



HAL
open science

Reinforcement and deep reinforcement learning for wireless Internet of Things: A survey

Mohamed Said Frikha, Sonia Mettali Gammar, Abdelkader Lahmadi, Laurent
Andrey

► **To cite this version:**

Mohamed Said Frikha, Sonia Mettali Gammar, Abdelkader Lahmadi, Laurent Andrey. Reinforcement and deep reinforcement learning for wireless Internet of Things: A survey. *Computer Communications*, 2021, 178, pp.98-113. 10.1016/j.comcom.2021.07.014 . hal-03409798

HAL Id: hal-03409798

<https://inria.hal.science/hal-03409798v1>

Submitted on 30 Oct 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Reinforcement and deep reinforcement learning for wireless Internet of Things: A survey

Mohamed Said Frikha^a, Sonia Mettali Gammar^a, Abdelkader Lahmadi^b, Laurent Andrey^b

^aCRISTAL Lab, National School of Computer Science, University of Manouba, Manouba, Tunisia

^bCNRS, Inria, LORIA, Université de Lorraine, F-54000 Nancy, France

Abstract

Nowadays, many research studies and industrial investigations have allowed the integration of the Internet of Things (IoT) in current and future networking applications by deploying a diversity of wireless-enabled devices ranging from smartphones, wearables, to sensors, drones, and connected vehicles. The growing number of IoT devices, the increasing complexity of IoT systems, and the large volume of generated data have made the monitoring and management of these networks extremely difficult. Numerous research papers have applied Reinforcement Learning (RL) and Deep Reinforcement Learning (DRL) techniques to overcome these difficulties by building IoT systems with effective and dynamic decision-making mechanisms, dealing with incomplete information related to their environments. The paper first reviews pre-existing surveys covering the application of RL and DRL techniques in IoT communication technologies and networking. The paper then analyzes the research papers that apply these techniques in wireless IoT to resolve issues related to routing, scheduling, resource allocation, dynamic spectrum access, energy, mobility, and caching. Finally, a discussion of the proposed approaches and their limits is followed by the identification of open issues to establish grounds for future research directions proposal.

Keywords: Internet of Things, Reinforcement learning, Deep reinforcement learning, Wireless Networks.

1. Introduction

Internet of Things has introduced more openness and complexity by connecting a large number and a variety of wireless-enabled devices. It allows the collection of a massive amount of data and appliance of control actions in various applications. [1, 2] such as healthcare [3], traffic congestion [4], agriculture [5], autonomous vehicle [6]. Wireless IoT devices such as connected vehicles, wearables, drones, and sensors, are able to interact with each other over the Internet, making people's life more comfortable. The deployment of these devices forms a set of Wireless Sensor Network (WSN), characterized by a large number of low-cost and low-power sensors with a short-range wireless transmission. WSN represents the primary source for collecting and monitoring information subsequently processed by the IoT due to its low cost and ease of integration.

Wireless technology has changed the way Internet Protocol (IP) devices communicate and share information using transmission through radio frequencies, light-waves, etc. These technologies also make it possible to deploy IoT networks in unreachable areas where it is unmanageable to build wired networks. Furthermore, various wireless technologies applied in IoT have been developed in the past few years to meet the requirements, including reducing energy consumption, compressing data overhead, and improving security and transmission efficiency for different networks. However, managing heterogeneous infrastructure is a complicated task, especially when dealing with large-scale IoT systems, and requires a complex system to ensure their operations and optimize data flow distribution.

Over the last five years, Machine Learning (ML) [7] techniques are adopted to integrate more autonomous decision-making in wireless IoT networks to effectively address their various issues and challenges, such as energy efficiency, load balancing, and cache management. Machine learning algorithms are also applied for IoT data analytics to discover new information, predict future insights, and offer new real-time services. Compared to statistical methods, ML algorithms provide better accurate predictions when dealing with very large data sets and they do not require heavy assumptions such as linearity or the distribution of variables [8]. They also have acceptable performance when using them for online classification or prediction [9].

ML techniques, especially Reinforcement Learning [10], attempt to make IoT nodes take self-decisions for multiple networking operations, including routing, scheduling, resource allocation, dynamic spectrum access, energy, mobility, and caching. The RL agent must be able to understand the environment dynamics, without any prior knowledge, through the collected data and take the best action to achieve a networking goal, like reducing energy consumption, improving security level, and changing transmission channel.

