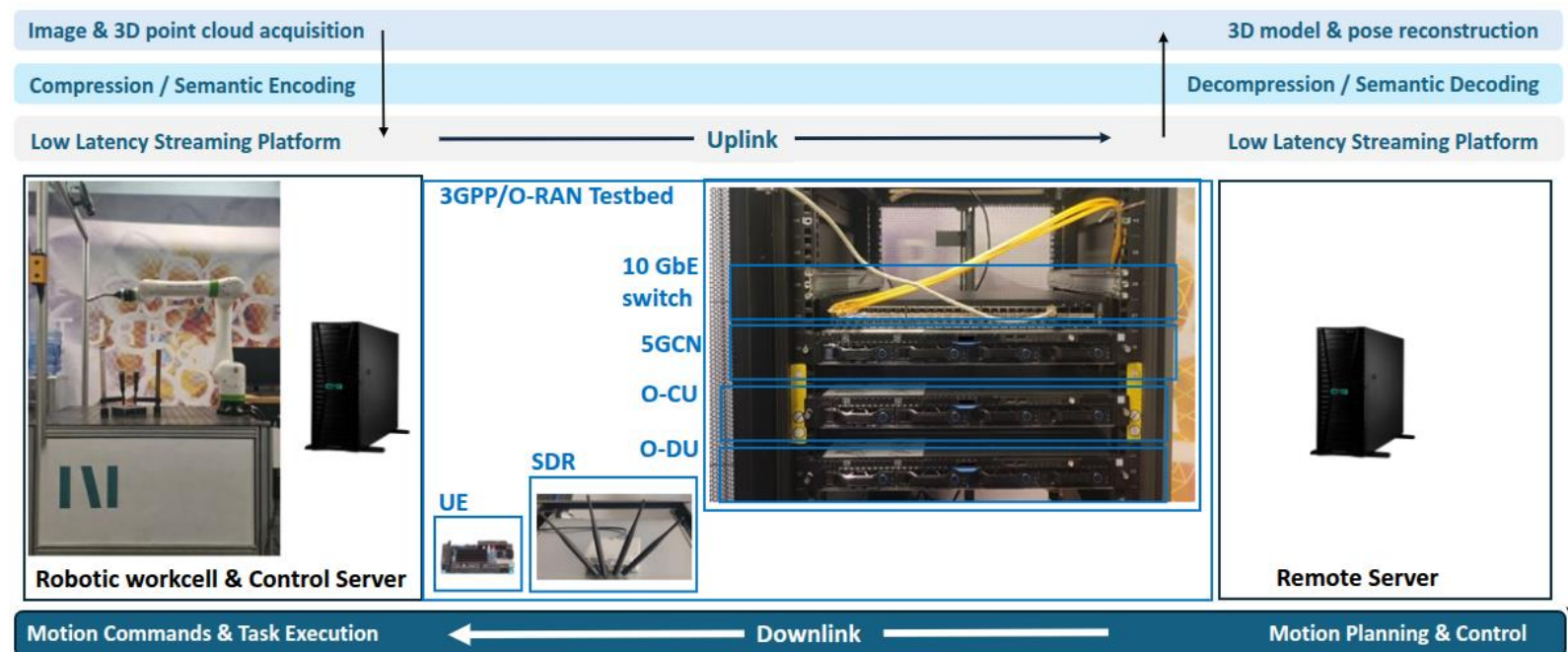
# Connected Robotic Workcell

## Hardware and Sensors

- Robotic hand (Fanuc CRX 10)
- Camera: 3D point cloud + stereo RGB image

## Edge AI

- AI model: 3D object and pose reconstruction
- Motion planning & control



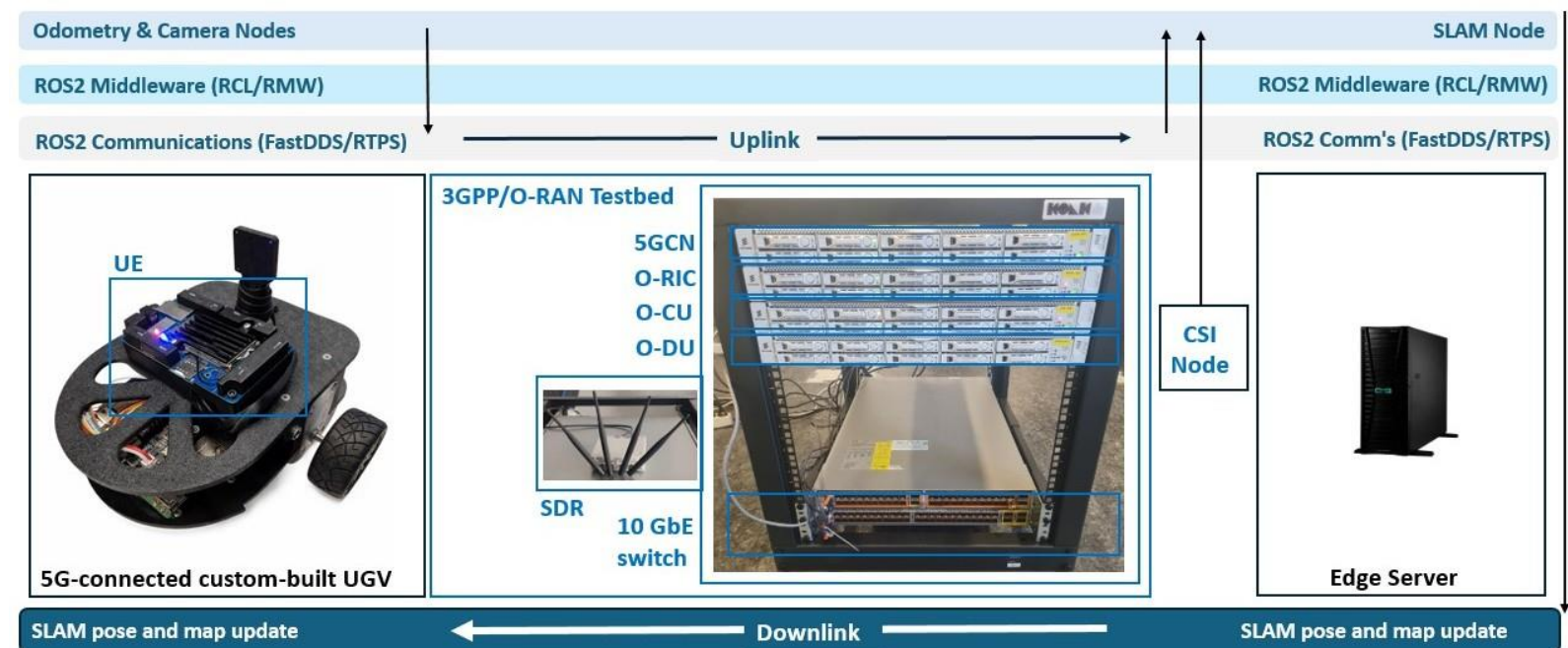
