# PlanIoT: A Framework for Adaptive Data Flow Management in IoT-enhanced Spaces

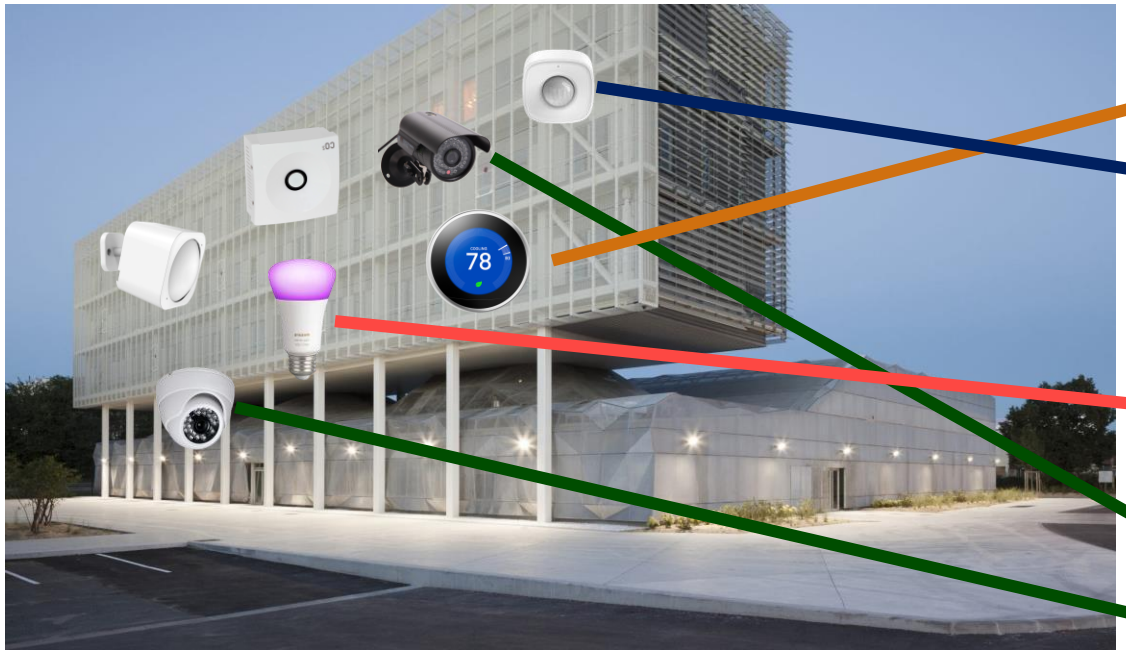
Houssam Hajj Hassan, Georgios Bouloukakis,
Ajay Kattepur, Denis Conan, Djamel Belaïd

*Télécom SudParis, IP Paris, France*
*Ericsson AI Research, India*

# Motivating Scenario

## Smart Spaces' IoT Applications

Télécom SudParis - Évry campus



Building occupants:

- Approximately 6,000 occupants / day

Shared rooms:

- 10 lecture halls, 220 conference & medium-size rooms
- 4 cafes and 3 restaurants

*Analytics (AN)*

Behavioral Analysis

best effort

req

*Real-Time (RT)*

Fire Detection

resp. time < 400 ms

req

*Transactional (TS)*

Room Reservation

resp. time <= 4 sec

req

*Video Streaming (VS)*

Security Footage

resp. time <= 2 sec

throughput >= 4 Mbps

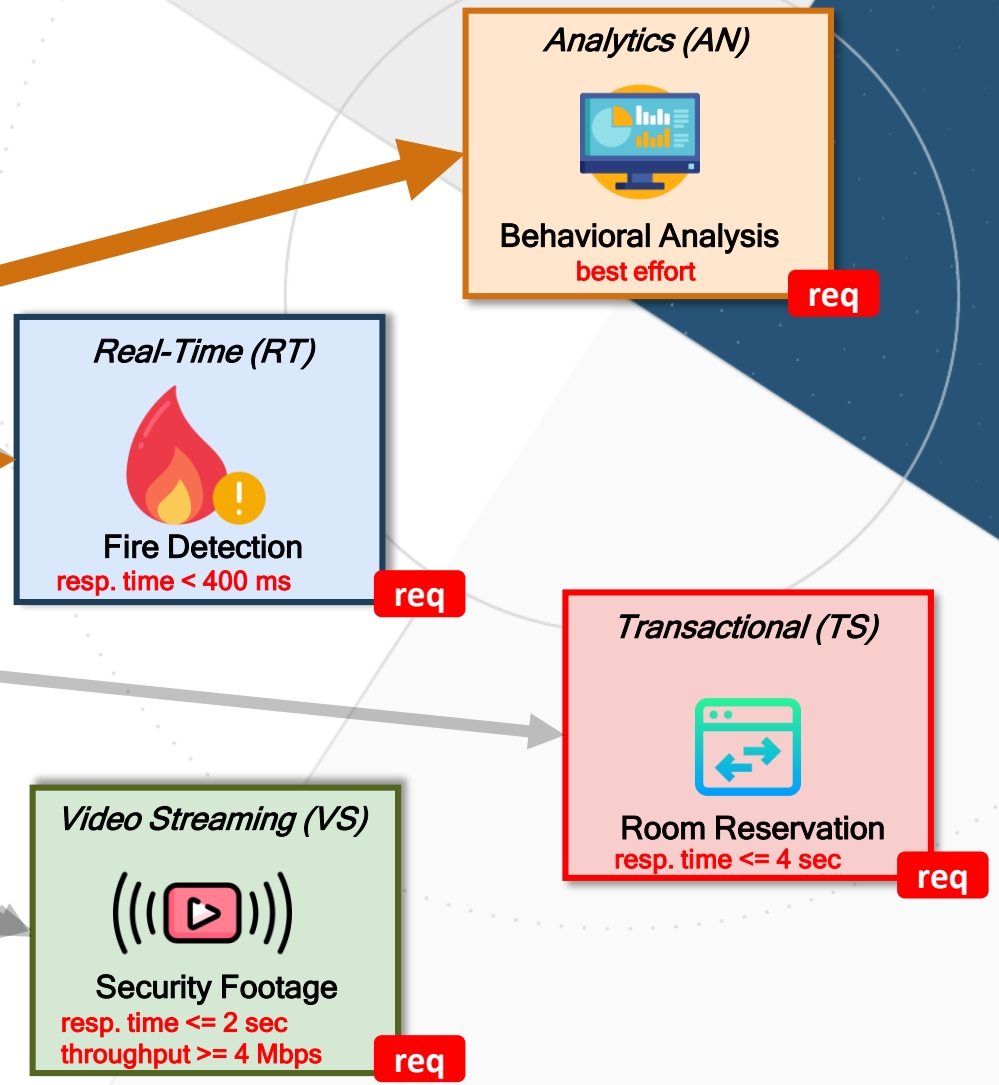
req

# Motivating Scenario

## Smart Spaces' *Intersecting* IoT Applications

Télécom SudParis - Évry campus

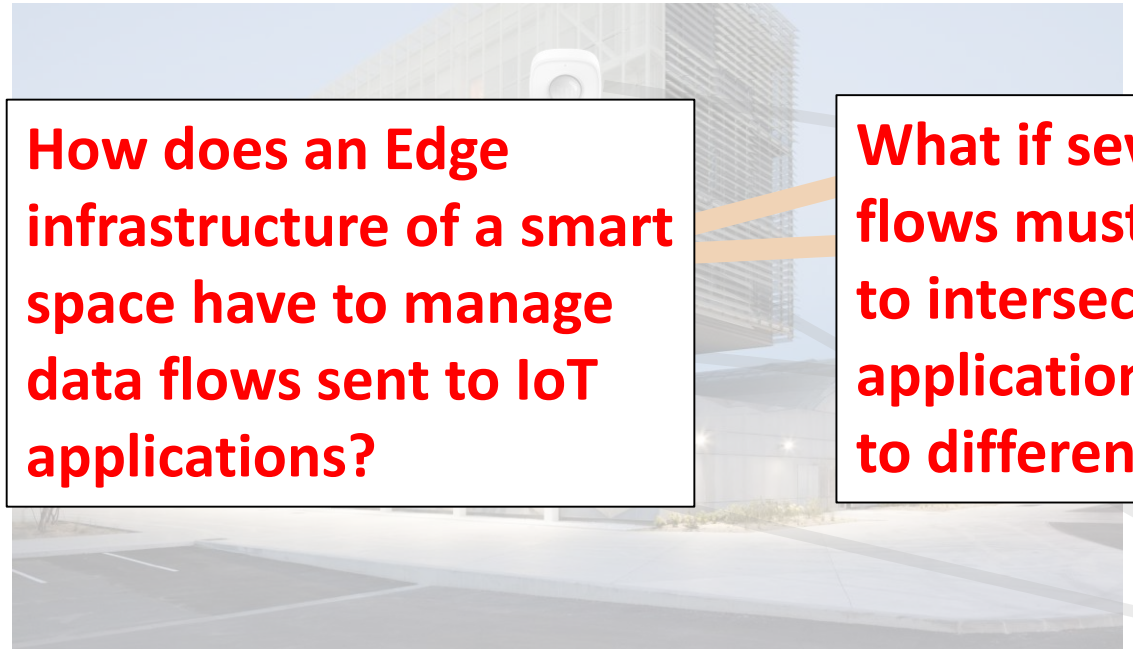
*Intersecting applications* have different QoS requirements yet receive the same flows of data from the same device.



# Motivating Scenario

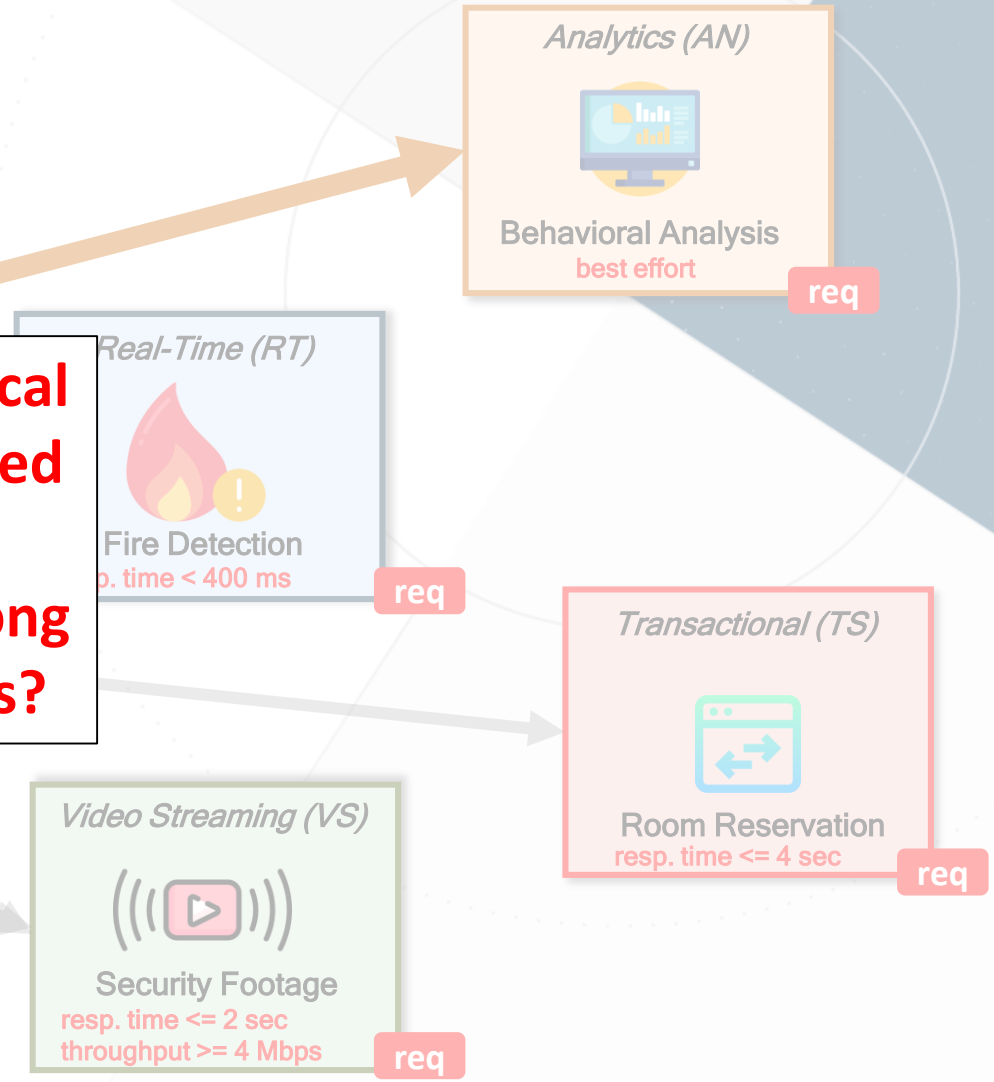
Smart Spaces' *Intersecting* IoT Applications

Télécom SudParis - Évry campus



**How does an Edge infrastructure of a smart space have to manage data flows sent to IoT applications?**

**What if several identical flows must be delivered to intersecting applications that belong to different categories?**




*Intersecting applications* have different QoS requirements yet receive the same flows of data from the same device.