However, as the complexity of the IoT networks increases with high-dimensional states and actions, traditional RL techniques show their limits regarding computation complexity and convergence towards a poor policy. Thus, Deep Reinforcement Learning techniques, a combination of RL and Deep Learning (DL) approaches [11, 12] based on Artificial Neural Networks (ANN) [13], are developed to overcome such limitations and make the learning and the decision operations more efficient.

In recent years, several surveys related to the integration of machine learning techniques in networks and IoT applications have been published. We provide in table 1 a summary of existing papers in this area. Papers [14, 15, 16] focused on the application of traditional RL in wireless networks. This technique can predict the near-optimal policy in cases where the number of states and actions is limited and improves the performance of networks with limited resources. The application of DRL has been discussed in [17, 18, 19] for IoT and real-world problems like cloud computing, autonomous robots, and smart vehicles. The studied papers in these surveys use DRL to accelerate the learning process, compared to the traditional RL, and reduce the storage space required by vast possible actions. Most surveys that study articles applying Machine Learning in networking focus on supervised and unsupervised methods [20, 21]. Only the survey proposed by [22] includes RL algorithms in its studied papers.

This paper provides a survey and a taxonomy of existing research which applies numerous RL and DRL algorithms for wireless IoT systems based on IoT application and network issues. An overview of these learning techniques is presented, and the main characteristics of the RL elements (i.e., state, action, and reward) are summarized. Finally, we highlight the lessons learned with the remaining challenges and open issues for future research directions. To the best of our knowledge, there does not exist an article in the literature that is dedicated to surveying the application of reinforcement learning methods in different wireless IoT technologies and applications. Our survey differs from previous ones by covering the two RL and DRL methods for solving the network and application problems in wireless IoT, as proposed in research papers published in the period 2016-2020. We reviewed papers that address the following key issues: routing, scheduling, resource allocation, dynamic spectrum access, energy, mobility, and edge caching.

The rest of this paper is organized as follows. Section 2 presents an overview of some wireless IoT networks. Section 3 introduces a brief description of the principle of RL, Markov Decision Process (MDP), and DRL. Section 4 reports research works that have applied RL and DRL techniques in the IoT environment according to their objective. A discussion is provided in Section 5 with statistics information on the articles reviewed in this work. Limitations of RL and DRL techniques and open challenges are identified in Section 6. Finally, Section 7 concludes this study.

2. Wireless IoT Systems

In this section, we provide an overview of wireless IoT systems studied in the surveyed papers and identifies their characteristics and challenges.

2.1. Wireless Sensor Network (WSN)

The evolution in the field of wireless communications and electronics has allowed building small and individual nodes, called sensors, that interact with the environment by sensing

and controlling physical parameters, such as temperature, pressure, and motion. WSNs are composed of low-cost and battery-powered nodes that can send/receive messages to/from the sink and interact with each other through short-distance wireless communication. Using WSN networks has increased with the advent of the IoT since it is one of the big data sources for collecting and monitoring information further processed by the IoT. However, it has several weaknesses, including limited processing power, smaller memory capacities, and energy constraint with the difficulty of recharging or replacing the battery. In addition, some problems are related to the management of WSN that limit the technologies in which used, such as deployment, routing, security, and network lifetime.

2.2. Wireless Body Area Network (WBAN)

WBAN is a small, short-range, low-power network with a dozen sensors attached to or implanted in/around the human body. The sensor nodes are employed to detect physiological phenomena and provide real-time patient monitoring of different physical parameters, such as body temperature, blood pressure, and electrocardiography (heart rate). Using wireless communication, the collected information is then transmitted to a coordinator (i.e., sink node) that will process it, make decisions or raise an alert. Depending on the WBAN services for medical or non-medical applications, the communication characteristics vary. Different wireless technologies are applied in WBAN, including Bluetooth Low Energy (BLE), IEEE 802.15.4 (Zig-Bee), and IEEE 802.15.6 (Ultra Wide-Band) [23]. The WBAN standard specified for short communication range, low transmission power in particular for nodes under the skin, a minimal latency period especially for medical applications, and also supports mobility due to body movements [24].

2.3. Underwater Wireless Sensor Network (UWSN)

UWSN [25] is a self-configuring network that contains several autonomous components, such as vehicles and sensors, distributed underwater to perform environmental monitoring and ocean sampling tasks, like pressure, depth, visual imaging, assisted navigation, etc. The underwater architecture can be classified into two common categories: a two-dimension architecture, where a group of nodes is connected to one or more fixed anchor nodes, and a three-dimension architecture, where the sensors float at different depths. Due to water currents, the network nodes are dynamic, and the connectivity can vary with time. Due to water currents, network nodes are dynamic and connectivity can vary over time. Compared to the terrestrial environment, the performance of submarine sensors faces different challenges related to the physical nature that limit the bandwidth, leading to a high propagation delay, raise resource utilization, etc. For that, three principal wireless communication technologies for underwater environments are used, with different characteristics, depending on services requirements: optical, radio-frequency, and acoustic [26].

