Towards an AI-Native User-Centric Air Interface for 6G Networks

WP4: AI-AI protocols & radio resource management

Emergent Communication Protocol Learning for Task Offloading in Industrial Internet of Things

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OUTLINE

WHAT IS IIoT ?

- **Production-oriented** and aims to improve industrial production efficiency.

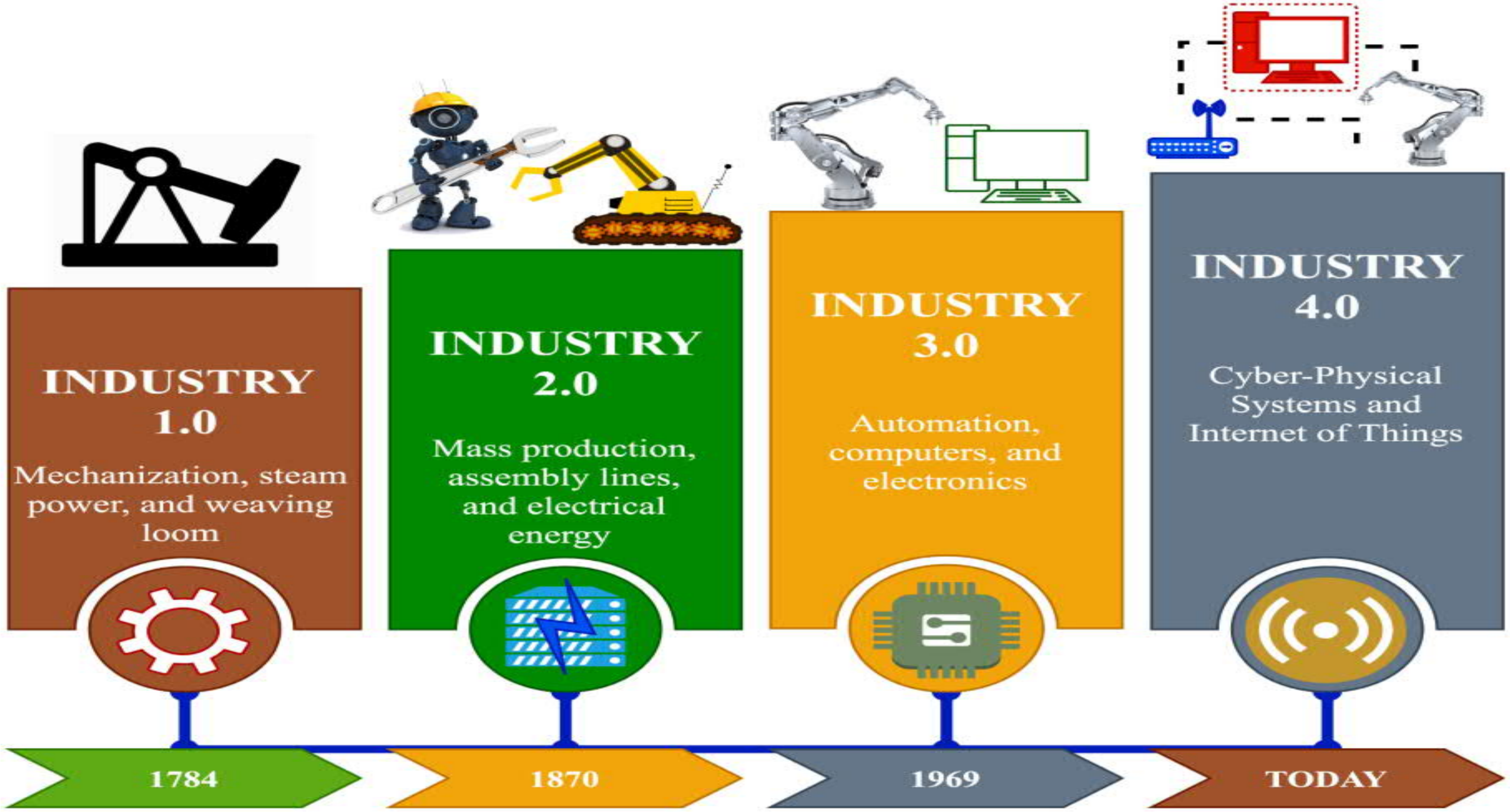


Fig.1 Revolution of smart industry.

Source: R. A. Khalil, N. Saeed, M. Masood, Y. M. Fard, M.-S. Alouini, and T. Y. Al-Naffouri, “Deep learning in the industrial internet of things: Potentials, challenges, and emerging applications,” IEEE Internet of Things Journal, vol. 8, no. 14, pp. 11016–11040, 2021.

WHAT IS IIOT USE-CASES ?