# Motivating Scenario

Smart Spaces' *Intersecting* IoT Applications

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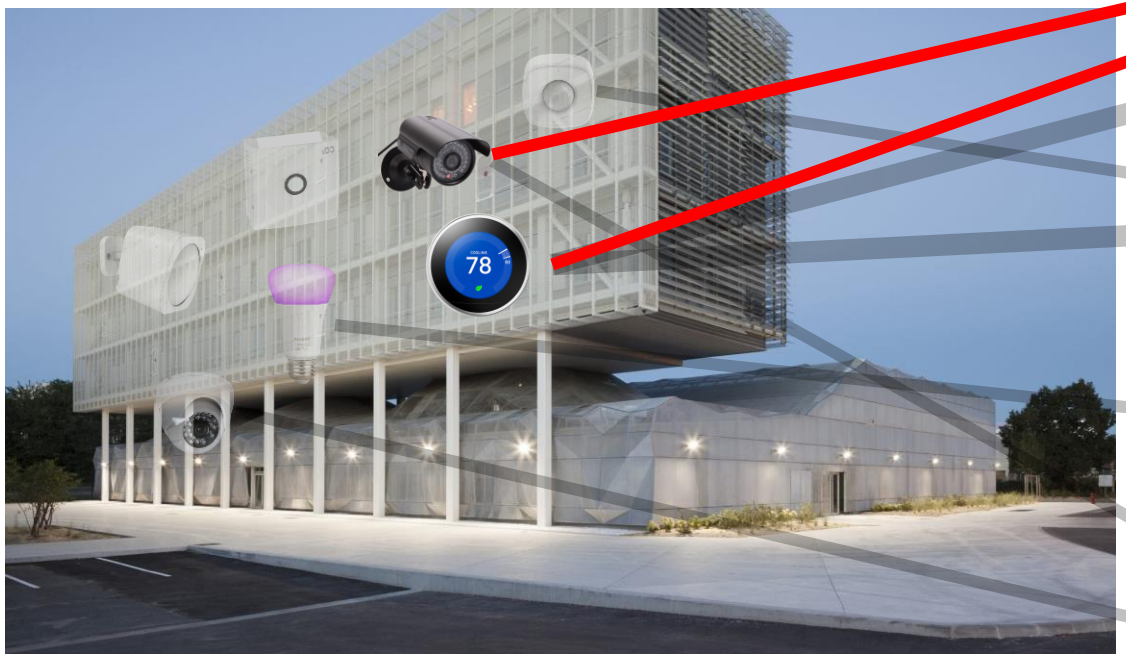
# Motivating Scenario

## Emergency Response Situation



*Emergency Response (EM)*

*Analytics (AN)*

Behavioral Analysis

best effort

req

*Real-Time (RT)*

Fire Detection

resp. time < 400 ms

req

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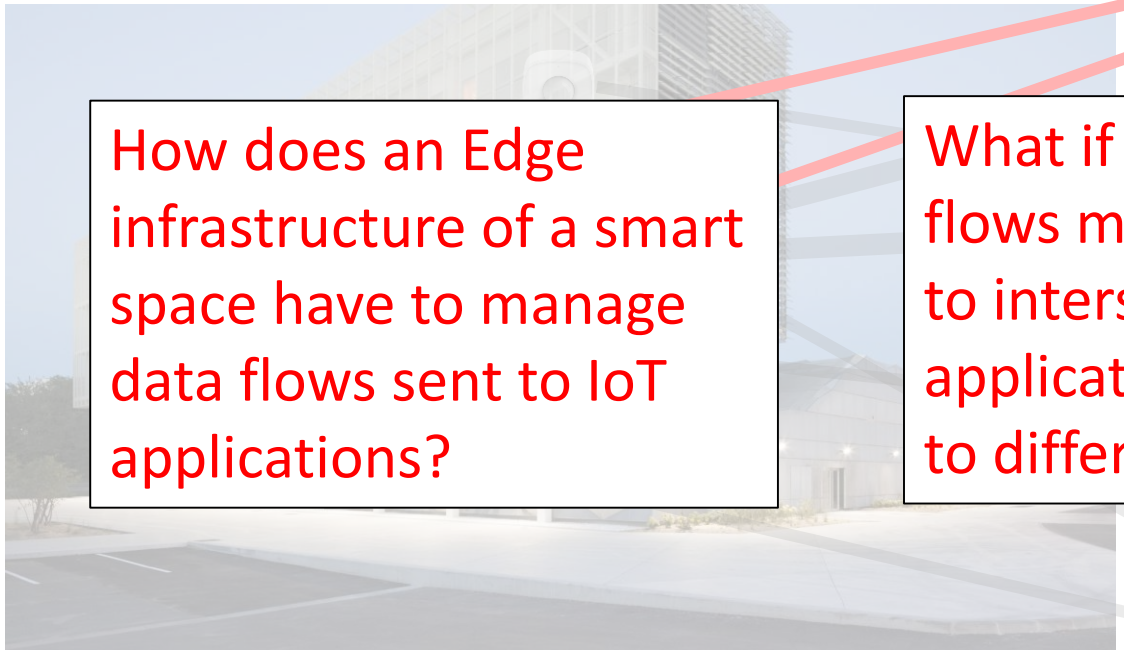
# Motivating Scenario

## Emergency Response Situation



How does an Edge infrastructure of a smart space have to manage data flows sent to IoT applications?

What if several identical flows must be delivered to intersecting applications that belong to different categories?

**How to enable the *adaptation* of the Edge infrastructure of smart spaces in dynamic situations?**

# State-of-the-Art Approaches

## IoT-enhanced Spaces:

- Data heterogeneity:
  uniform schemas for representing metadata in smart buildings [1] / communication between IoT devices and cloud [2]
- Conflict detection and resolution wen exchanging data [3]
- Ensuring reliable delivery of mission-critical data under challenging network conditions [4]

*What about different application categories?*

## QoS-aware Data Exchange

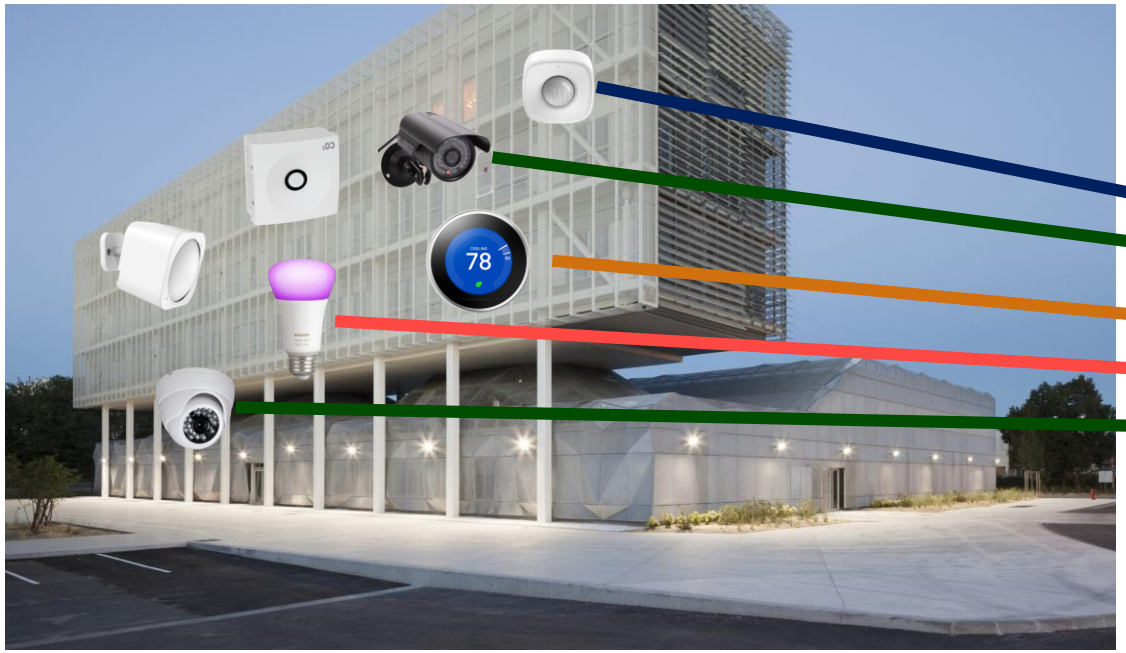
- Middleware approaches focus on policy-based solutions to manage QoS in Internet traffic [5], or assign priorities based on the validity span of data [6]
- Network approaches leverage SDN for bandwidth allocation and buffer sharing and prioritization [7] [8]

*How to handle data exchange for intersecting applications?*
*How to handle readaptation in dynamic environments?*


[1] B. Balaji, A. Bhattacharya, G. Fierro, J. Gluck, J. Gao et al. BuildSys. 2016.
[2] C. Hu, W. Bao, D. Wang, Y. Qian, M. Zheng, S. Wang. ACM TOSN. 2018.
[3] R. Liu, Z., Wang, L. Garcia, M.I. Srivastava. BuildSys. 2019.
[4] G. Bouloukakis, K. Benson, L. Scalzotto, P. Bellavista et al. TIOT. 2021.
[5] F. Martinelli, C. Michailidou, P. Mori, A. Sracino. PerCom. 2019.
[6] M. Saghian, R. Ravanmehr. CCGrid. 2015.
[7] D. Singh, B. Ng, Y.-C. Lai, Y.-D, Lin, W.K.G Seah. BuildSys. 2017.
[8] Y. Wang, Y. Zhang, J. Chen. ICWS. 2017.