# Connected Edge SLAM

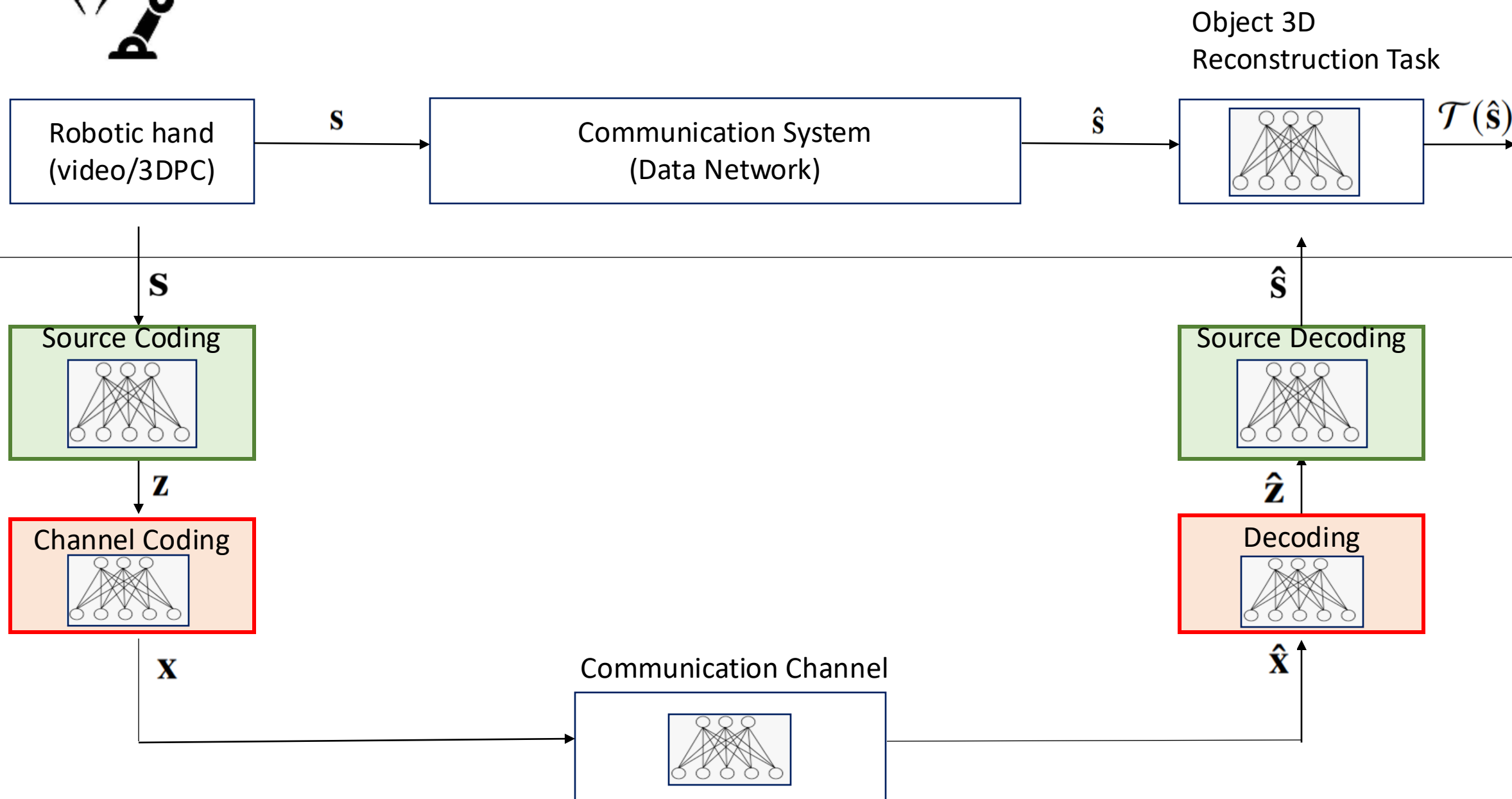
## Hardware and Sensors

- UGV platform
- Wheel odometry, lidar, camera, **CSI data**

## Edge AI

- Edge model: Factor Graph SLAM running Gaussian BP





**Data Source:**  
3D point cloud +  
stereo RGB image

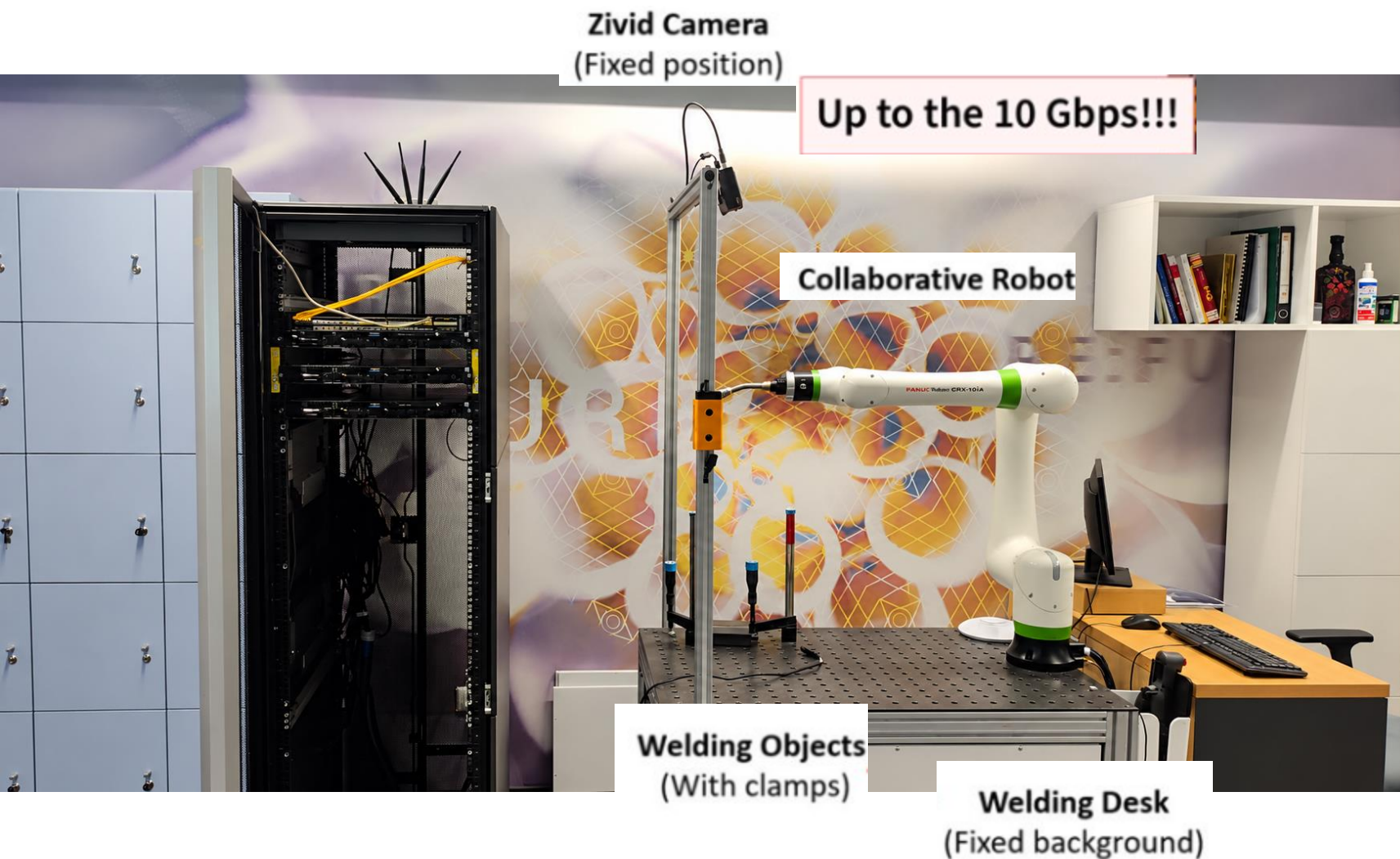
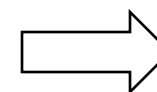
$S$

Communication System  
(Data Network)

$\hat{S}$

**Task:** Accurate 3D  
pose reconstruction of  
the relevant object

$\mathcal{T}(\hat{S})$



**Data Source:**  
3D point cloud +  
stereo RGB image

$S$

Communication System  
(Data Network)