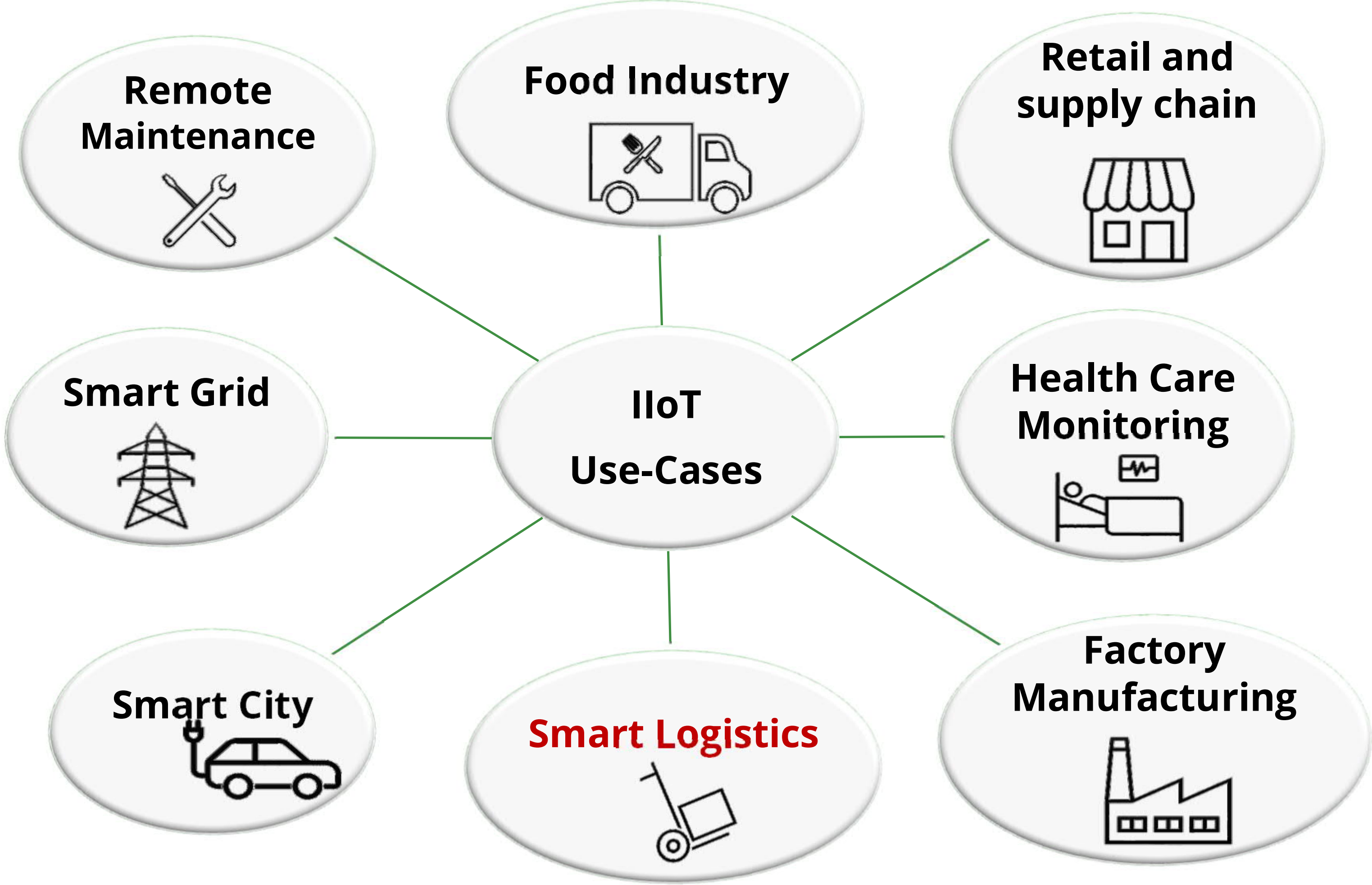


Fig.2 IIoT use-cases.

Source:

WHAT IS IIoT ARCHITECTURE ?

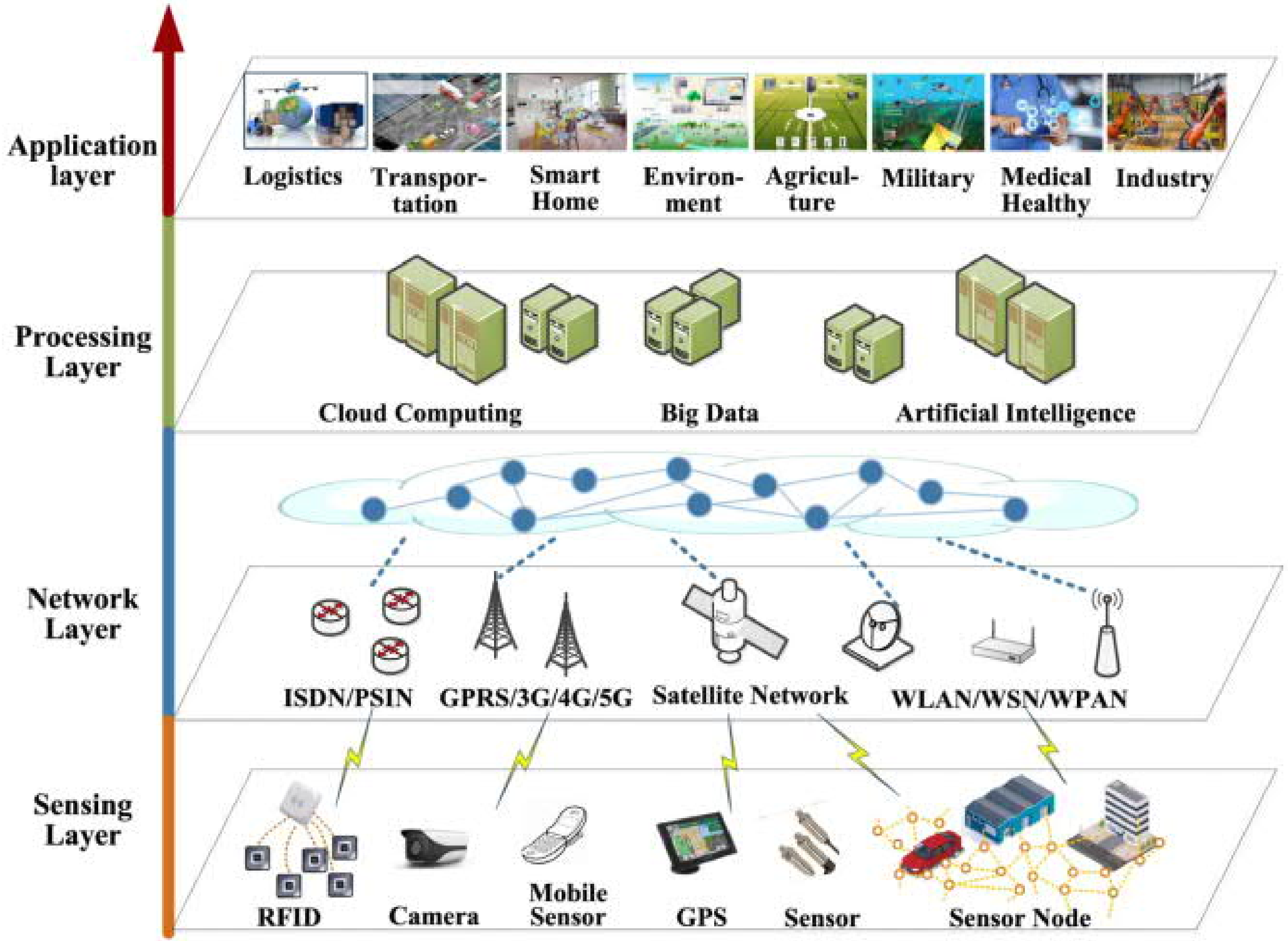


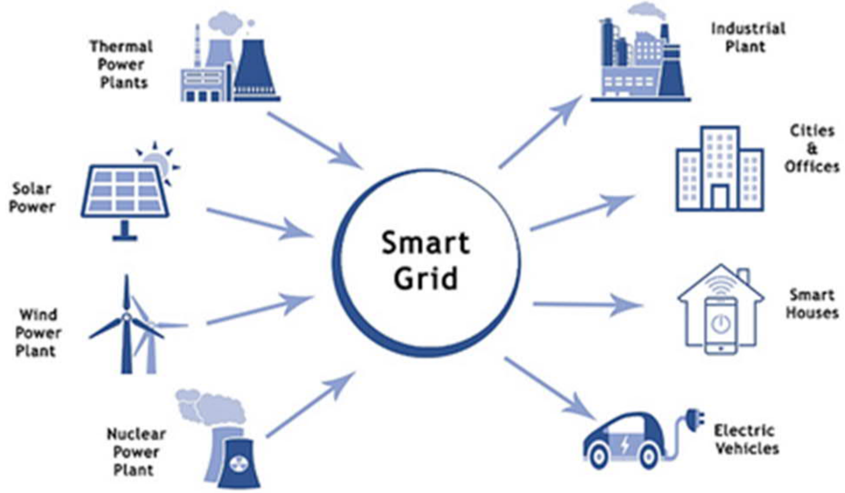
Fig.3 IoT architecture.