# PlanIoT

## A Framework for Adaptive Data Flow Management in IoT-enhanced Spaces



PlanIoT

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resp. time <= 2 sec

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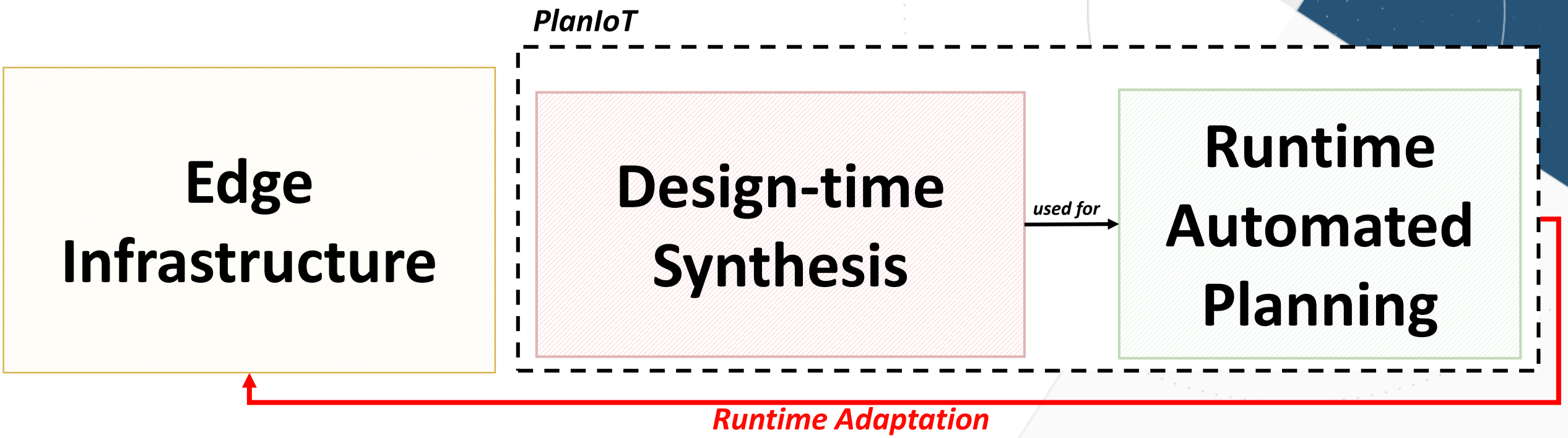
PlanIoT is a *framework-based solution* that enables adaptive data flow management at the **middleware-layer**.
This is achieved by:

1. Defining **application categories** according to their QoS requirements.
2. Designing **QoS models** for performance evaluation of Edge infrastructures of smart spaces.
3. Using **automated planning** methodologies for the adaptive management of data flows.

# The PlanIoT Approach

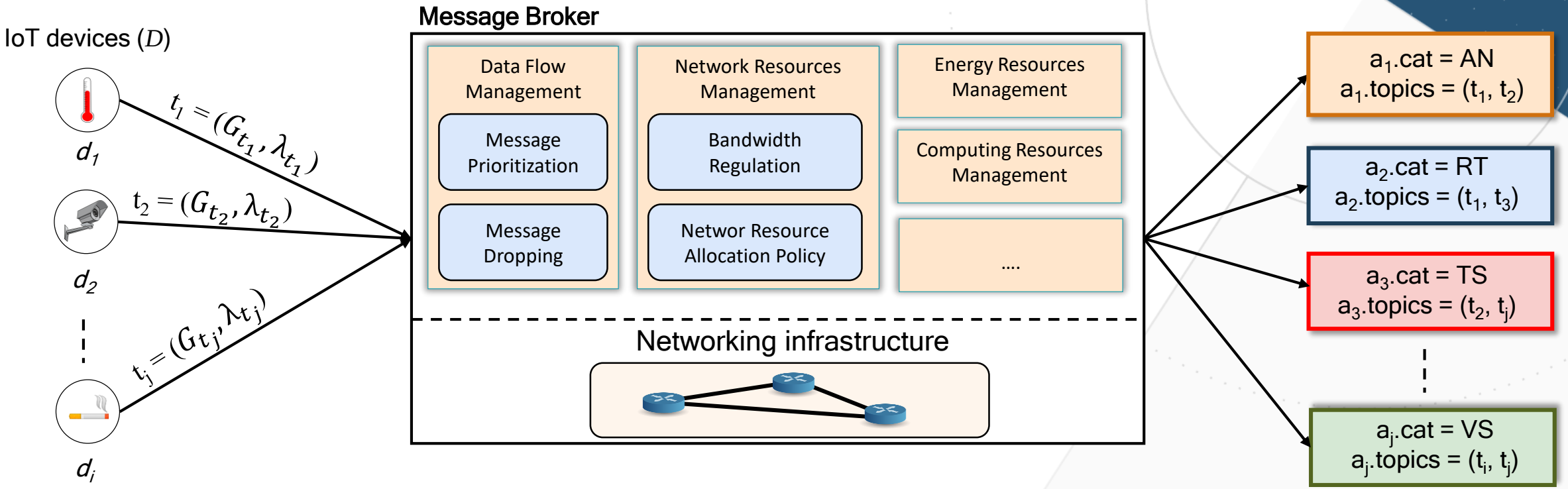
## High-Level Overview



# Edge Infrastructure Representation

## IoT Data Exchange Model

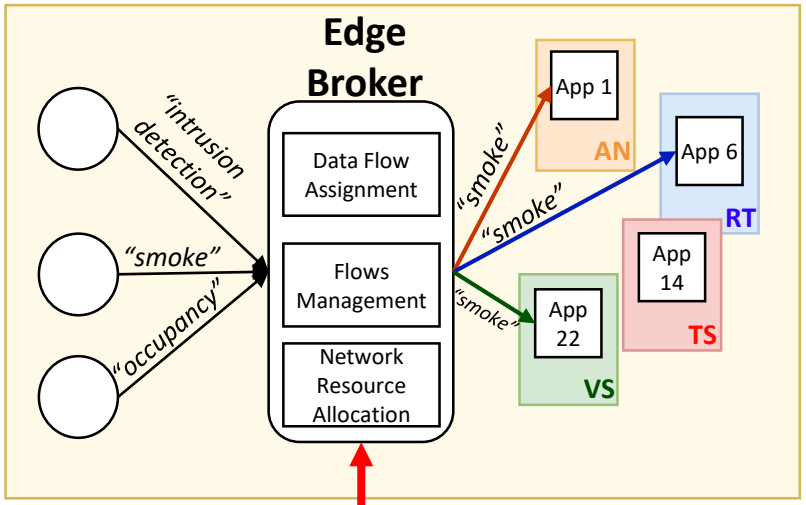
| *Notation* | *Description* |
|---|---|
| $d_i \in D$; $a_i \in A$ | IoT devices; IoT applications |
| $t_j \in T$ | topics |
| $G_{t_j}$ | message size |
| $\lambda_{t_j}$ | publication rate |