$\hat{S}$

**Task:** Accurate 3D  
pose reconstruction of  
the relevant object

$\mathcal{T}(\hat{S})$

Stereo Image & 3DPC acquisition

3D model & pose reconstruction

Compression / Semantic Encoder

Decompression / Semantic Decoder

Streaming Platform & Transport

Streaming Platform & Transport

Uplink



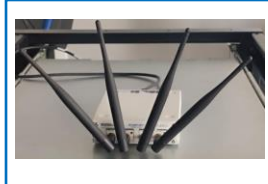
Robotic workcell & Control Server

3GPP/O-RAN Testbed

UE



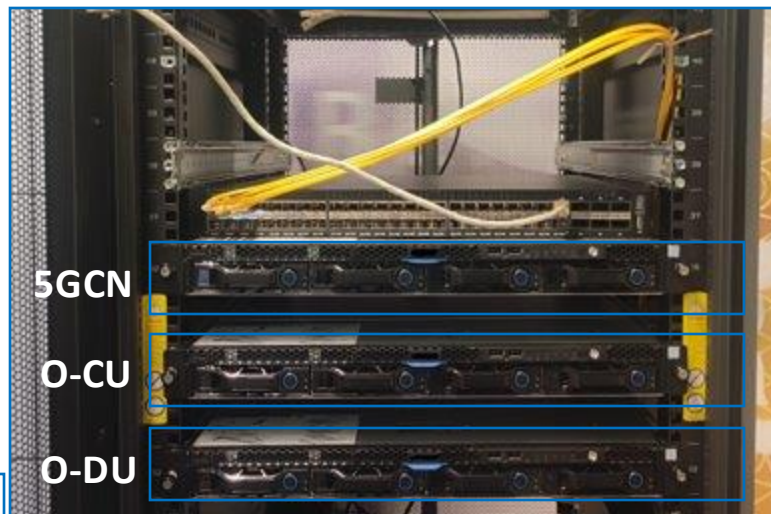
SDR



5GCN

O-CU

O-DU



Remote Server

Downlink

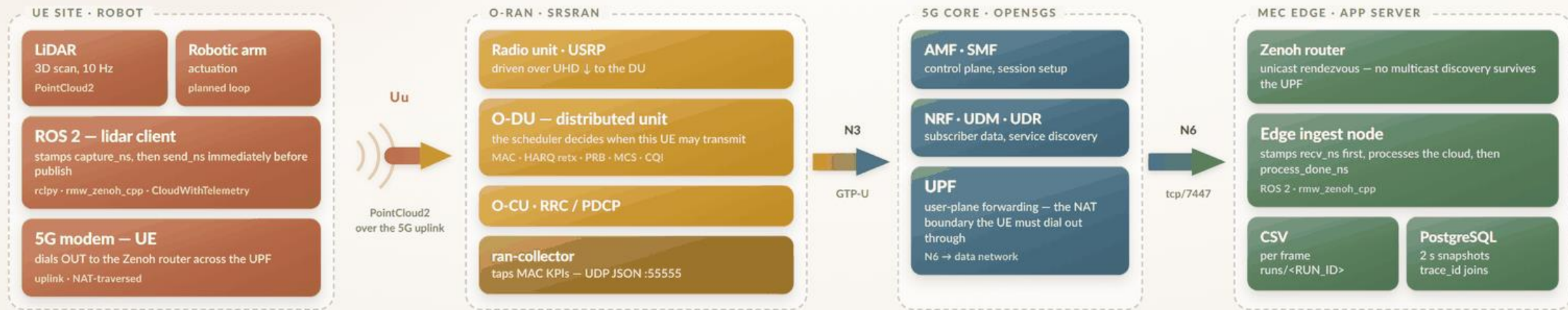
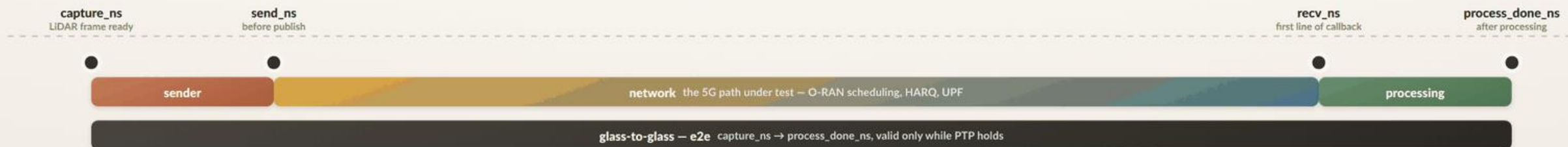
Motion Commands & Task Execution

Motion Planning & Control

# mec-cast

industrial communication testbed on private 5G — sensor → O-RAN → UPF → MEC

UE site O-RAN 5G core MEC edge



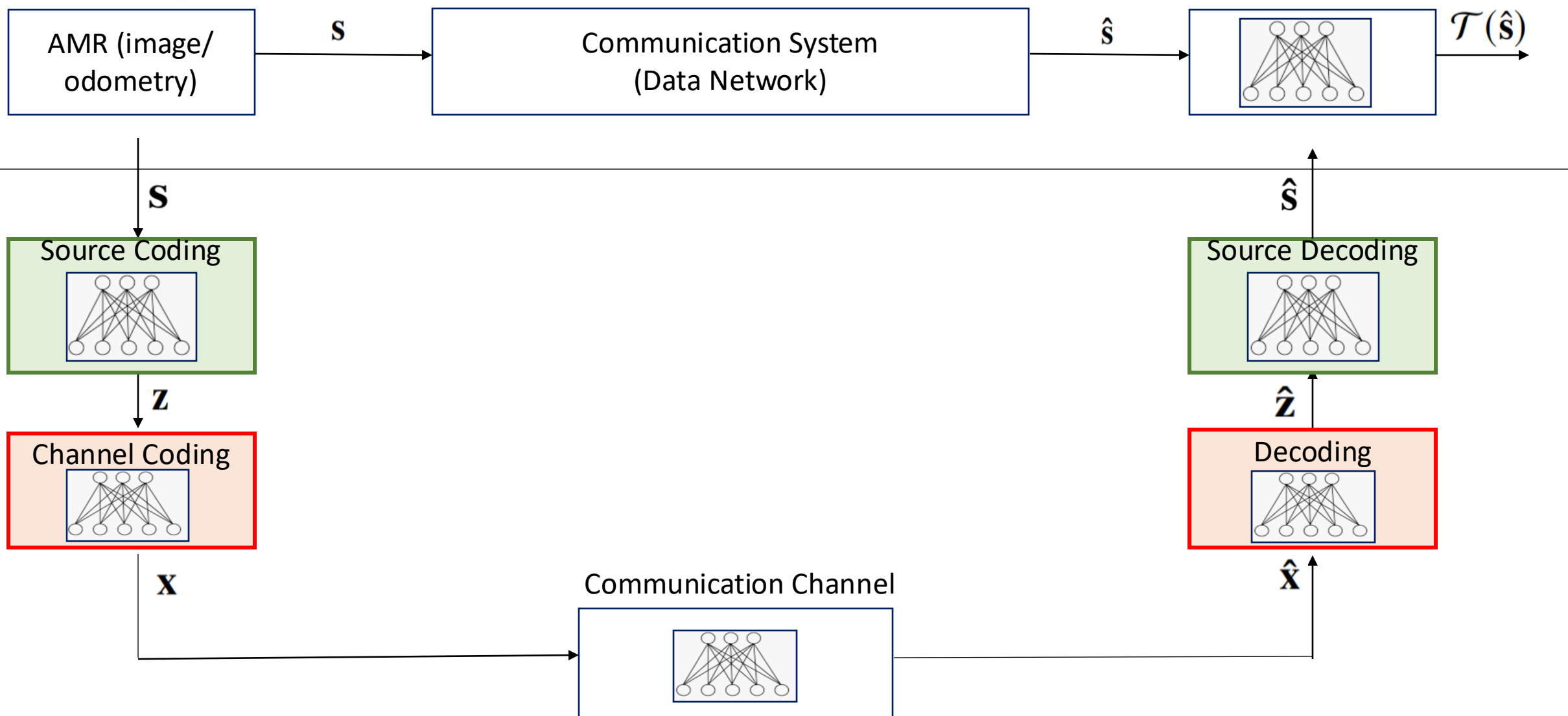
**mec-cast-telemetry**  
SHARED MEASUREMENT PLANE