Source: T. Qiu, J. Chi, X. Zhou, Z. Ning, M. Atiquzzaman, and D. O. Wu, "Edge computing in industrial internet of things: Architecture, advances and challenges," IEEE Communications Surveys & Tutorials, vol. 22, no. 4, pp. 2462–2488, 2020.

WHAT ARE THE CHALLENGES IN IIOT ?

- Devices have limited power and computation resources and low delay tolerance.
- Machines continuously generate various types of computation tasks, leading to a large amount of computation data traffic.
- Tasks need to be processed in a timely, reliable, and efficient way.

(a) Warehouse management.



(b) Smart grid power distribution.

Fig.4 (b) IIoT computation tasks examples.

T. Qiu, J. Chi, X. Zhou, Z. Ning, M. Atiquzzaman, and D. O. Wu, "Edge computing in industrial internet of things: Architecture, advances and challenges," IEEE Communications Sur Tutorials, vol. 22, no. 4, pp. 2462–2488, 2020.

WHAT IS THE SOLUTION ?

- ❑ MEC reduces the decision-making latency and saves bandwidth.
- ❑ Task offloading adds an additional transmission delay to the computation delay.
- ❑ Decide whether to remotely or locally execute the tasks.
- ❑ The availability and quality of communication resources.

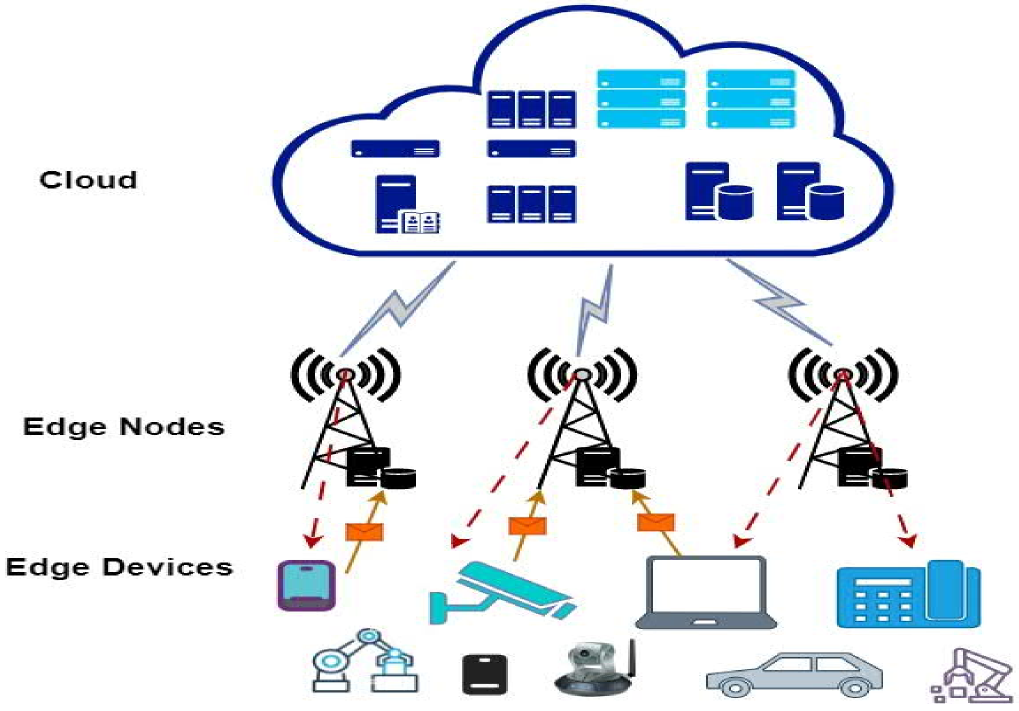


Fig. 2 Mobile Edge Computing (MEC).

HOW DEVICES CONNECT ?

- ❑ Support massive IIoT MDs with dynamic data traffic load.
- ❑ **<u>Dynamic multichannel access</u>** for efficient spectrum utilization.
- ❑ Sensing the spectrum and transmitting if the energy detected is below a certain threshold.

  LTE-U: Listen-Before-Talk (LBT). **IEEE 802.11:** Request-To-Send/Clear-To-Send (RTS/CTS).
- ❑ Spectrum sensing is susceptible to

  1. False detection and errors. 2. High energy consumption 3. Overhead and delay.

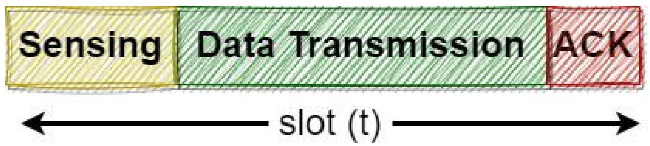


Fig.6 (a) Time slot structure.

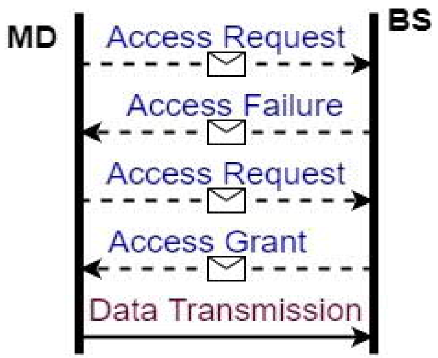


Fig.6 (b) Control messages exchange.

HOW DEVICES CONNECT ?

- ❑ Difficult for the IIoT MD to observe the state of all channels.
- ❑ Low-efficient task offloading.
- ❑ Task offloading may not give better performance than local computing.

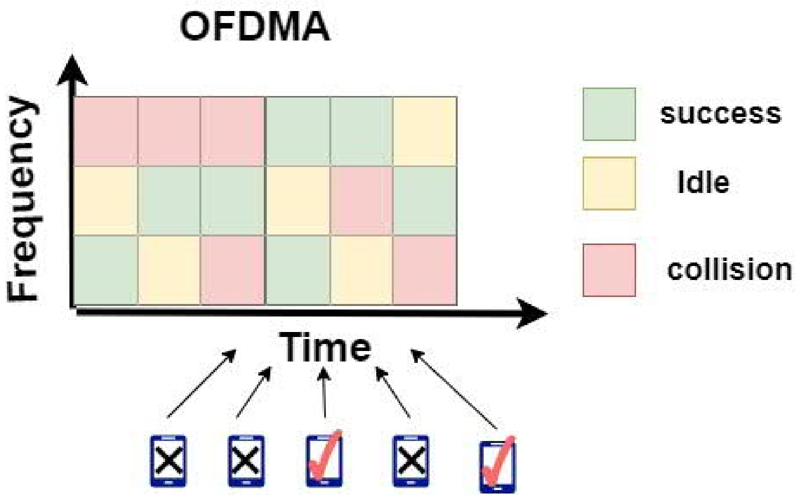


Fig.3 (a) Contention-based.