# The PlanIoT Approach

## High-Level Overview

*Edge Infrastructure*




***PlanIoT***

**Design-time Synthesis**

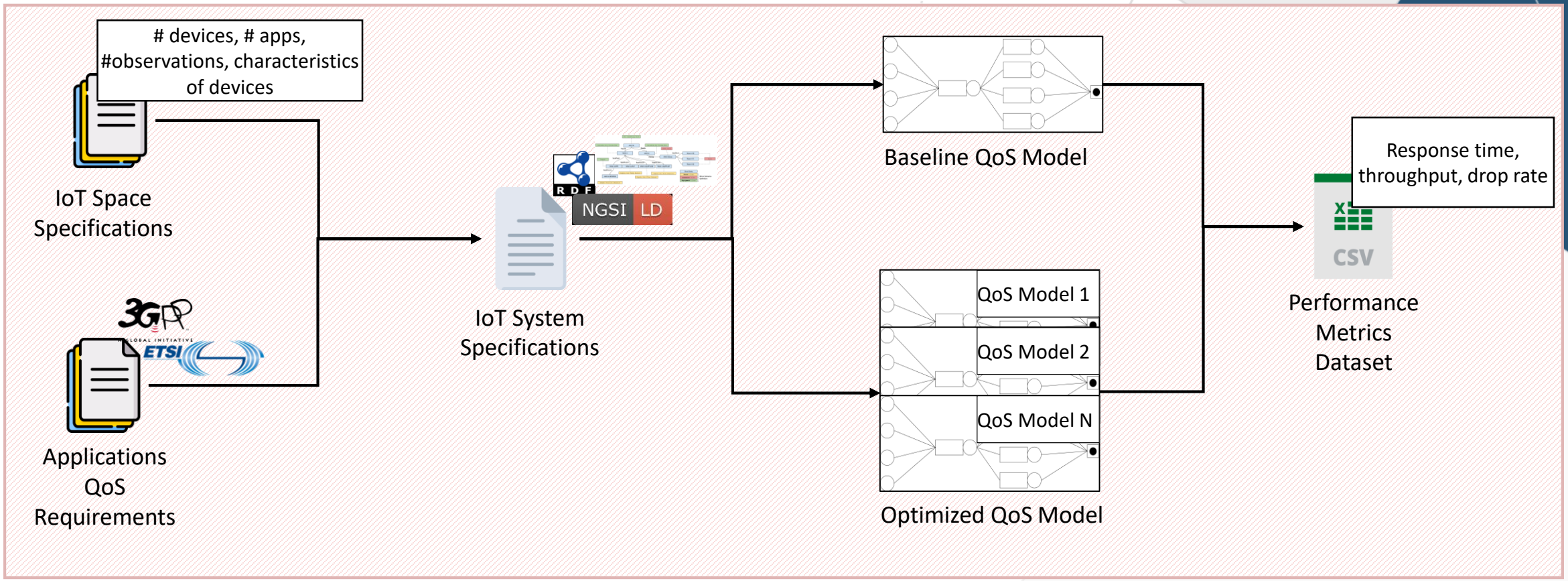
*used for*

**Runtime Automated Planning**

***Runtime Adaptation***

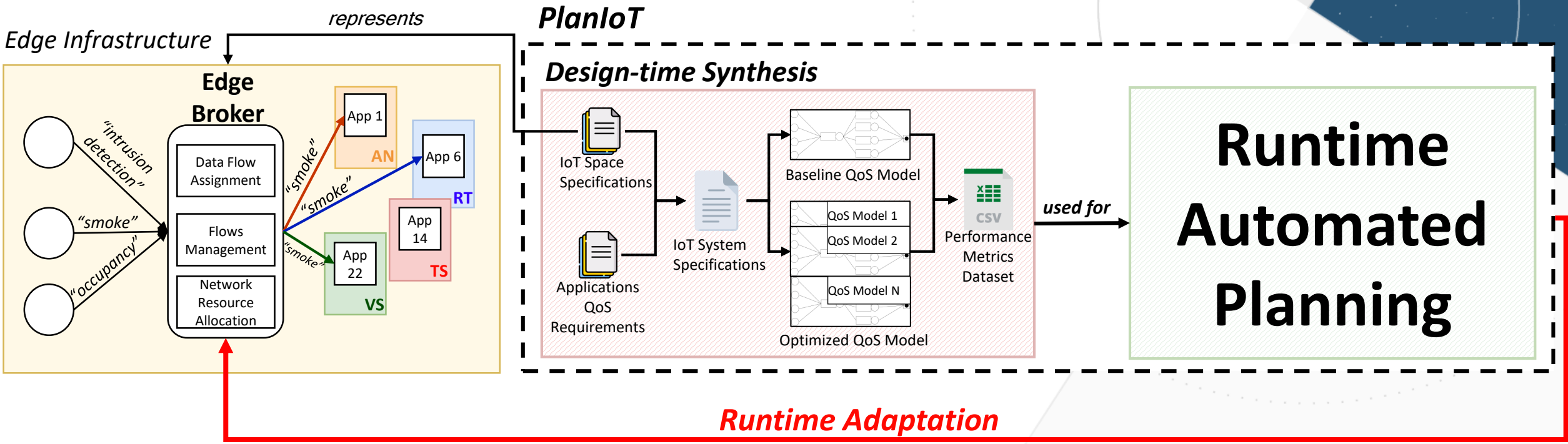
# The PlanIoT Approach

## Design-time Synthesis



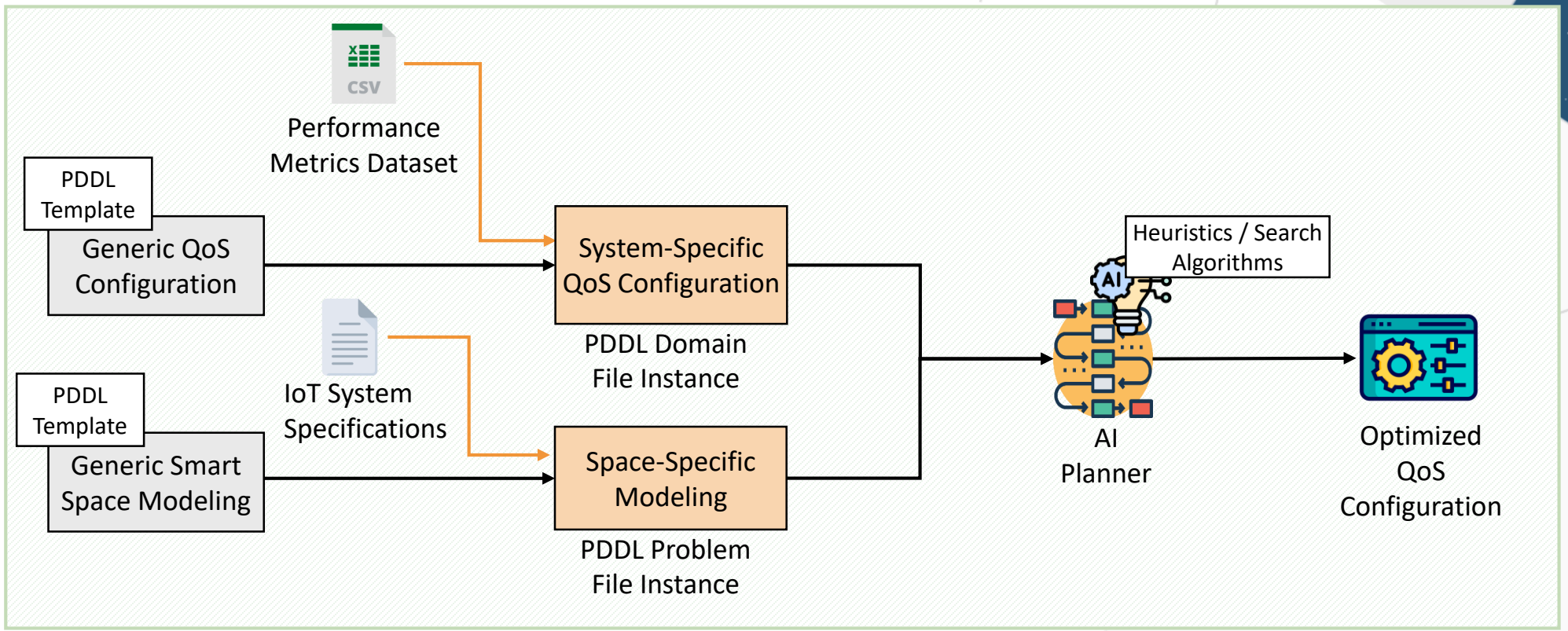
# The PlanIoT Approach

## High-Level Overview



# The PlanIoT Approach

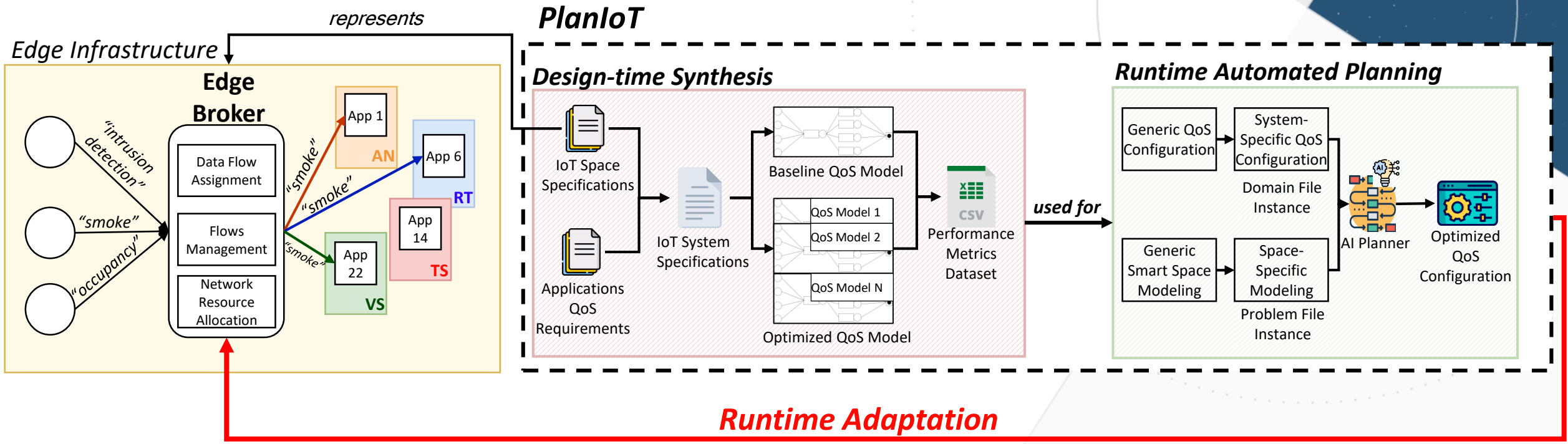
## Runtime Automated Planning



# The PlanIoT Approach

## High-Level Overview

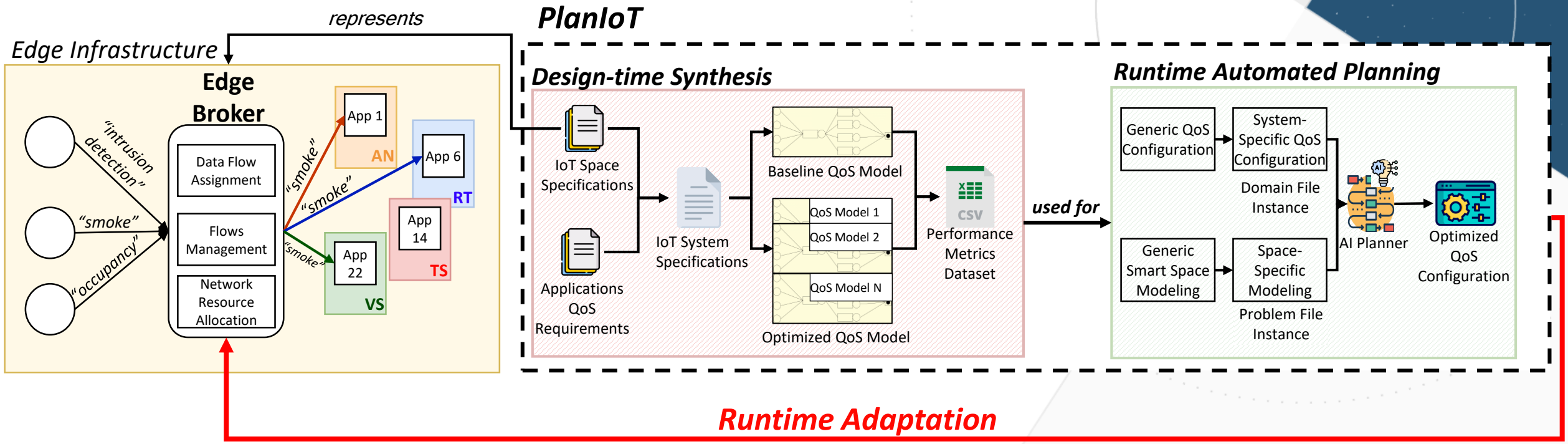
*How to get metrics related to the performance of the Edge infrastructure under different situations?*



# The PlanIoT Approach

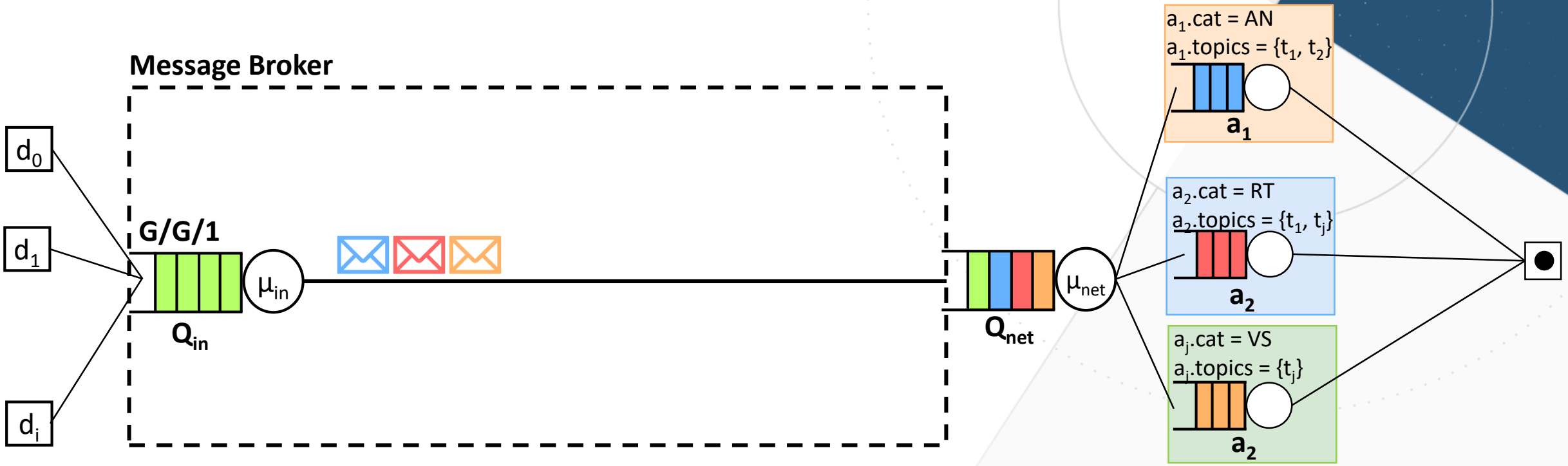
## High-Level Overview

*How to get metrics related to the performance of the Edge infrastructure under different situations?*