**PTP · ptp4l + phc2sys**  
management LAN, never the user plane — srsRAN and Open5GS carry no 5G-TSN

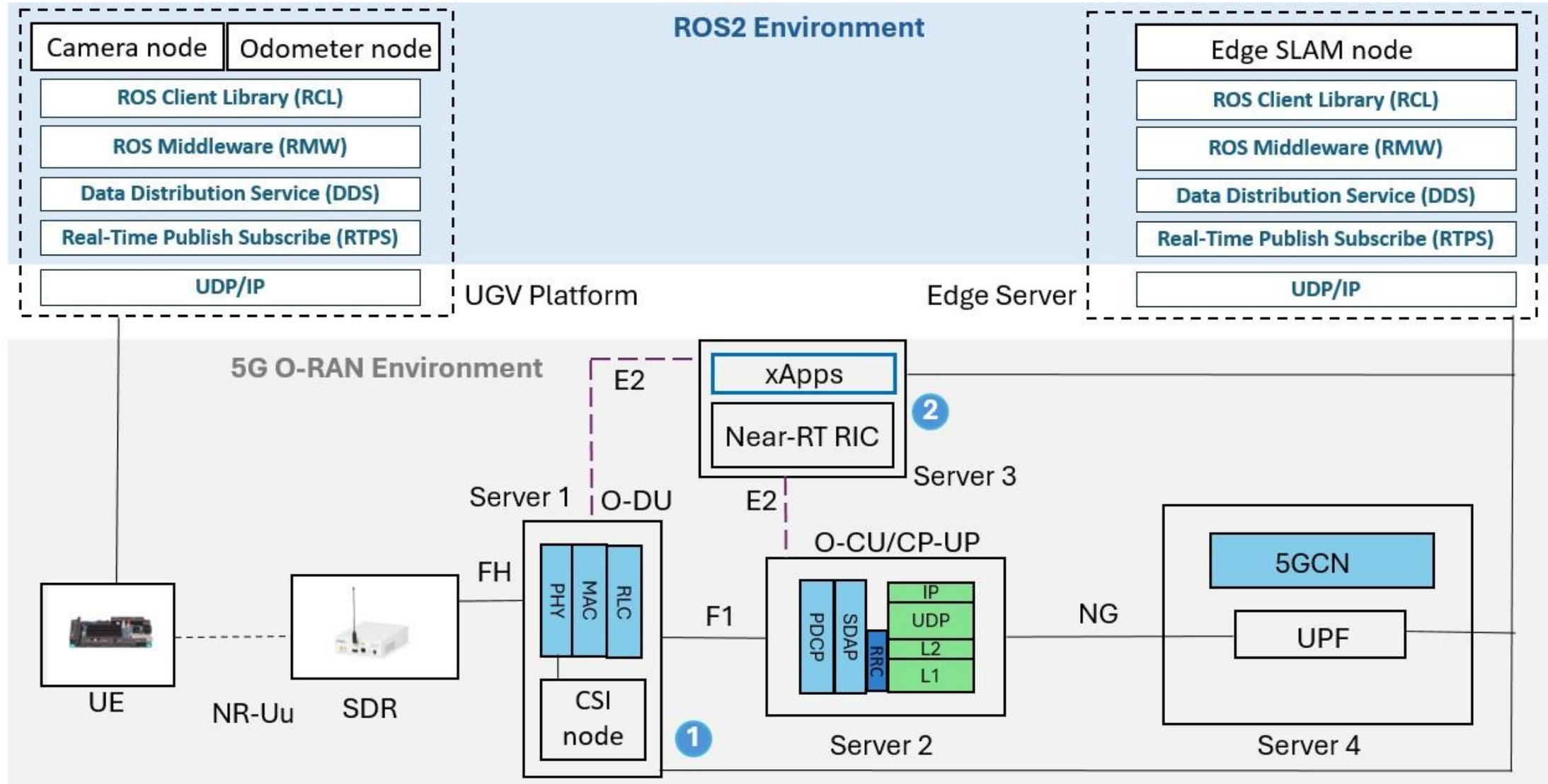
**TimingEnvelope · 64 B**  
`capture_ns · send_ns · recv_ns · process_done_ns · seq · trace_id`