Table 1: Related surveys on the use of RL/DRL/ML in communication networks

| Survey | Year | Contribution | Application domain | ML | RL | DRL |
|------------------------------|------|--|--------------------------------|----|----|-----|
| Al-Rawi <i>et al.</i> [14] | 2015 | The authors in this paper provided an overview of the application of RL based routing schemes in distributed wireless networks. The challenges, the advantages brought, and the performance enhancements achieved by the RL on various routing schemes have been identified. | Wireless networks - Routing | | ✓ | |
| Cui <i>et al.</i> [20] | 2018 | The authors in this survey provided an overview of the ML techniques and solutions, in particular, the supervised and unsupervised solutions for IoT. | IoT | ✓ | | |
| Althamary <i>et al.</i> [15] | 2019 | The paper summarized some issues related to vehicular networks and reviews the applications using the Multi Agent Reinforcement Learning (MARL) that enables decentralized and scalable decision making in shared environments. | Vehicular networks - MARL | | ✓ | |
| Wang <i>et al.</i> [16] | 2019 | A classification of the Dynamic Spectrum Access (DSA) algorithms based on RL in cognitive radio networks has been presented. | Cognitive radio networks - DSA | | ✓ | |
| Luong <i>et al.</i> [17] | 2019 | A comprehensive literature review on techniques, extensions, and applications of DRL to solve different issues in communications and networking has been surveyed in this paper. | Communications and networking | | | ✓ |
| Da Costa <i>et al.</i> [21] | 2019 | The security methods in terms of intrusion detection, for IoT and its corresponding solutions using ML techniques, have been studied in this work. | IoT - Security | ✗ | | |
| Kumar <i>et al.</i> [22] | 2019 | The authors of this paper reviewed ML-based algorithms (includes RL methods) for WSNs, covering the period from 2014-March 2018. The different issues in WSNs and the advantages of selecting an ML technique in each case have been presented. | WSN | ✓ | ✓ | |
| Lei <i>et al.</i> [18] | 2020 | This paper initially described the general model of Autonomous Internet of Things (AIoT) systems based on the three-layer (i.e., perception layer, network layer, and application layer) structure of IoT. The classification of DRL AIoT applications and the integration of the RL elements for each layer have been summarized. | Autonomous IoT | | ✓ | ✓ |
| Nguyen <i>et al.</i> [19] | 2020 | An overview of different technical challenges in multi-agent learning has been present, as well as their solutions and applications to solve real-world problems using DRL methods. | Multiagent Systems | | | ✓ |

Legend: ✓ Covered; ✗ Partially Covered

2.4. Internet of Vehicle (IoV)

The integration of Vehicular Ad-Hoc Network (VANET) [27] into the IoT was an important milestone on the way to the advent of the IoV [28]. It refers to a network of different entities regarding vehicles, roads, smart cities, pedestrians that exchanged real-time information among them efficiently and securely. IoV has brought new applications to driving and using vehicles, for instance, safe and autonomous driving, crash response, traffic control, infotainment. Vehicular networks have various characteristics that differ from mobile node networks as a dynamic height topology since vehicles move at high speed and in a random way, a large-scale network with a variable den-

sity depending on the traffic situation, and without a constraint on computing power or energy consumption. Many special requirements therefore arise, includes processing big data using cloud computing, providing good connection links with an unstable mobile network, and achieving height reliability, security, and privacy of information. In terms of connectivity, the IoV consists of two types of wireless communications: Vehicle-to-Vehicle used to inter-vehicular exchanged information using, for example, the IEEE 802.11p [29] standard, and Vehicle-to-Infrastructure, also now as Vehicle-to-Road, where the vehicle exchanges information with roadside equipment with long-distance and high-scalability wireless technologies.

2.5. Industrial Internet of Things (IIoT)

The Industrial IoT [30] system refers to the adoption of the IoT framework for a large number of devices and machines in industrial sectors and applications. Machine-to-Machine (M2M) communication is a key technology in IIoT that allows devices to communicate and exchange data with each other. These intelligent machines can operate the highest level of automation without needing or with very minimal human intervention. The goal of IIoT is to achieve high operational efficiency, limit human errors, increase productivity, and reduce operating costs in both time and money, as well as predictive maintenance, using data collected from machines. The heterogeneity of the various communication protocols used and the complex nature of the system pose many challenges for designing wireless protocols for IIoT, such as higher levels of safety and security, efficient management of big data, and ensuring real-time communication in critical industrial systems.