# Design-time Syntesis

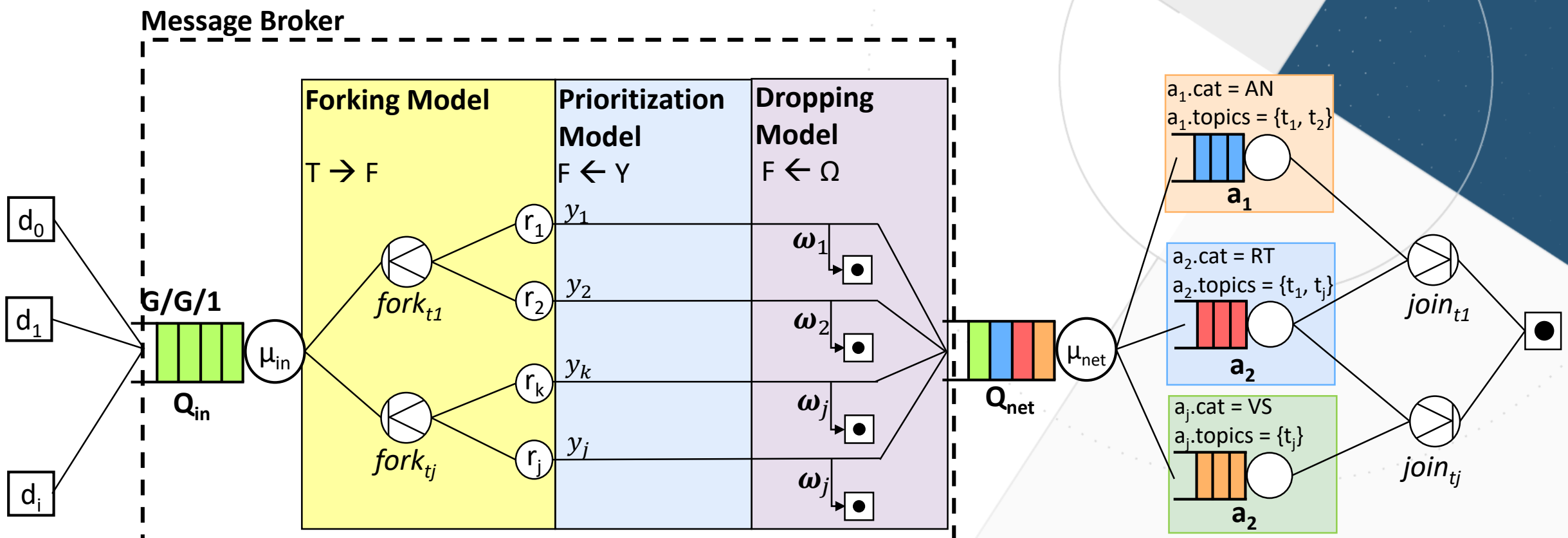
## Baseline QoS Model



# Design-time Syntesis

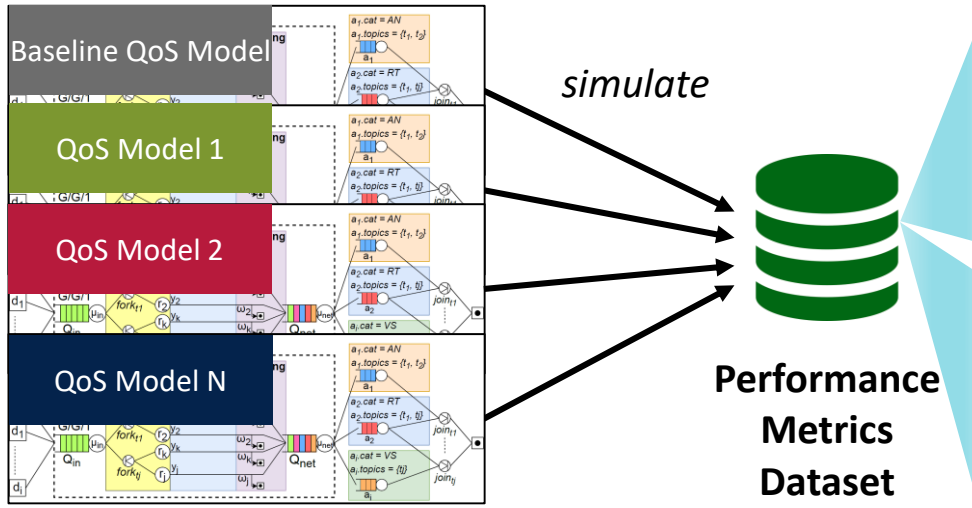
## Optimized QoS Model

| Notation | Description |
|---|---|
| $d_i \in D$; $a_i \in A$ | IoT devices; IoT applications |
| $r_j$ | subscription |
| $f_i$ | subscription flow |
| $y_i$; $\omega_i$ | priority of flow; drop rate of flow |



# Design-time Synthesis

## Performance Metrics Dataset Generation




*simulate*

**Performance Metrics Dataset**

| App | Topic | Prioritize RT | Prioritize TS | ... | Drop 2% VS | Drop 5% AN | ... | Shared | Max-Min | ... |
|---|---|---|---|---|---|---|---|---|---|---|
| app 1 | smoke | 0.2015 | 0.560679 | | 0.4761 | 0.4651 | | 0.81563 | 0.498188 | |
| app 1 | temp | 0.515479 | 0.13125 | | 0.5193 | 0.4950 | | 0.4980 | 0.131307 | |
| app 3 | temp | 0.633439 | 0.5532327 | | 0.4624 | 0.3168 | | 0.51384 | 0.23485 | |
| app j | occupancy | 0.134651 | 0.345628 | | 0.2156 | 0.5138 | | 0.31564 | 0.154152 | |

Response times per subscription

| App | Topic | Prioritize RT | Prioritize TS | ... | Drop 2% VS | Drop 5% AN | ... | Shared | Max-Min | ... |
|---|---|---|---|---|---|---|---|---|---|---|
| app 1 | smoke | 452.141 | 262.432 | | 450.14 | 453.51 | | 363.43 | 479.532 | |
| .. | ... | ... | ... | | ... | ... | | ... | ... | |

Throughput per subscription

| App | Topic | Prioritize RT | Prioritize TS | ... | Drop 2% VS | Drop 5% AN | ... | Shared | Max-Min | ... |
|---|---|---|---|---|---|---|---|---|---|---|
| app 1 | smoke | 0.00 | 0.008243 | | 0.0014 | 0.0005 | | 0.000 | 0.000 | |
| .. | ... | ... | ... | | ... | ... | | ... | ... | |

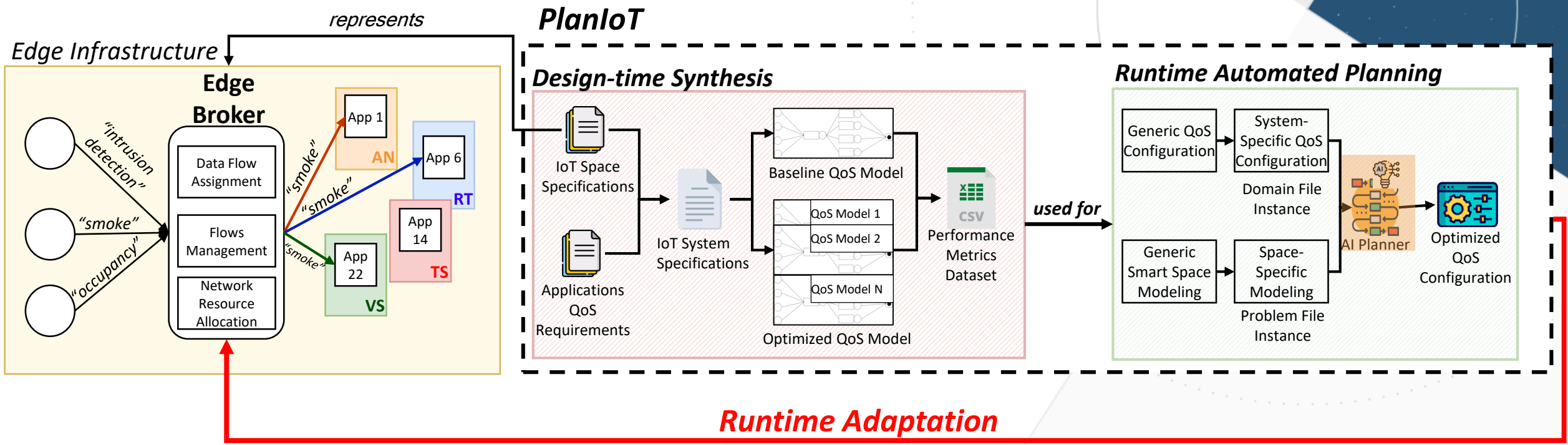
Drop rate per subscription

# The PlanIoT Approach

## High-Level Overview

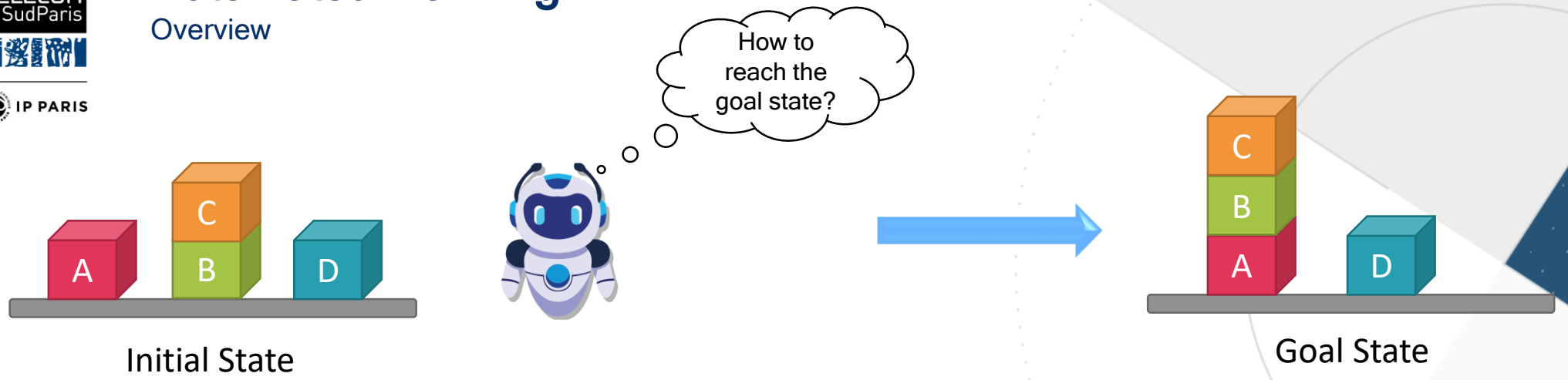
*How to decide which configuration is the most suitable based on the performance of the Edge infrastructure?*

*How to adapt the IoT data exchange system when changes occur?*



# Automated Planning

## Overview




> Automated Planning is an area of artificial intelligence where the task is to **choose** and arrange **actions** in order **to achieve some goal**.

Application Domains

- Robotics [1]
- Web services composition [2], [3]
- Orchestration of IoT applications [4]


[1] A. Kattepur, B. Purushothaman. Cognitive Computation and Systems. 2020.
[2] S. Qi, X. Tang, D. Chen. IEEE CGC. 2012
[3] G. Zou, Y. Chen, Y. Yang, R. Huang, Y. Xu. ntl. Conf.on Cloud Computing and Virtualization.
[4] U. Bellur, N. Narendra, and S. Mohalik. IEEE Services. 2017

# QoS-aware Planning of IoT Flows

A Planning Domain $\Sigma$ is a state transition system that contains:
- A finite set of states of the system $(S)$
- A set of actions $\alpha$ to be performed by an agent (e.g., PlanIoT)
- A state transition function $\gamma: S \times A \rightarrow S$
- A cost function $C: S \times A \rightarrow [0, \infty)$

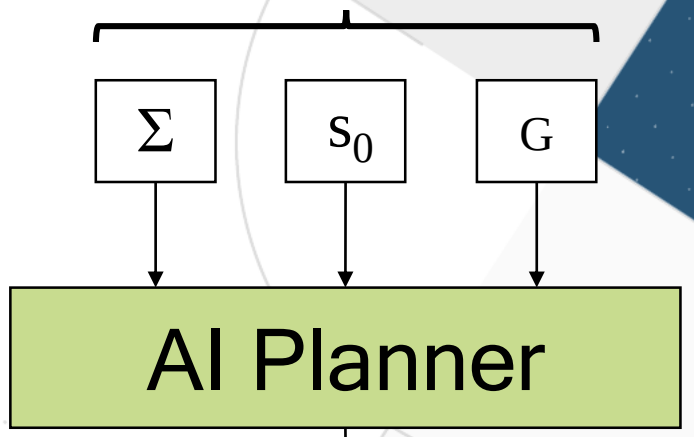
*Initial State*

- $f_i \in F$ mapped to applications $a_i \in A$ regardless of the application category.
- $Y = \{y_{AN}, y_{RT}, y_{TS}, y_{VS}, y_{EM}\} = \{0, 0, 0, 0, 0\}$
- $\Omega = \{\omega_{AN}, \omega_{RT}, \omega_{TS}, \omega_{VS}, \omega_{EM}\} = \{0, 0, 0, 0, 0\}$

*Goal State*

- $\Delta_{f_i} \leq \delta_{max}$
- $\Theta_{f_i} \geq \theta_{min}$
- $\Omega_{f_i} \leq \omega_{max}$

**Planning Problem**: $P = (\Sigma, s_0, G)$




**Plan**

$\pi = <\alpha_1, \alpha_2, \alpha_3>$

$\alpha_1: f_i \rightarrow r_j$

$\alpha_2: f_i \rightarrow Y = \{y_{AN}, y_{RT}, y_{TS}, y_{VS}, y_{EM}\}$

$\alpha_3: f_i \rightarrow \Omega = \{\omega_{AN}, \omega_{RT}, \omega_{TS}, \omega_{VS}, \omega_{EM}\}$

$\pi$

A solution for a planning problem $P$ is a plan $\pi$ such that $\gamma(s_0, \alpha_1) \ldots (s_m, \alpha_\pi)$ satisfies $G$.