**network = recv - send**  
`e2e = done - capture · Welford + exact windowed percentiles`

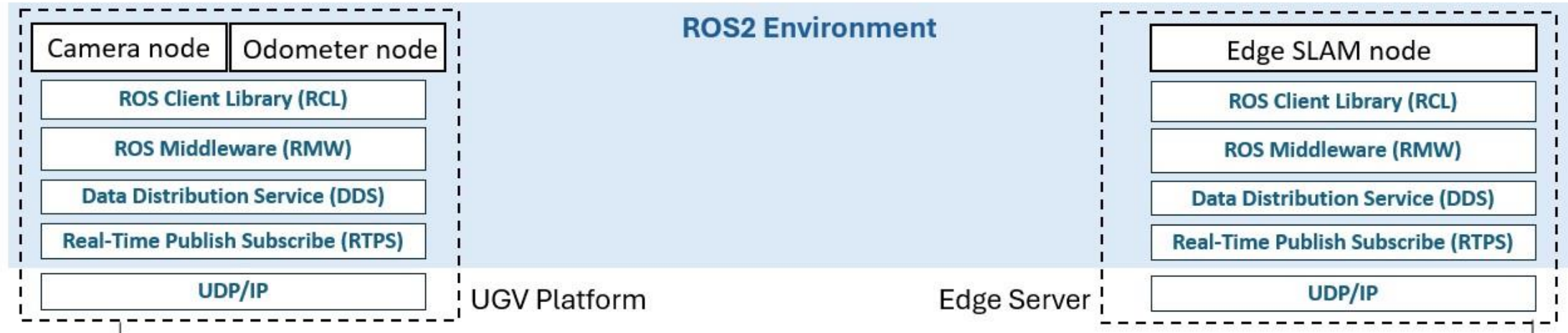
**one RUN\_ID**  
joins UE samples, O-DU KPIs and edge samples in a single query



# 5G Edge Connected SLAM



# 5G Edge Connected SLAM



**ROS2 Environment:** Consists of inter-connected ROS2 nodes that exchange data

## UGV platform

**Camera Node:** Periodically generates and publishes camera image

**Odometry Node:** Periodically generates and publishes wheel odometry

**CSI Exposure Node: ?**

## Edge Server

**Edge SLAM Node:** Collects messages from sensor nodes, preprocess them, extract SLAM-relevant information, runs SLAM algorithm (pose estimation of UGV and relevant map features)

## ROS2 Data Distribution Service

Built-in ROS2 data distribution service (DDS) solution. Many different realizations (FastDDS). Optimize for 5G?

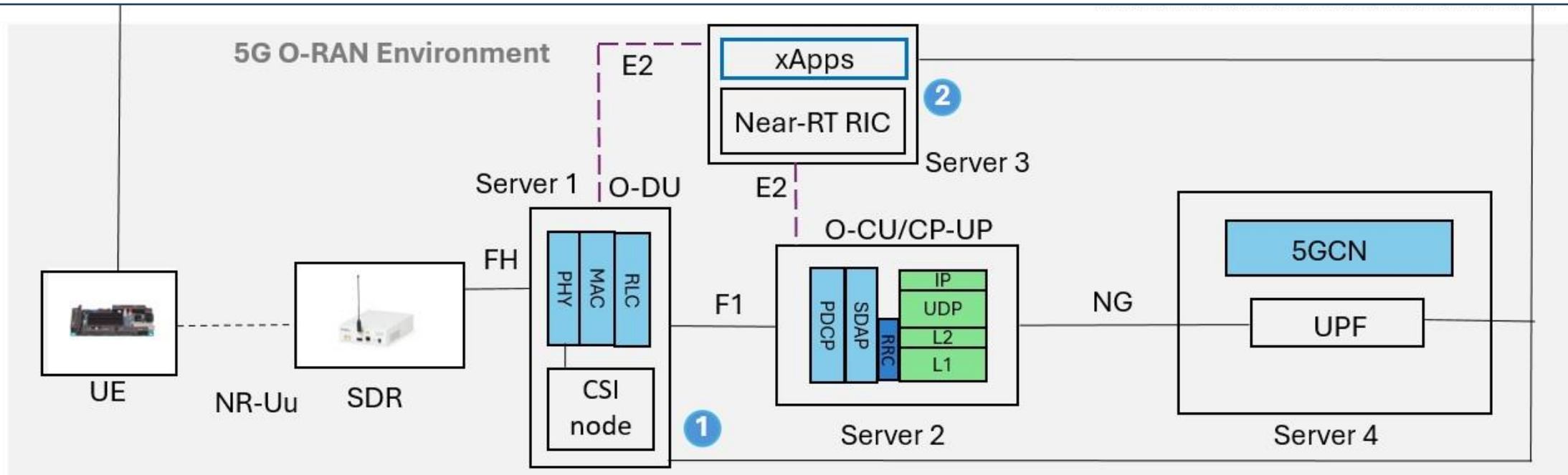
# 5G Edge Connected SLAM

**5G O-RAN Environment:** 3GPP/O-RAN compliant lab testbed

**Setup:** High-performance servers running 3GPP/O-RAN compliant implementations of O-CU/O-DU, O-RAN RICs and 5G core network.