3. Overview of Reinforcement Learning

This section provides a comprehensive background on different RL methods, including the principle of Markov Decision Process, Partially Observable Markov Decision Process (POMDP), and Deep RL models with their respective characteristics.

3.1. Reinforcement Learning and Markov Decision Process

Reinforcement learning is an experience-driven technique of machine learning where a learner (autonomous agent) makes an experience by a trial-and-error process in order to improve its choices in the future. In such a situation, the problem to solve is formulated as a discrete-time stochastic control process, so-called MDP [10]. Typically, a finite MDP is defined by a tuple (S, A, p, r) where S is a finite state space, A is a finite action space for each state $s \in S$, p is the state-transition probability from state s to state $s' \in S$ taking an action $a \in A$, and $r \in \mathbb{R}$ is the immediate reward value obtained after an action a is performed. The agent's primary goal is to interact with its environment, at each time step $t = 0, 1, 2, \dots$, to find the optimal policy π^* in order to reach the goal while maximizing the cumulative rewards in the long run. A policy π is a function that represents the strategy used by the RL agent. It takes the state s as input and returns an action a to be taken. The policy can be also stochastic. In such a case, it returns a probability distribution over all actions instead of a single action a . Mathematically, the objective of the agent is to maximize the expected discounted return R_t as follows:

$$R_t = \sum_{i=0}^{\infty} \gamma^i r_{t+i+1} \quad (1)$$

where $\gamma \in [0, 1)$ is the discount factor. It controls the importance of future rewards (weight) compared to the immediate one. The larger γ is, the more the estimated future rewards will be concerned. If $\gamma = 0$ the agent is "myopic" in being concerned only with maximizing immediate rewards.

In many applications, the agent does not have all information about the current state of the environment and had only a partial observation. Thus, the POMDP, a variant of the MDP, can be used to make decisions based on the potentially stochastic observation it receives. A POMDP can be defined by the tuple (S, A, p, Ω, O, r) where S, A, p, r are the states, actions, transitions and rewards as in MDP, Ω is a finite set of observations, and O is the observation probability from state $s \in S$ to state $s' \in S$ taking an action $a \in A$. A set of a probability distribution over the states S is maintained as "belief state", and the probability of being in a particular state is denoted as $b(s)$. Based on its belief, the agent selects an action $a \in A$, and move to a new state $s' \in S$ and receive an immediate reward r and a current observation $o \in O$. Then the belief about the new state is updated as follows [31]:

$$b_a^o(s') = \frac{p(o|s') \sum_s p(s'|s, a) b(s)}{\sum_{s'', s} p(o|s'') p(s''|s, a) b(s)} \quad (2)$$

In RL, the problems to resolve are formulated as an MDP. Several RL solutions can be applied, depending on the problem type considered. RL methods can be classified into multiple types as illustrated in Figure 1.

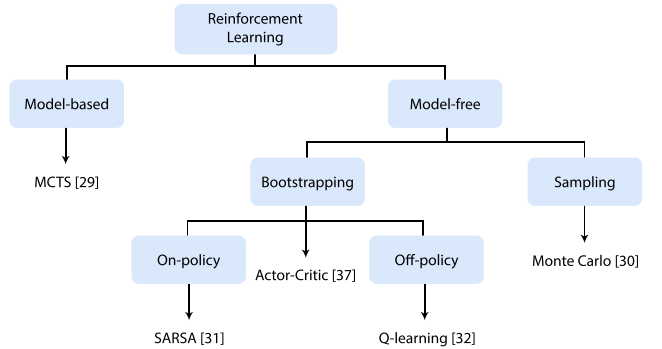


Figure 1: Classification of popular RL algorithms based on their operating features.