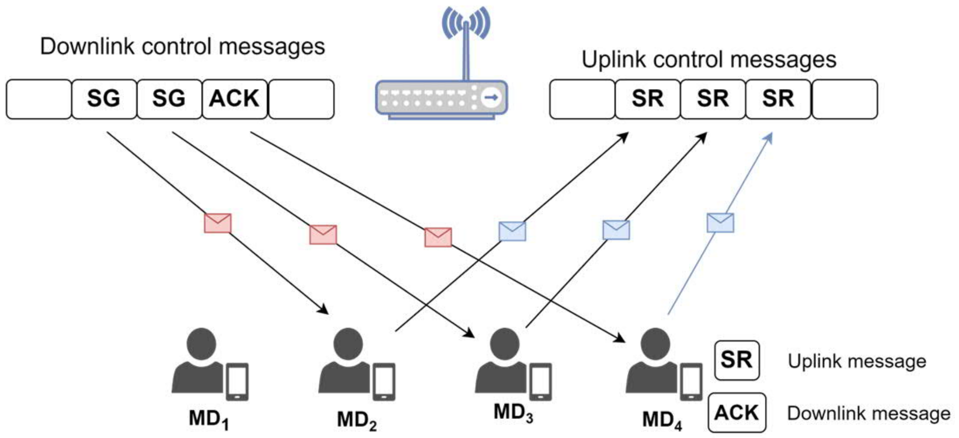


Fig.3 (b) Contention-free .

PROBLEM DEFINITION

- **Problem:** joint task offloading decision and scheduling of computation tasks.
- **Objective:** maximizing the number of tasks that can be executed within the deadline constraint.
- Problem has two parts:

1) Task Offloading Decision: Should the task be Locally or Remotely computed ?
2) Multichannel Access: If Remotely which channel ?

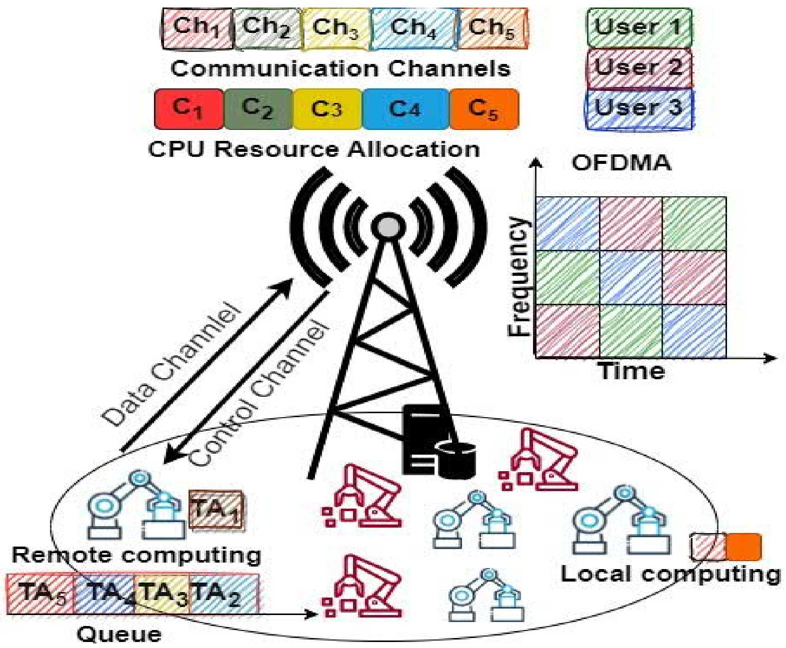


Fig. 5 Mobile Edge Computing Usecase.

MARL FRAMEWORK

- ❑ Agents interact in a dynamic environment and learn how to coordinate their behavior.
- ❑ 5G-NR ultra-lean design principle to minimize always-on signaling.
- ❑ Learn robust policies that are able to generalize to new scenarios.

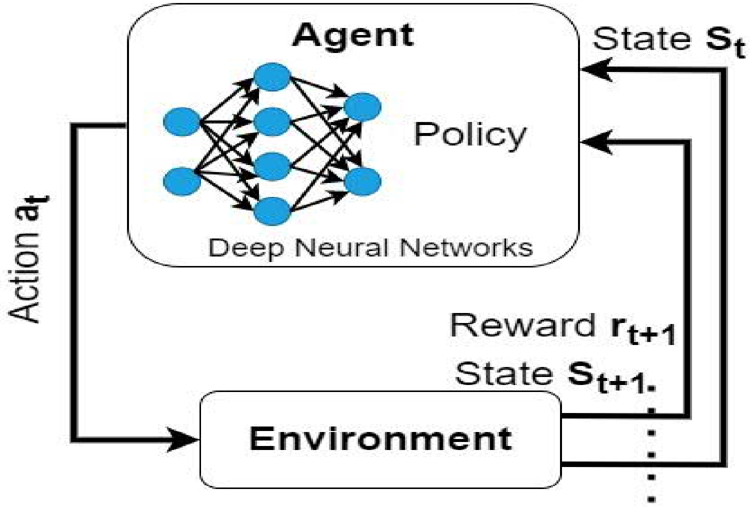


Fig.7 Deep Reinforcement Learning.

Emergent Communication Protocol Learning for Task Offloading in Industrial Internet of Things

SYSTEM MODEL

❑ Network Model

➢ **1. Base station**

M downlink multiaccess channels each with bandwidth **W** MHz.

$F_{\max}$ CPU allocated equally among scheduled users.

2. *N* IIoT MDs

f_nCPU

FIFO computation queue with capacity **K**.

Transmit power level p_n.

➢ Computation task (A_k , L_k , τ_k) is non-dividable

A_k : task size in bits.

L_k : no. of req. CPU cycles per bit.

τ_k : task delay deadline.

➢ Tasks arrival rate is a **Poisson process** $\lambda = p_k \times T$

p_k : task arrival probability. T : communication time period.