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*Goal State*

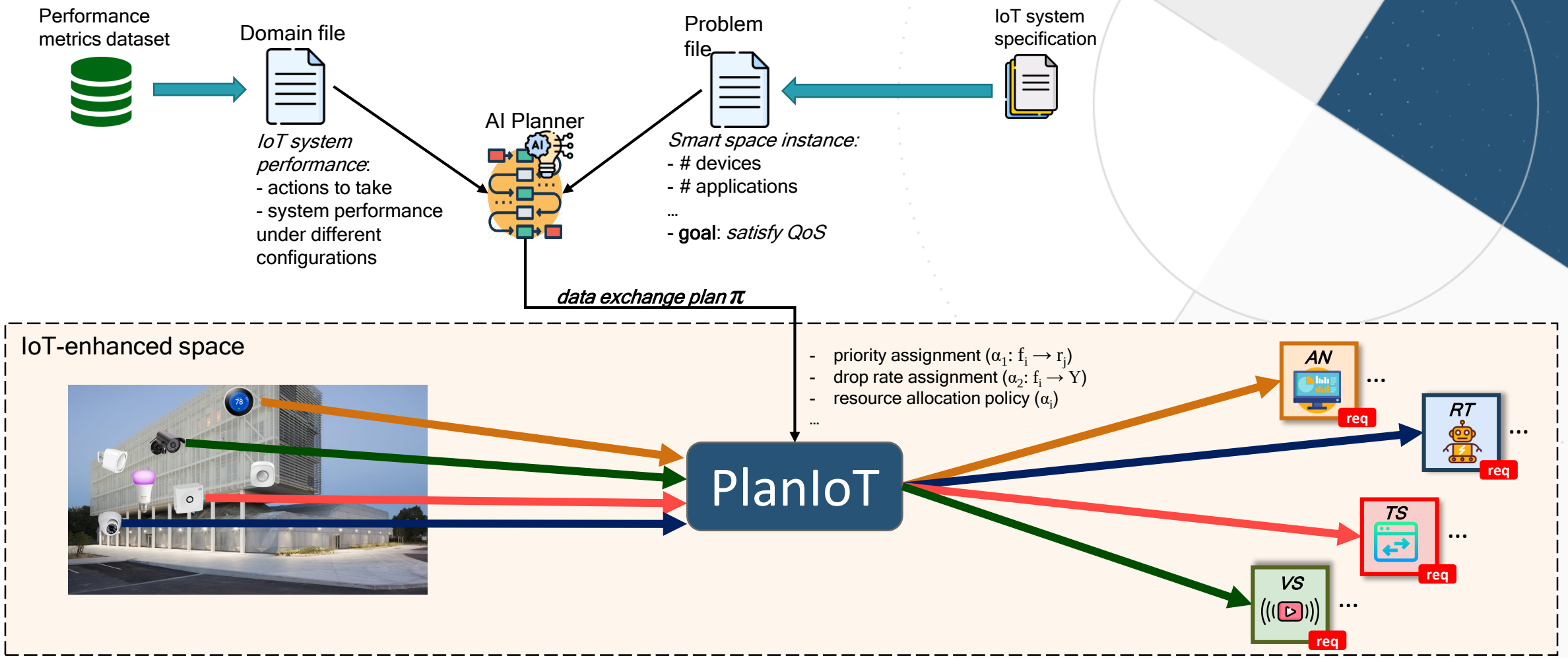
- $\Delta_{f_i} \leq \delta_{max}$
- $\Theta_{f_i} \geq \theta_{min}$
- $\Omega_{f_i} \leq \omega_{max}$

Planning problems are expressed using the Planning Domain Definition Language (PDDL), an action centered language that provides a standard syntax to describe actions by their parameters, preconditions, and effects.

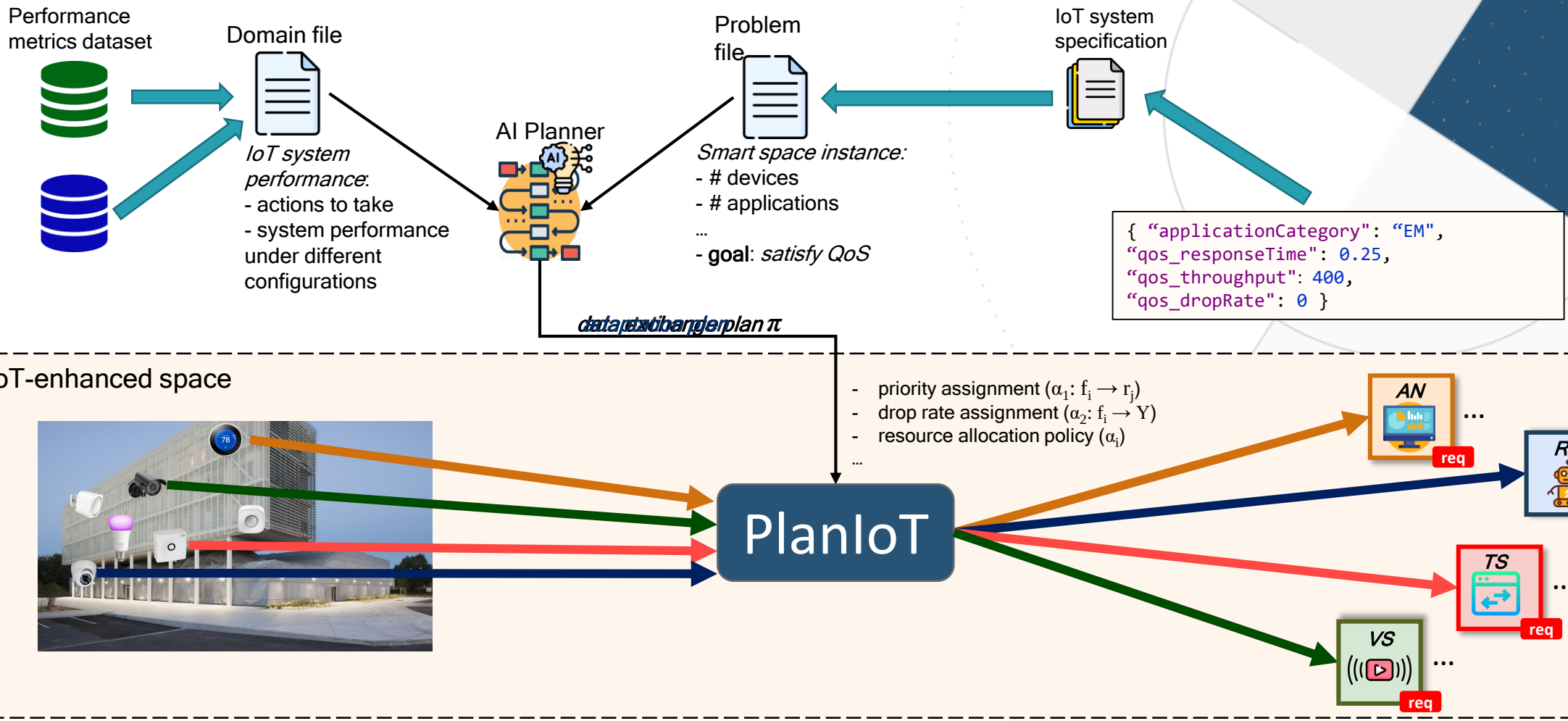
```
(:action prioritize_RT
   :parameters (?t  - topic ?app - application)
   :precondition (and (priority_not_set ?t  ?app))
   :effect (and (priority_not_set ?t  ?app)
                (priority_set ?t  ?app) …))
```

```
(:objects
   printing energymanagement … topic_all  - Topic
   app1 app2 app3 app4 … app_all - Application)
(:init
      (baseline topic_all app_all)
      (priority_not_set topic_all app_all)
      (= (latency intrusiondetection app2) 0)
      (= (latency intrusiondetection app21) 0))
(:goal (and  (QoS_achieved topic_all app_all)
      (priority_set topic_all app_all)))
(:metric minimize ( + ( + (* 1 (latency videosurveillance app5 )))
                          (* 1 (latency energymanagement app2 )))…)
```

# Data Exchange Plan Generation



# Design-time Adaptation



# Experimental Results

## Experimental Setup

| PlanIoT System Properties | | | | | QoS Requirements | | |
|---|---|---|---|---|---|---|---|
| | $\|T\|$ | $\|R\|$ | $\Sigma\lambda_{t_j}$ (MB/s) | $W_{DX}$(MB/s) | $\delta_{max}$ | $\theta_{min}$ | $\omega_{max}$ |
| **AN** | 15 | 21 | 18.5 | 230 | best effort | best effort | best effort |
| **RT** | 18 | 21 | 31.5 | | <400 ms | 384 KB/s | 0% |
| **TS** | 11 | 18 | 16 | | <4 s | - | 0% |
| **VS** | 16 | 20 | 55.4 | | <2 s | 384 KB/s | <2% |
| **Total** | 30 | 80 | 121.4 | 230 | | | |

# topics # subscriptions used bandwidth available bandwidth based on ETSI TS 1212 105

- We use the Java Modelling Tools[1] (JMT) queueing simulator to compose QoS models and generate performance metrics datasets.
- We use the Metric-FF[2] AI planner to generate adaptation plans.

**Scenario 1:**

- Medium-loaded system
- Evaluation against default approach
- Evaluation against (i) using the max-min resource allocation policy and (ii) approaches that prioritize topics

**Scenario 2:**

- Using real traces
- Increasing number of subscriptions from 20 → 100
- Evaluation of the performance of an overloaded system

| $t_j$ | topic id | $\|d_i\|$ | app. categories |
|---|---|---|---|
| amazon_echo_controller | 1 | 13 | RT, TS |
| building_management_system | 2 | 300 | AN, RT, TS |
| energy_management | 3 | 200 | AN, RT, TS |
| fire_detection | 4 | 100 | AN, RT |
| intrusion_detection | 5 | 50 | AN, RT, VS |
| occupancy_management | 6 | 16 | AN, RT, TS, VS |
| printing | 7 | 20 | AN, TS |
| smart_things_controller | 8 | 12 | RT, TS |
| video_surveillance | 9 | 15 | AN, RT, VS |