3.1.1. Model-based vs Model-free

With a model-based strategy, the agent learns the environment model, consisting of knowledge of state transitions and reward function. Then, simple information about the state's values is sufficient to derive policy. Whereas with a model-free, the agent learns directly from experience by collecting the reward from the environment and then updating their value function estimation. Model-based RL tends to emphasize planning to take action given a specific state, without the need for environmental information or interaction. Nevertheless, this solution fails when the state space becomes too large. Besides, these types of algorithms are very memory-intensive since transitions between states are explicitly stored. However, many model-based methods have been studied in the literature, such as Imagination-Augmented Agents (IAA) [32], Model-Based RL with Model-Free Fine-Tuning (MBMF) [33], AlphaZero [34], and Monte

271 Carlo Tree Search (MCTS) [35] remaining one of the frequently
272 used methods in learning agents.

273 MCTS is based on a random sampling of the search space to
274 build up the tree in memory and improve the estimation accu-
275 racy of the following choices. An MCTS strategy consists of
276 four repeated steps: (i) selection step, where the algorithm tra-
277 verses the current tree from the root node downwards to select
278 a leaf node; (ii) expansion step, where one or more new child
279 nodes (i.e., states) are added from the leaf node reached during
280 the selection step; (iii) a simulation is performed from the se-
281 lected node or one of the newly added child node with actions
282 selected by the followed strategy; (iv) Backup step, where the
283 return generated by the simulated episode is propagated back up
284 to the root node and updates the node action values accordingly.

285 3.1.2. Bootstrapping vs Sampling

286 If the estimation of the state’s values is based on another
287 learned estimation function (i.e., a part or all successor states),
288 the RL method is called a bootstrapping method. Otherwise,
289 the RL method is called a sampling method whose estimation
290 for each state is independent. This method is based only on the
291 real observation of the states, but it can suffer from high vari-
292 ance, which requires more samples before the estimates reach
293 the optimal solution. The bootstrapping method can reduce the
294 variance of an estimator without the need to store each element.

295 3.1.3. On-policy vs Off-policy

296 An on-policy method estimates the value of the poli-
297 cy used to make decisions. In an off-policy method,
298 the agent selects a different policy, called ”behavior poli-
299 cy”, regardless of the policy followed, called ”target poli-
300 cy”. State–Action–Reward–State–Action (SARSA) [37], an
301 on-policy method, and Q-learning [38], an off-policy method,
302 are the most RL techniques used in the literature. The equa-
303 tions below represent the updated function for SARSA and Q-
304 learning respectively:

$$296 \quad Q(s_t, a_t) = Q(s_t, a_t) + \alpha[r_{t+1} + \gamma Q(s_{t+1}, a_{t+1}) - Q(s_t, a_t)] \quad (3)$$

$$297 \quad Q(s_t, a_t) = Q(s_t, a_t) + \alpha[r_{t+1} + \gamma \max_a Q(s_{t+1}, a_{t+1}) - Q(s_t, a_t)] \quad (4)$$

305 where $Q(s_t, a_t)$ represents the estimate Q-value of taking ac-
306 tion a in state s at time t ; r_{t+1} represents the immediate reward
307 returned at time $t + 1$; $\max_a Q(s_{t+1}, a_{t+1})$ represents the esti-
308 mate Q-value of taking the optimal action a in state s at time
309 $t + 1$; $0 \leq \alpha \leq 1$ is the learning rate; and $0 \leq \gamma \leq 1$ is
310 the discount factor. The results of these equations are stored
311 in a policy table, called Q-table, where rows represent the pos-
312 sible states, columns represent the potential actions, and cells
313 represent the expected total reward, as depicted in Figure 2a.
314 In SARSA, the estimation of the Q-value uses the current poli-
315 cy based on the same action, while Q-learning selects a new
316 greedy action during the learning, independently of the policy

317 being followed. This makes SARSA more cautious as it tries to
318 take into account any negative circumstances of explorations,
319 while Q-learning will ignore them since it followed another in-
320 dependent policy.

321 Besides the value-based algorithms, such as SARSA and Q-
322 learning, which select actions according to the value function,
323 policy-based methods [39] such as REINFORCE [40], Trust
324 Region Policy Optimization (TRPO) [41], and Proximal Policy
325 Optimization (PPO) [42] search directly for the optimal policy
326 maximizing the expected cumulative reward. The advantage of
327 each method depends on the task. Policy-based methods are
328 better for continuous and stochastic environments, while value-
329 based learning methods are more sample efficient and stable.
330 The actor-critic methods [43] merge both: the ”critic” esti-
331 mates the value function to evaluate the action performed us-
332 ing the temporal difference error and the ”actor” updates the
333 policy distribution according to the critic suggestion. It takes
334 advantage of both policy and value functions. The policy actor
335 computes continuous actions without the need for an optimiza-
336 tion procedure, while the value critic supplies the actor with a
337 low-variance knowledge of the performance [44].