**Edge AI Services:** Deployed at Edge AI servers connected to 5GCN.

**USRP Radios:** B210 (20 MHz) and X300 (100 MHz).



Odometry & Camera Nodes

ROS2 Middleware (RCL/RMW)

ROS2 Communications (FastDDS/RTSPS)

SLAM Node

ROS2 Middleware (RCL/RMW)

ROS2 Comm's (FastDDS/RTSPS)

Uplink

UE



5G-connected custom-built UGV

3GPP/O-RAN Testbed

5GCN  
O-RIC  
O-CU  
O-DU



SDR

10 GbE  
switch



CSI  
Node



Edge Server

SLAM pose and map update

Downlink

SLAM pose and map update

# How to Split Processing between UGV & Edge Server?



Tag detection,  
identification and  
ROI extraction



+ Tag ID

Keypoint  
extraction

Keypoints

Pose  
estimation

Pose

SLAM

ROS2 Middleware (RCL/RMW)

ROS2 Middleware (RCL/RMW)

ROS2 Communications (FastDDS/RTSPS)

ROS2 Communications (FastDDS/RTSPS)

Uplink

3GPP/O-RAN Testbed

5GCN  
O-RIC  
O-CU  
O-DU

UE

SDR



Remote Server

Downlink

5G custom-built UGV

SLAM Pose & Map Update

SLAM Pose & Map Output

# How to integrate CSI to SLAM?

**SLAM Algorithms:** Modern SLAM methods are derivatives of Kalman filtering

**Prediction Step:** Based on the motion model and odometry data. Can CSI help?

Can CSI data serve as a cheap odometer?

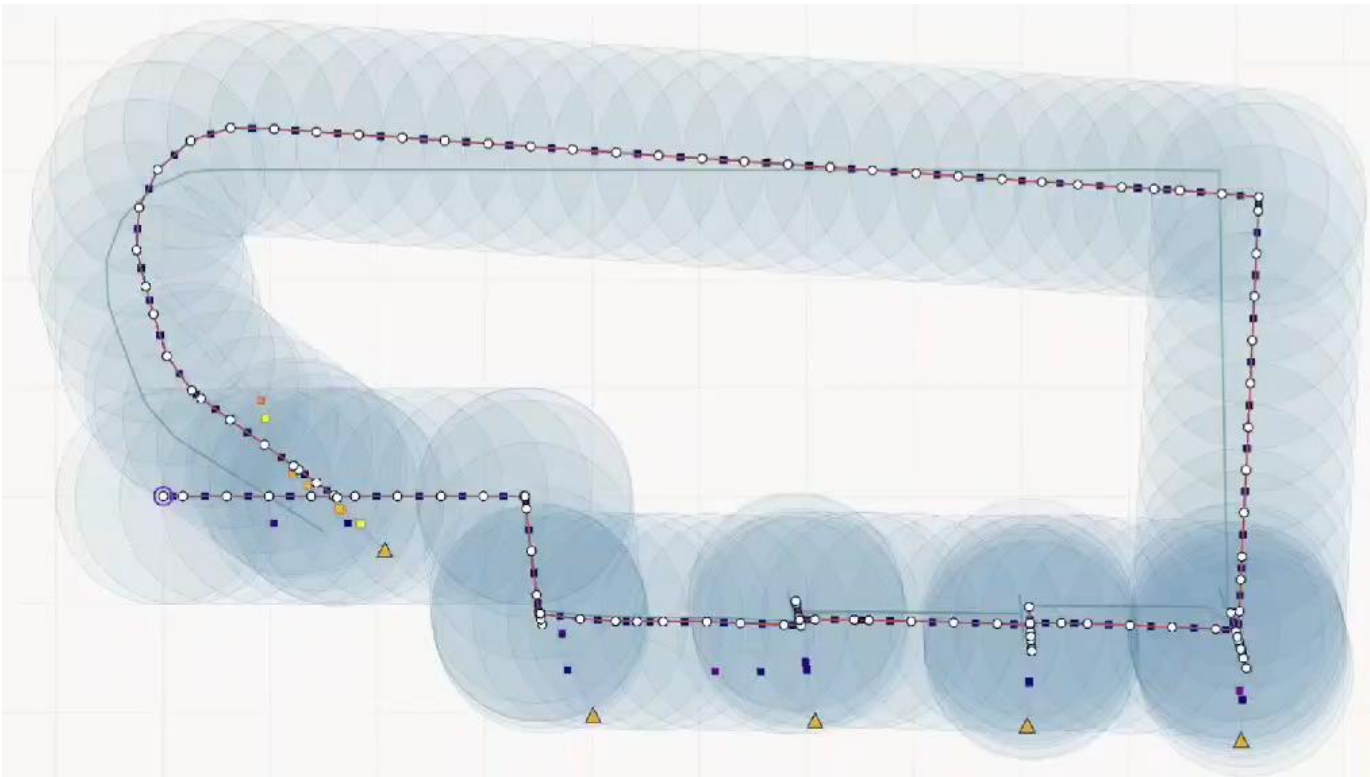
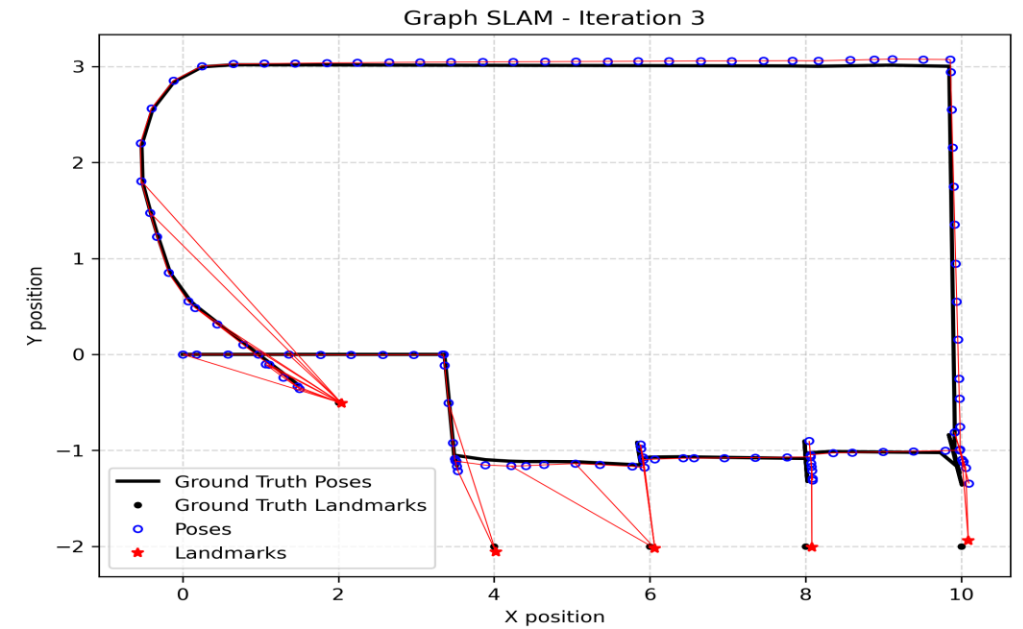
**Correction Step:** Based on observation model. Can CSI provide distance estimate from map anchor points (location of 5G radio nodes)