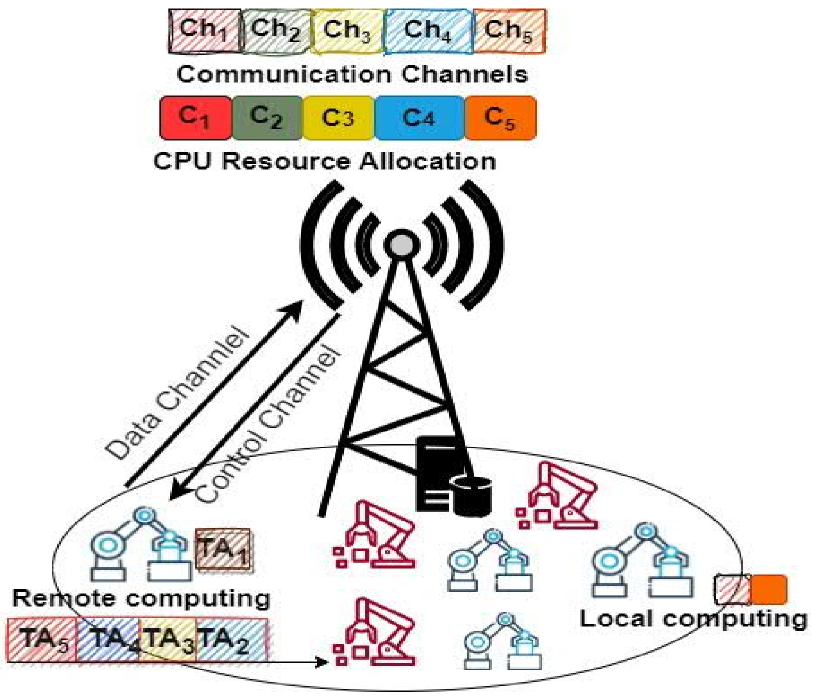


Fig.8: Mobile Edge Computing.

SYSTEM MODEL

- **Communication Model**

1) Uplink and downlink control channels are dedicated and error-free.

2) Data channels are time-invariant Gaussian channel with AWGN $z \sim CN(0, \sigma^2)$.

3) Uplink rate of IIoT MD n is $R_n = W \log_2 \left(1 + \frac{g_{n,m} p_n}{\sigma^2}\right)$ *bps* $g_{n,m}$ is the data channel gain.

4) **OFDMA** transmission scheme, where channels are shared.

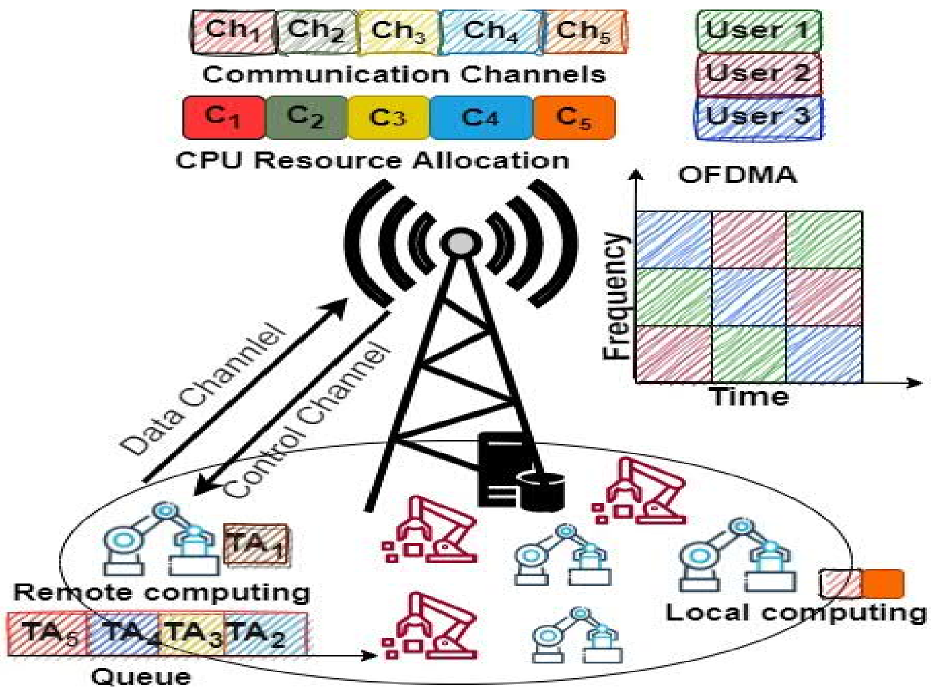


Fig.9 Mobile Edge Computing.

SYSTEM MODEL

Computation Model

1) Tasks can be either computed **locally** at the IIoT MDs or **remotely** at the BS.

2) Computation model is based on the advanced dynamic voltage and frequency scaling (DVFS) technique.

3) **Local computation time**

$$t^{l}_{k,n} = \frac{A_{k,n} \times L_{k,n}}{f_n}$$

4) Remote computation time includes only the upload time and execution time at the base station

$$t^{r}_{k,n} = t^{u}_{k,n} + t^{\mathrm{e}}_{k,n} = \frac{A_{k,n}}{R_n} + \frac{A_{k,n} \times L_{k,n}}{f_m} \qquad f_m = F_{max}/M$$

Download time is ignored as the computation results are usually small in the smart logistic use case.

PROBLEM FORMULATION

- **MARL cooperative task**, BS and IIoT MDs are RL agents learn how to communicate with each other to solve the problem of joint offloading decision and scheduling of computation tasks.
- **Dec-POMDP**, augmented with communication.

✓ **Main Objective:**

Maximize the number of computation tasks that can be executed within the delay constraint.

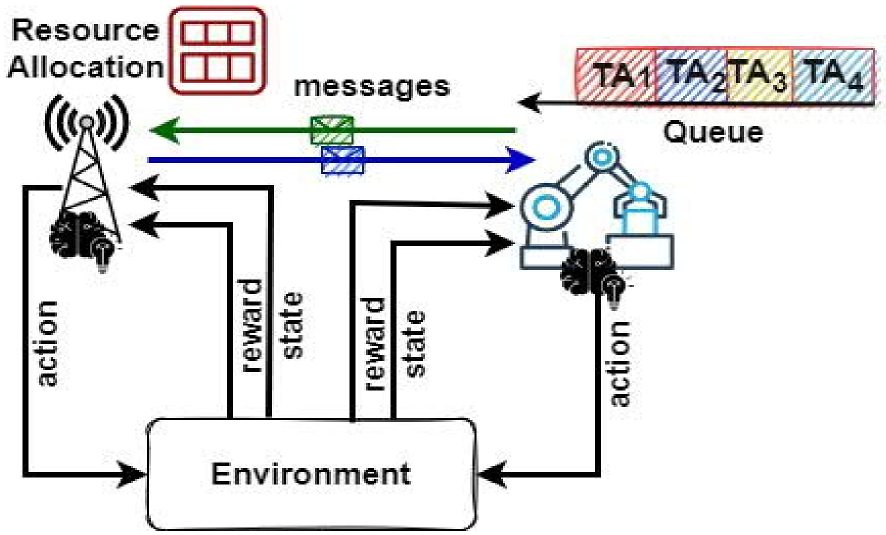


Fig.10 IIoT MDs and BS are cooperative MARL.