**Scenario 3:**

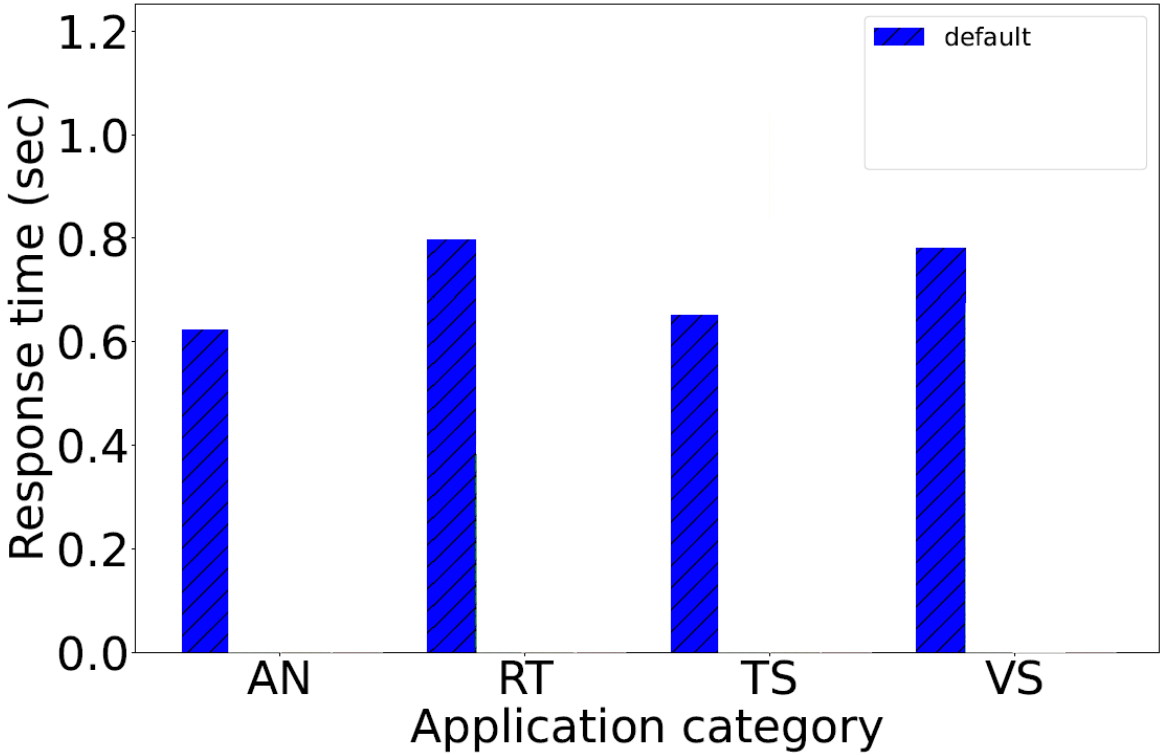
- Adaptation in emergency situations

1 https://jmt.sourceforge.net/
2 https://fai.cs.uni-saarland.de/hoffmann/metric-ff.html

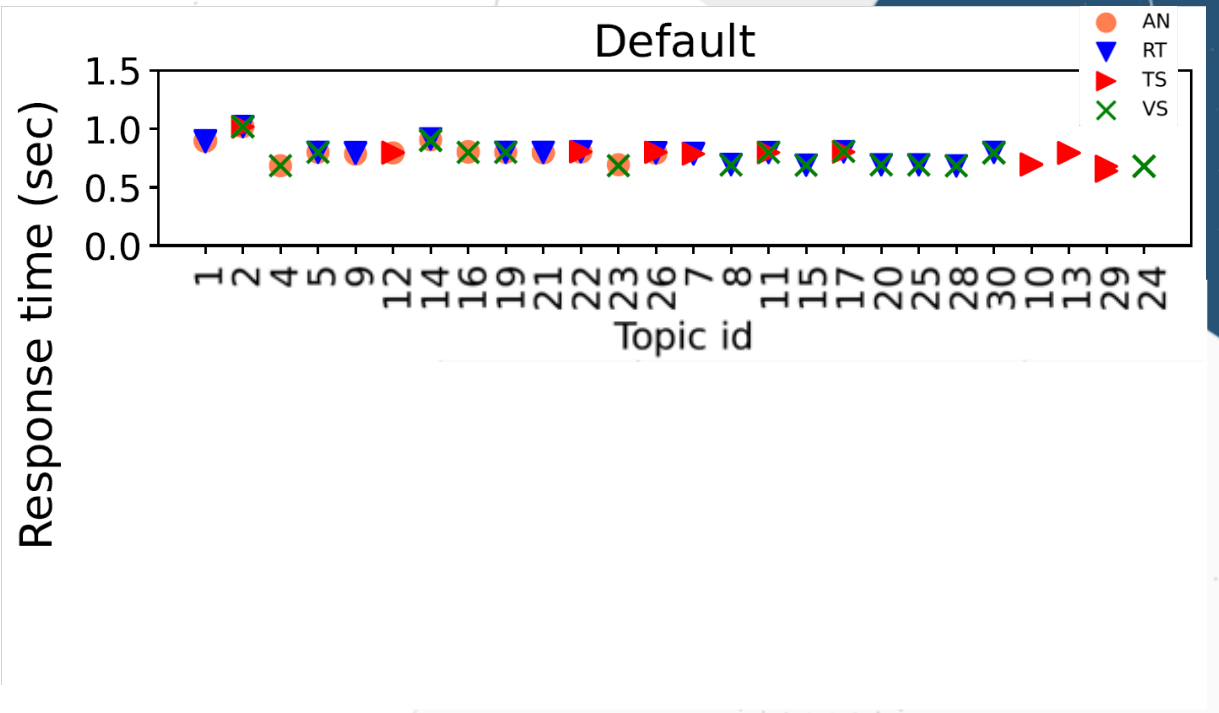
# Experimental Results

## Scenario 1: Baseline Evaluation

*Response time per application category*




*Response time per topic*

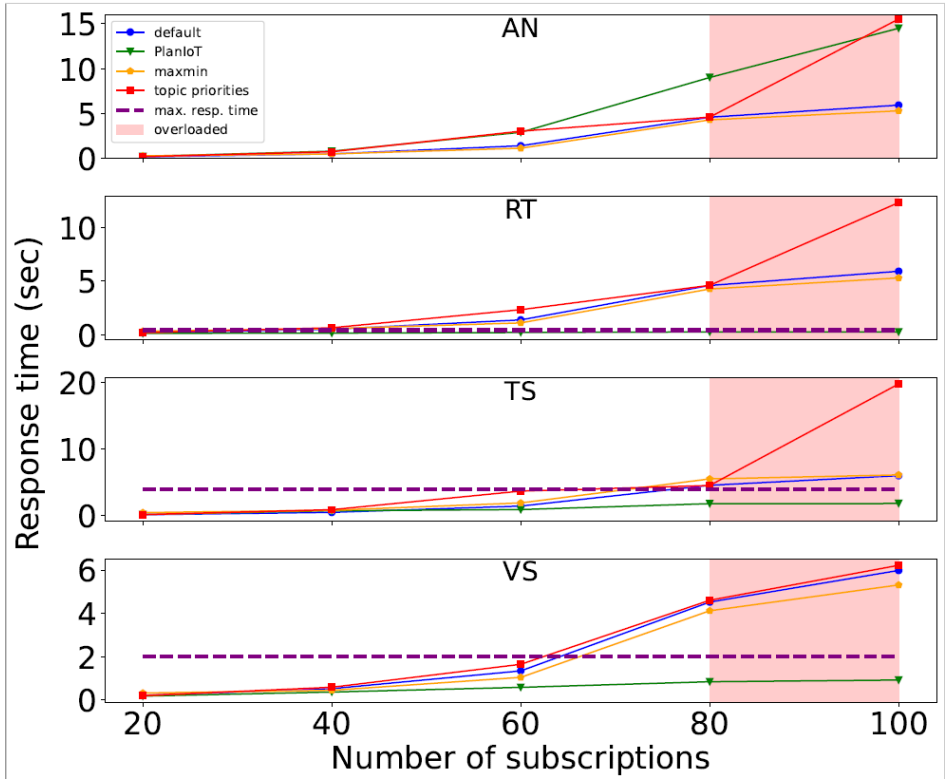


# Experimental results

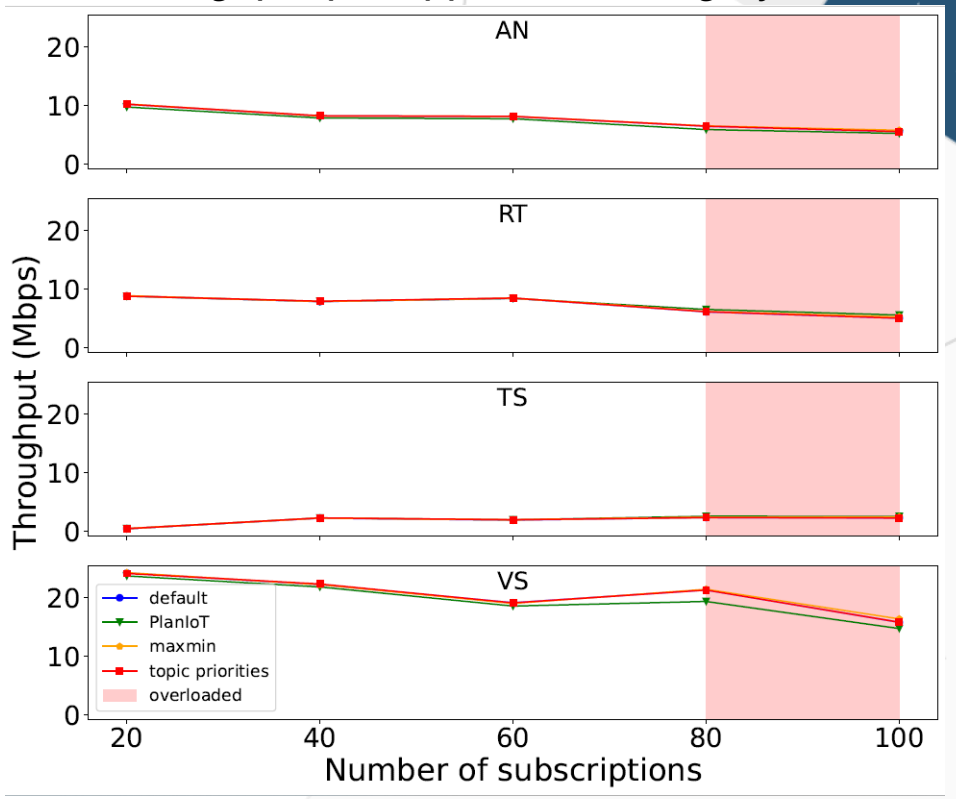
## Scenario 2: Scaling Up PlanIoT

| $t_j$ | topic id | $\lfloor d_i \rfloor$ | app. categories |
|---|---|---|---|
| amazon_echo_controller | 1 | 13 | RT, TS |
| building_management_system | 2 | 300 | AN, RT, TS |
| energy_management | 3 | 200 | AN, RT, TS |
| fire_detection | 4 | 100 | AN, RT |
| intrusion_detection | 5 | 50 | AN, RT, VS |
| occupancy_management | 6 | 16 | AN, RT, TS, VS |
| printing | 7 | 20 | AN, TS |
| smart_things_controller | 8 | 12 | RT, TS |
| video_surveillance | 9 | 15 | AN, RT, VS |