# Further SLAM Improvements

**SLAM State-of-the-art:** Factor Graphs and Gaussian Belief Propagation

Can we improve complexity, speed, convergence, implementation, etc.



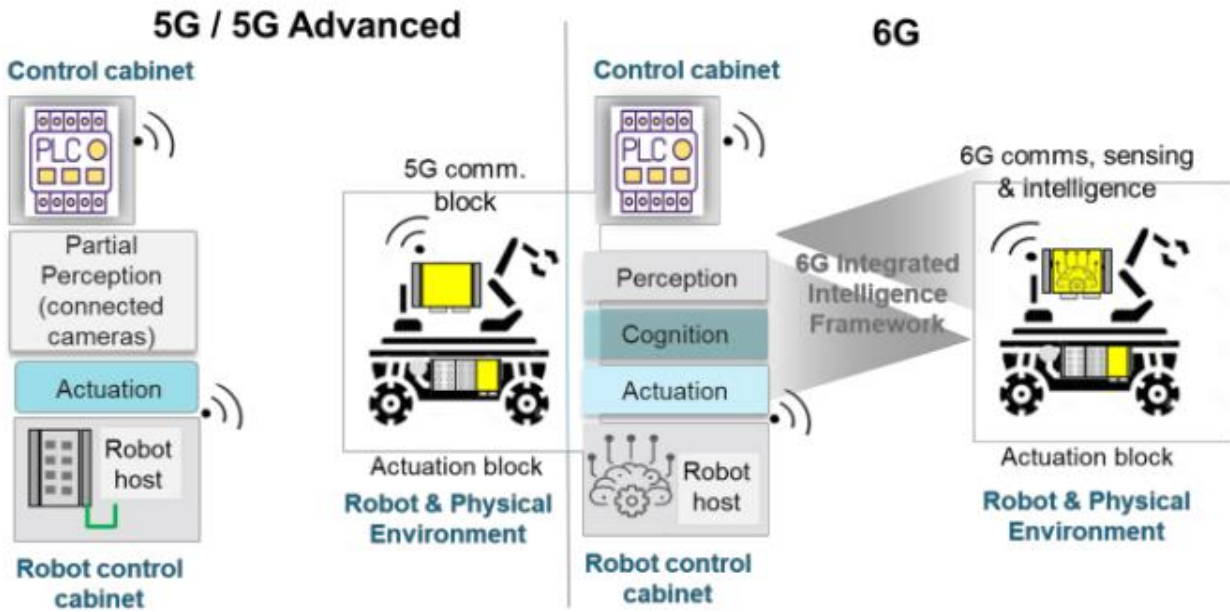
# **Outline of the Talk**

Task-Oriented Communications: High-Level Introduction

Task-Oriented Communications in 6G Connected Robotics

**Bonus**

# 6G Connected Robotics



| Functional Blocks                 | 6G Enablers                           | Metrics                                                  | Robotic Impact                                 |
|-----------------------------------|---------------------------------------|----------------------------------------------------------|------------------------------------------------|
| Sensing and Perception            | ISAC, edge AI, HRLLC                  | 50–200 Gbps; 300–500 Mbps; 1–10 cm                       | Shared perception, SLAM, situational awareness |
| Cognition, Reasoning and Planning | AI-native, semantic comms, edge/cloud | 1.5–3× spectrum efficiency; AI inference latency         | Distributed reasoning & fleet coordination     |
| Execution, and Actuation          | HRLLC, TSN, edge control              | 0.1–1 ms; 10 <sup>-5</sup> –10 <sup>-7</sup> reliability | Teleoperation, collision avoidance, safety     |
| Self-learning                     | FL, edge intelligence, AI agents      | FL update time; energy/bit reduction                     | Cooperative learning & adaptive autonomy       |

# One6G & euRobotics whitepaper



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## Standard for 6G Empowering Robotics: Use Case Scenarios, Requirements, Architectural Impact, and Technical Assumptions

Express Interest in this Project

Active PAR

This standard defines a framework for the International Telecommunication Union Radiocommunication Sector (ITU-R) working party (WP5D) International Mobile Telecommunications (IMT) IMT-2030 (also known as the 6th Generation (6G) of mobile network technology) empowering robotics applications. The framework incorporates potential robotics use case requirements, 6G enabling technologies, and defines the architectural impact necessary to enhance robotics and automation processes. Additionally, the framework includes a reference model and architecture, which defines functional requirements, common architectural entities, interfaces between those entities, and the mapping of functions to those entities. The standard specifies wireless connectivity, sensing and positioning capabilities for addressing robotics application requirements for perception, cognition, and actuation that can be employed to advance operational reliability, capability, and efficiency. 6G enabling robotics encompasses mission critical applications (e.g., disaster recovery), as well as health care assistance, industry-related scenarios, remote operation, automation, and inventory management.



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