PROBLEM FORMULATION

❑ Observation Space

➢ IIoT MD n has $O_n(t)$ = (|K|, S)

No. of tasks in the queue |K|, $S \in \{0,1,2\}$ selected channel state.

➢ BS $O_b(t) = (h_1, h_2, \ldots, h_M)$ contains the states of the M channels and users successfully computed their tasks.

$$h_m = \begin{cases} 0, & \text{if the channel is idle} \\ n, & \text{if IIoT MD } n \text{ transmits on the channel} \\ N+1, & \text{if the channel has collision} \end{cases}$$

❑ Action Space

1) **Environment action:** contains an offloading decision and a channel selection action $a_n(t) = (a_0, a_c)$.

$$a_o(t) = \begin{cases} 0 & \text{Local Computing} \\ 1 & \text{Remote Computing} \end{cases}$$

$$a_c(t) \in \{0, 1, 2, \ldots, M\}$$

2) **Communication action:**

Uplink messages $U^n \in \{0, 1\}$ Downlink messages $D_n \in \{0, 1, 2, M, M+1\}$

PROBLEM FORMULATION

❑State Space

1) IIoT mobile device state: $(o_t^n, \ldots, o_{t-l}^n, a_t^n, \ldots, a_{t-l}^n, U_t^n, \ldots, U_{t-l}^n, D_t^n, \ldots, D_{t-l}^n)$
2) Base station state: $(o_t^b, \ldots, o_{t-l}^b, \boldsymbol{U}_t, \ldots, \boldsymbol{U}_{t-l}, \boldsymbol{D}_t, \ldots, \boldsymbol{D}_{t-l})$

$\boldsymbol{U} \triangleq [U_1, U_2, \ldots, U_N]$ and $\boldsymbol{D} \triangleq [D_1, D_2, \ldots, D_N]$ are the uplink and downlink messages.

❑Reward Function

$$r_n(t) = \begin{cases} +\rho & \text{if the task computed within the delay deadline.} \\ -\rho & \text{if the task computation exceeded the delay deadline.} \\ 0 & \text{otherwise} \end{cases}$$

Team reward $r(t) = \sum_{n \in \mathcal{N}} r_n(t),$

BASELINES FOR COMPARISION

1) **Local Computation:** all IIoT MDs locally compute their computation tasks.
2) **Remote Computation with Communication:** all IIoT MDs remotely compute their computation tasks at the BS and exchange messages.
3) **Remote Computation without Communication:** all IIoT MDs remotely compute their computation tasks at the BS without exchanging messages.
4) **Contention-based:** Each IIoT MD transmits with a certain probability if the computation queue is not empty and randomly accesses the channels.
5) **Contention-Free:** BS controls and schedule the resources.

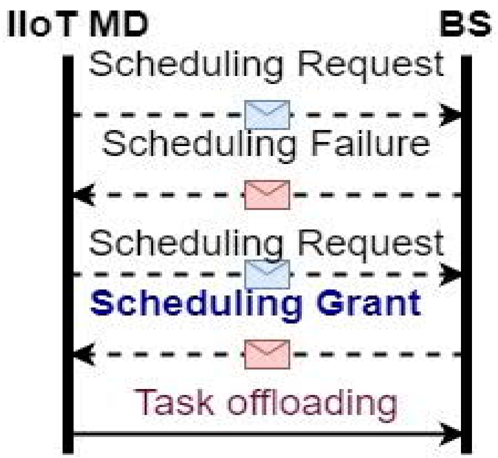


Fig.12 (a) control messages

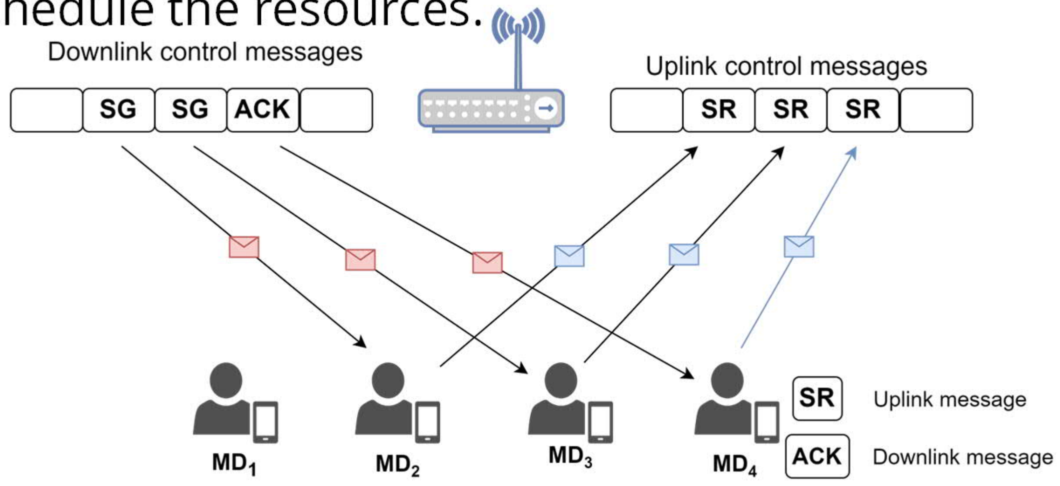


Fig.12 (b) Contention-free control messages

SIMULATION PARAMETERS

- Consider a warehousing logistic area with a BS that covers a 10 m × 10 m region and N = 3 IIoT MDs.
- The frequency range 1 (FR1) **0.45–7.125GHz.**
- 5G – NR operating band (n1) uplink range (1920-1980 MHz) and downlink range (2110-2170 MHz) and duplex mode FDD.

Table.1 System Parameters

Parameters	Values
No. of Sub-carriers	2
Sub-carrier Bandwidth	5 MHz
No. of IIoT MDs	3
Distance-dependent Path loss	$128.1 + 37.6 \log_{10} d$, dB
Channel Fading Model	Rayleigh fading with variance 1
Tasks Size	100 − 500 bits
Tasks Computation Requirement	$10^2 - 10^4$ CPU cycles per bit
Tasks Delay Tolerance	0.20 − 0.50 millisecond
Noise Power Spectral Density	-174 dBm/Hz
BS Computation Capacity	100 GHz
IIoT MD Computation Capacity	1 GHz
IIoT MD Queue Capacity	10
Probability of Task Arrival	0.50
Duration of episode	25

CENTRIC

MARL ALGORITHM

- **Multi-agent Proximal Policy Optimization (MAPPO)**

✓ On-policy policy gradient algorithm.