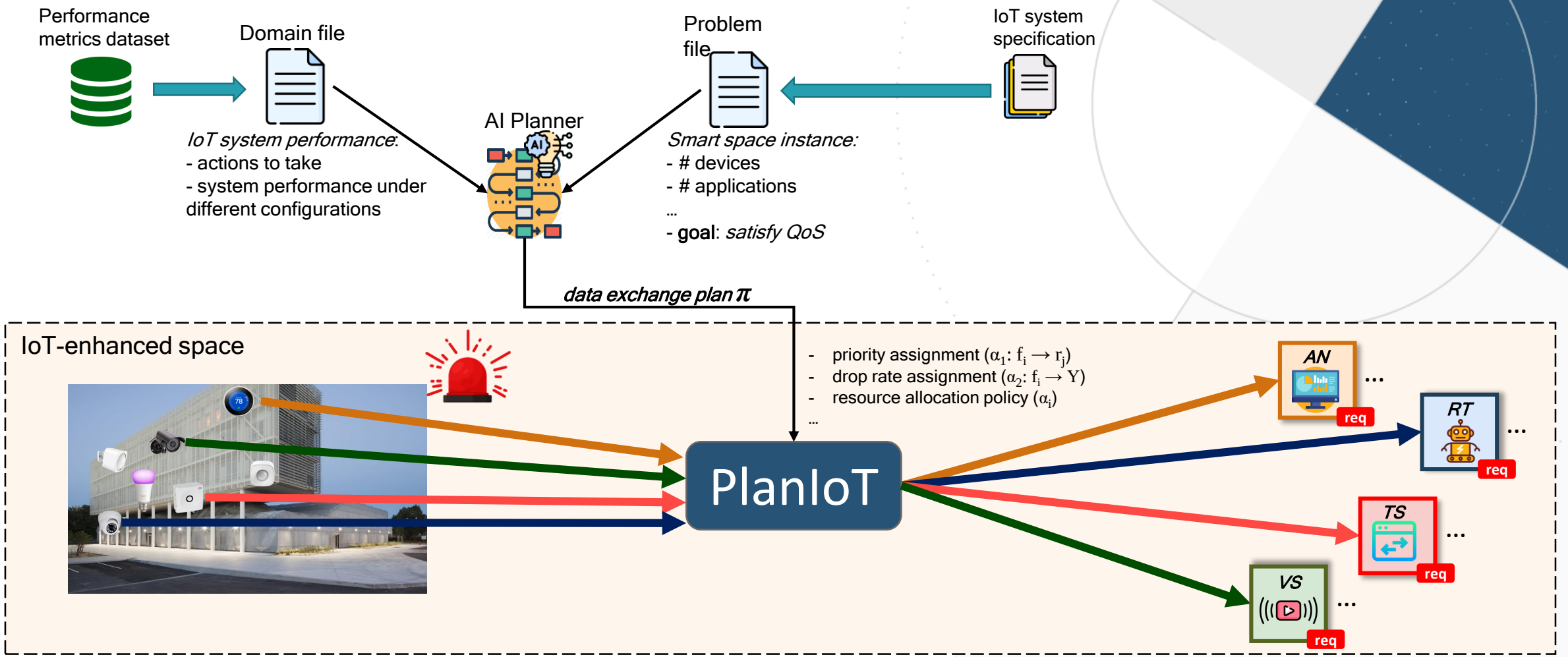
*Response time per application category*



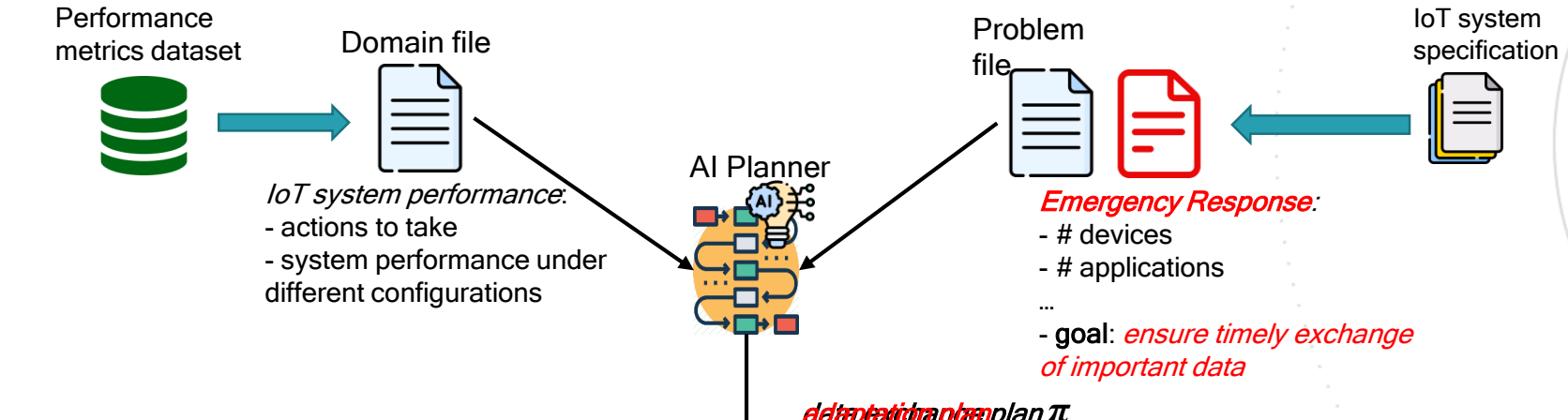

*Throughput per application category*

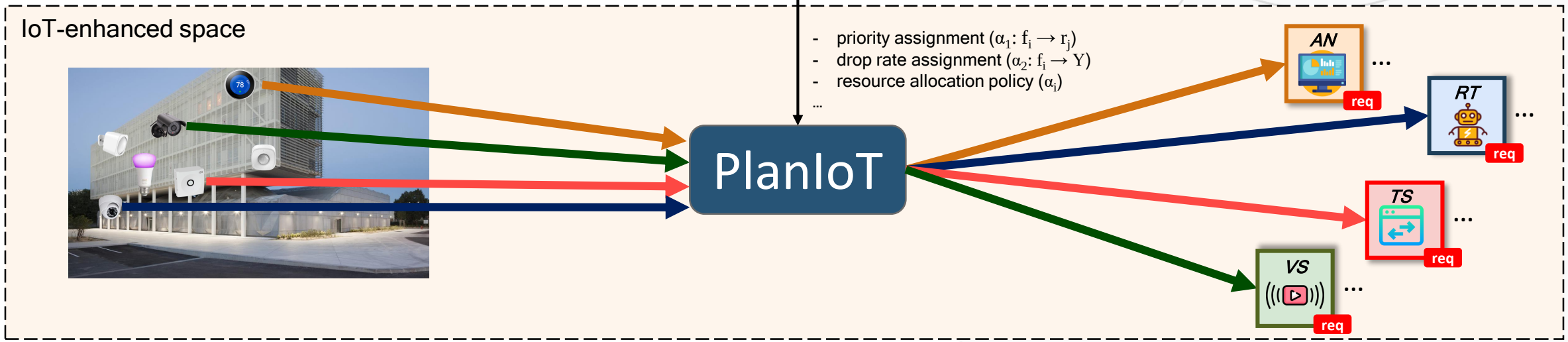


# Runtime Adaptation



# Runtime Adaptation

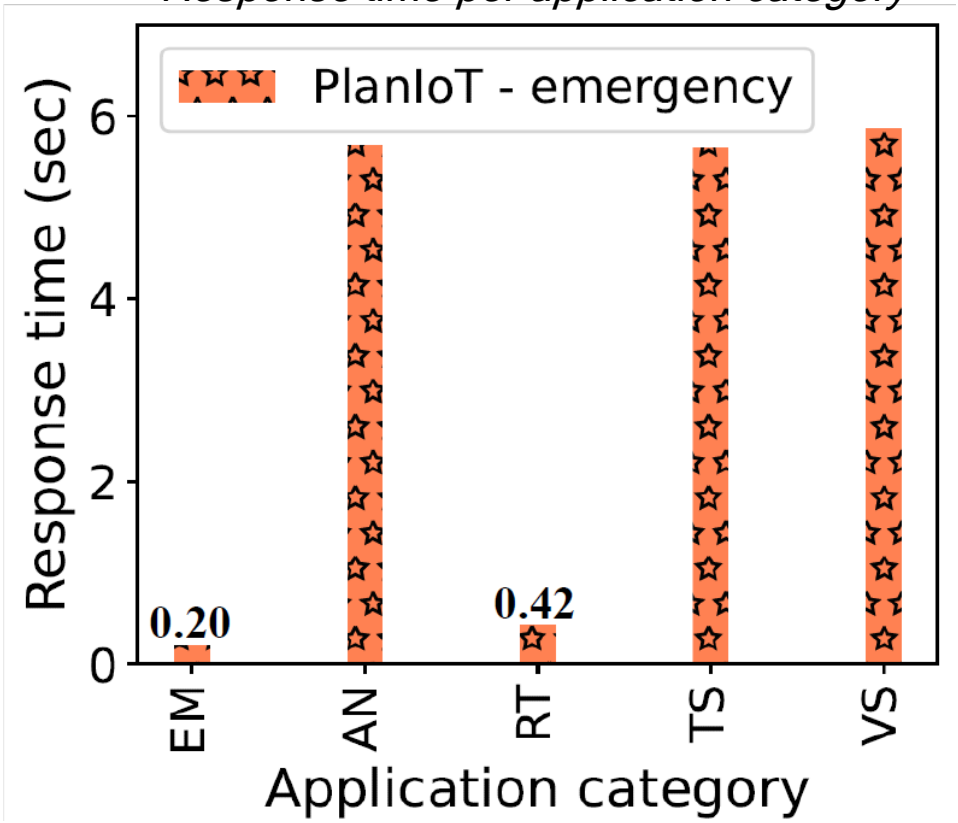


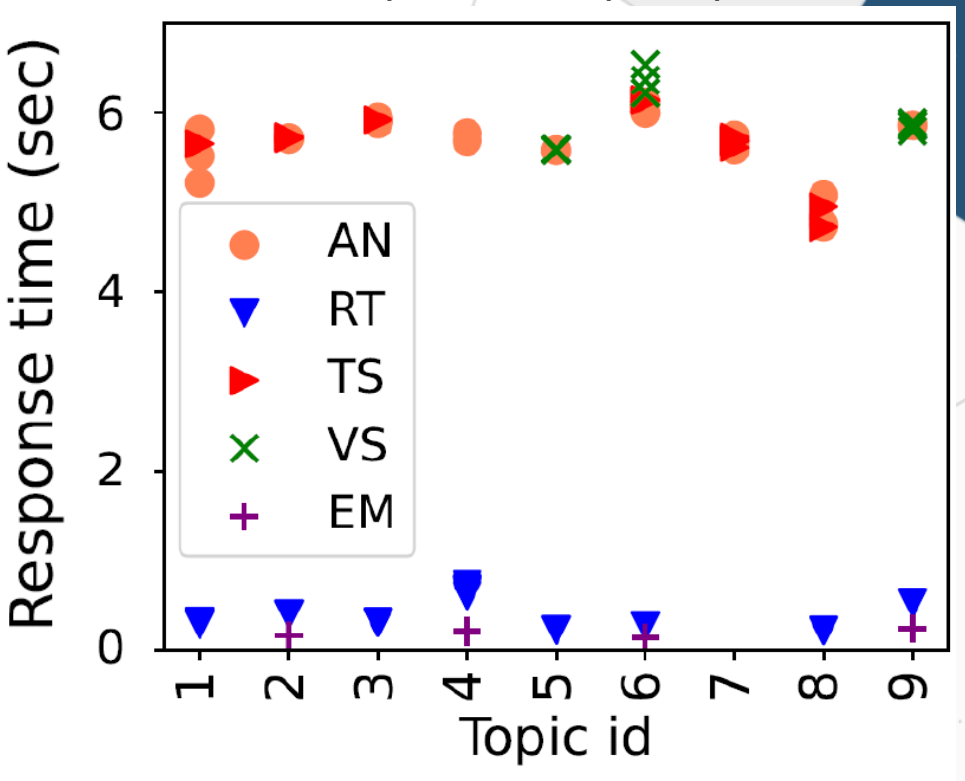
# Experimental results

Scenario 3: Emergency Situations

*Response time per application category*




*Response time per topic*



# Key Takeaways and Future Directions

- We propose PlanIoT, a middleware-based framework for adaptive data flow management in IoT-enhanced spaces.
- **QoS models** are created and composed to generate a metrics dataset that evaluates the performance of Edge infrastructure.
- **Automated planning techniques** are used to configure and adapt IoT systems in dynamic situations.
- The experiments show that PlanIoT can **reduce response times of time-sensitive** applications by 50% and satisfy QoS of applications deployed in smart spaces.
- The PlanIoT code is publicly available on: https://gitlab.com/planiot/planiot-seams2023
- How to effectively predict the changes in the IoT system *before* they happen?
- How to adapt the system in response to *unseen changes*?

# Thank you!

## **PlanIoT:** A Framework for Adaptive Data Flow Management in IoT-enhanced Spaces

Houssam Hajj Hassan, Georgios Bouloukakis, Ajay Kattepur, Denis Conan, Djamel Belaïd

*Télécom SudParis, IP Paris, France*
*Ericsson AI Research, India*

Contact: houssam.hajj_hassan@telecom-sudparis.eu