✓ MAPPO allows centralized training and decentralized execution (CTDE), where the agents learn a shared optimal policy instead of individual policy for each agent.

Table.2 MAPPO/IPPO Hyperparameters

Hyperparameter	Values
No. of episodes	10000
No. of epochs	100
Minibatch size	64
Discount factor	0.99
GAE parameter	0.95
Clipping parameter	0.2
VF coeff.	0.2
Entropy coeff.	0.2
Optimizer	Adam
Optimizer epsilon	10^{-5}

KPI

- **No. of Successfully Computed Tasks:**

No. of computation task computed within the delay deadline.

- **Channels Collision Rate:**

$$R_c = \frac{N_c}{M \times T}$$

- **Successful Channels Access Rate:**

$$R_s = \frac{N_s}{M \times T}$$

Simulation Results

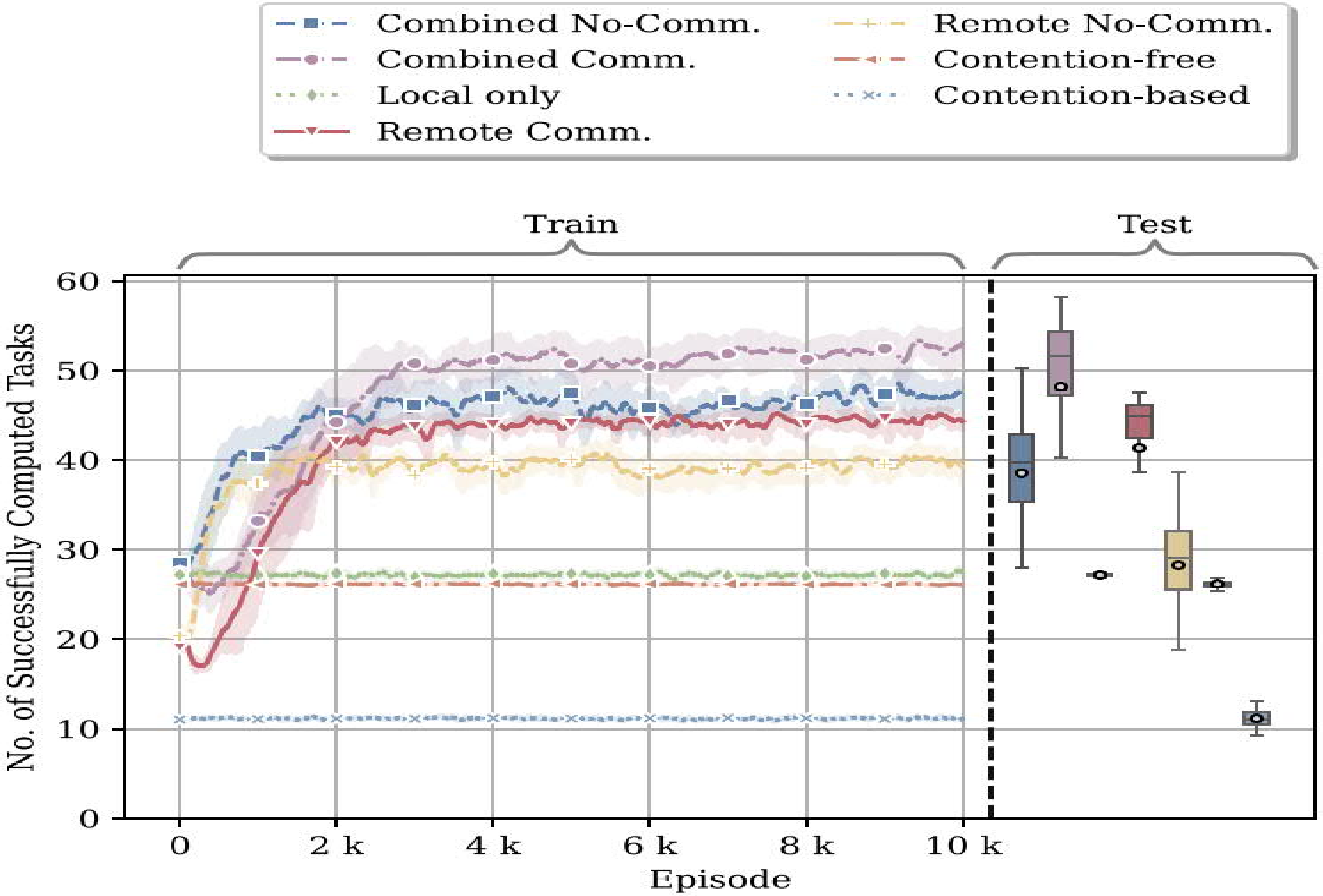


Figure 3: Number of tasks successfully computed versus training episodes.

Simulation Results

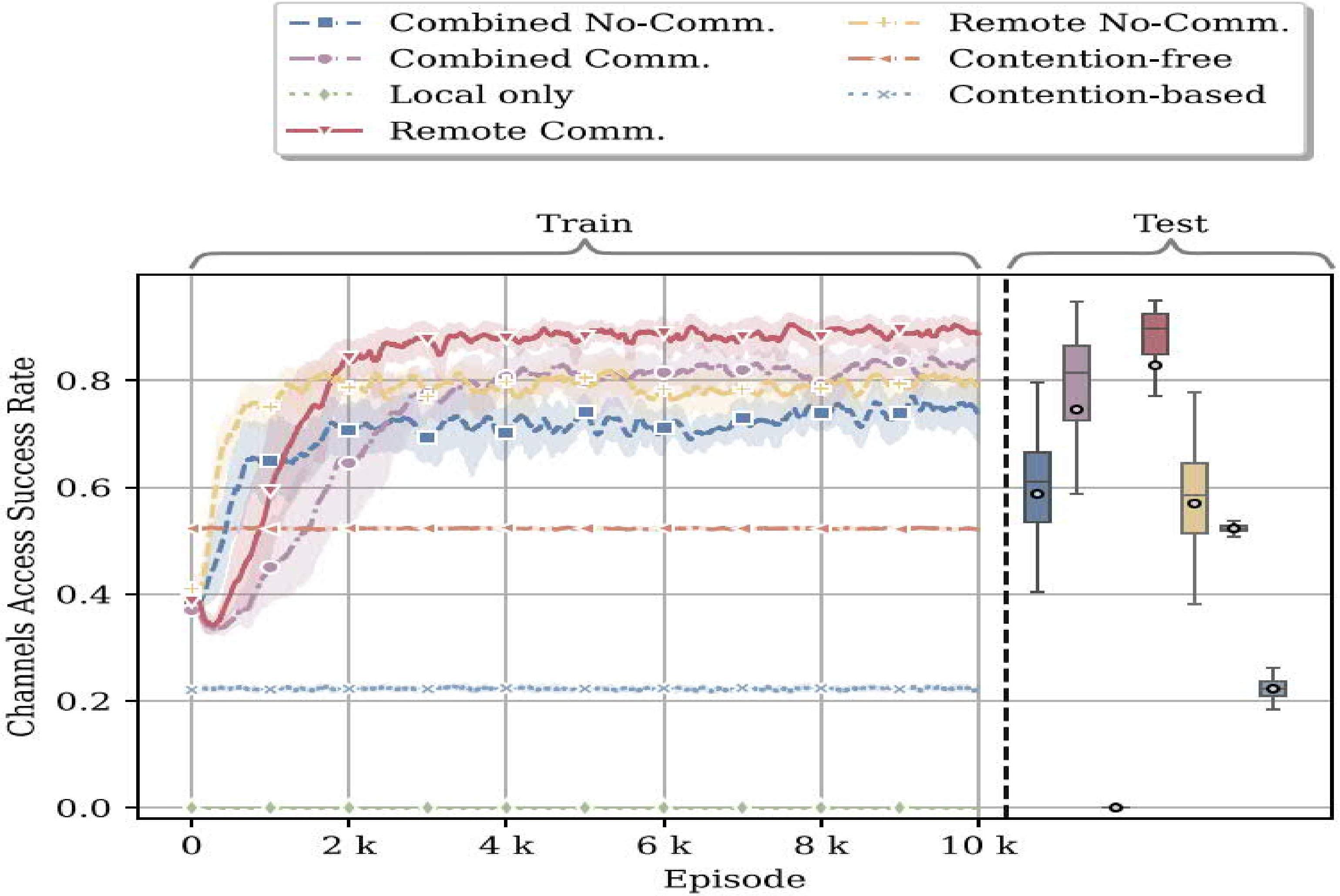


Figure 4: Channel access success rate versus training episodes.

Simulation Results

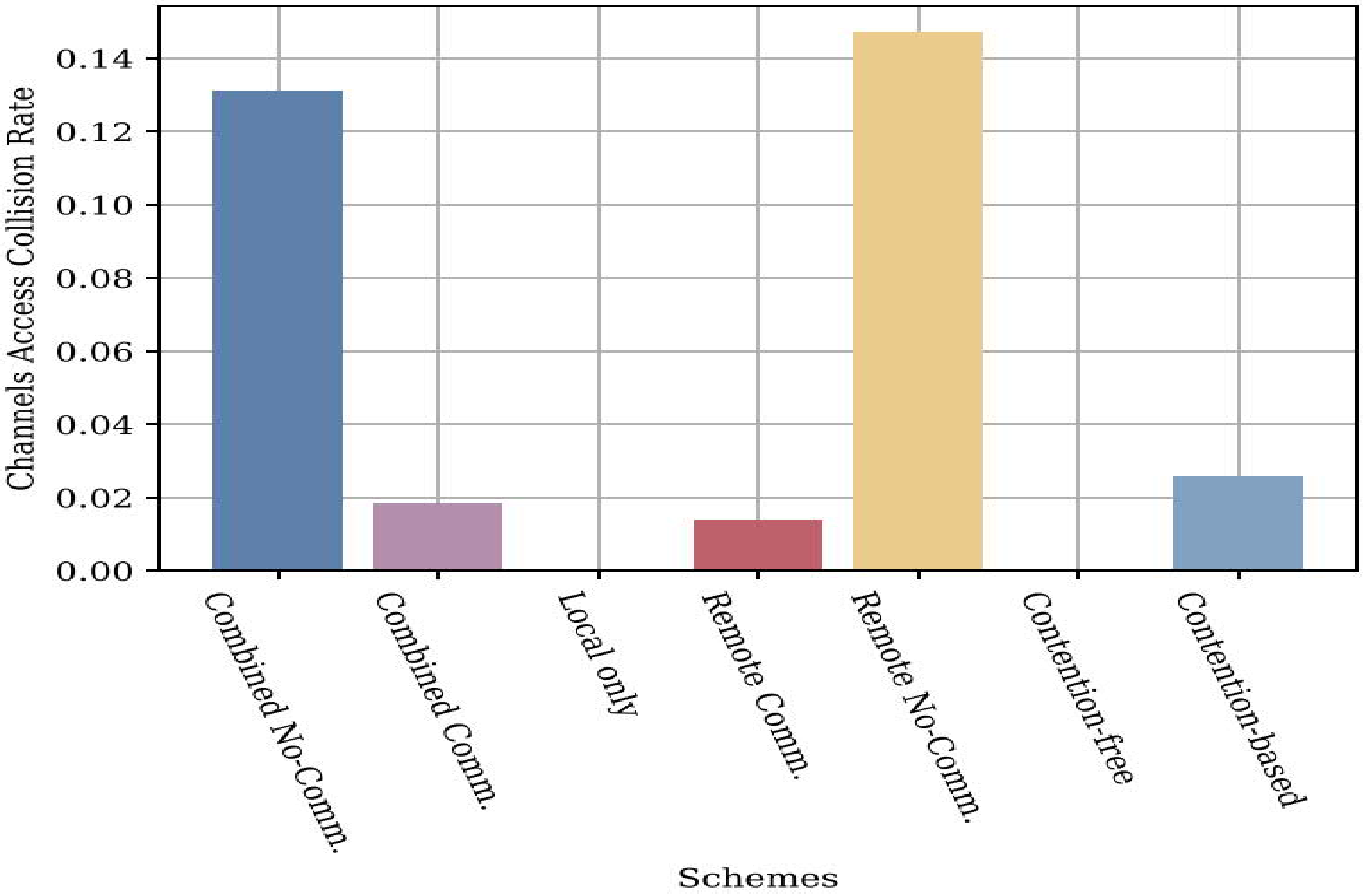


Figure 5: Collision rate for different schemes.

Conclusion & Future Work

Conclusion

- We proposed an emergent communication protocol learning framework for solving the problem of joint task offloading decision and scheduling of computation tasks.
- MARL framework is adopted so that BS and IIoT MDs learn how to communicate with each other to solve the problem in a cooperative manner.
- The simulation results indicated the effectiveness of the learned protocols in maintaining highly efficient task offloading and maximizing the number of successfully computed.

Future Work

- The scalability of the proposed approach in which a large number of IIoT MDs are connected to the network.

QUESTIONS & SUGGESTIONS

Questions

Suggestions

Feedback

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Many thanks for your attention!

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