338 3.2. Deep Reinforcement Learning

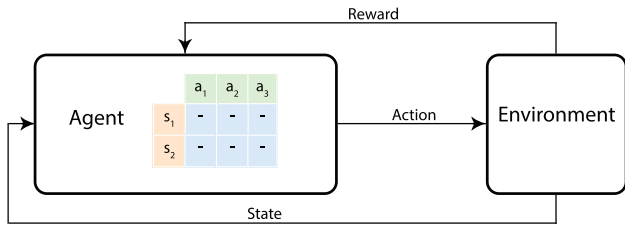
339 RL is effective in a variety of applications, where state and
340 action spaces are limited. However, these spaces are usually
341 large and continuous in real-world applications, and traditional
342 RL methods cannot find the optimal value functions or policy
343 functions for all states within an acceptable delay. Thus, DRL
344 was developed to handle high-dimensional environments [45]
345 based on the Deep Neural Network (DNN) value-function ap-
346 proximation as shown in Figure 2.

347 The DNN is a deeper version of the ANN family with, usually,
348 more than two hidden layers [46]. Generally, an ANN consists
349 of three principal layers, as presented in Figure 2b:

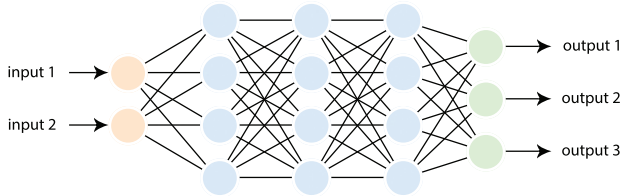
- 350 • A single input layer receives the data. The input data in
351 DRL represent the information that describes the actual
352 state of the environment.
- 353 • A single output layer generates the predicted values. In
354 some works, the nodes in the output layer present the pos-
355 sible actions that the DRL agent can select.
- 356 • One or multiple hidden layers located between the input
357 and output layers according to the problem complexity.

358 Mnih *et al.* [47] introduce in 2015 the concept of Deep Q-
359 Network (DQN) that performed well on 49 Atari games. DQN
360 exploits a Convolutional Neural Network (CNN), commonly
361 applied in image processing, instead of a Q-table, as shown
362 in Figure 2c, to analyze input images and derive an approximate
363 action-value $Q(s, a|\theta)$ by minimizing the loss function $L(\theta)$ de-
364 fined as follows:

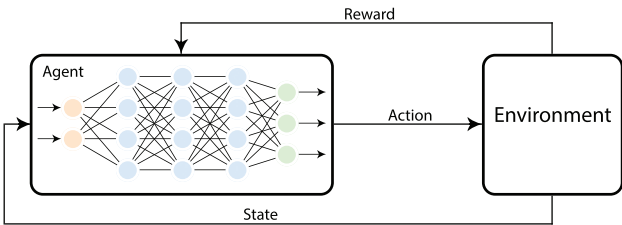
$$365 \quad L(\theta) = \mathbb{E} \left[\left(r + \gamma \max_{a'} Q(s', a'|\theta') - Q(s, a|\theta) \right)^2 \right] \quad (5)$$



(a) Standard Reinforcement Learning technique.



(b) A deep Neural Network with three hidden layers.



(c) Deep Reinforcement Learning technique.

Figure 2: Principles of RL, DNN and DRL techniques.

sues, where the agent needs many steps to get the optimal policy and achieve the goal, Hierarchical RL (HRL) forms several sub-policies that work together into hierarchically dependent sub-goals. Unlike the RL, the action space in the HRL grouped to form higher-level macro actions and then executed hierarchically rather than at a single level.

4. RL and DRL algorithms for IoT applications

Multiple research work adopted RL and DRL techniques to enhance IoT systems operations or resolve some of their issues. We categorize them into seven classes according to the addressed IoT problems: routing, scheduling, resource allocation, dynamic spectrum access, energy, mobility, and edge caching. Tables 2 and 3 summarize these papers with an emphasis on RL and DRL models, their state spaces, action spaces and reward functions respectively.

4.1. Routing

IoT undergoes an exponential evolution in recent years [52, 53]. Recent developments in the technologies of wireless communications have enabled the emerging of several types of networks such as mobile networks, Vehicular Ad-Hoc Network, sensor networks. The routing functionality in these networks is a fundamental network task due to the large amount of data generated. Routing optimization with respect to the traffic demands comes up against the uncertainty of the traffic conditions. Besides, optimizing the routing configurations against a previously observed set of network scenarios or a range of feasible traffic scenarios may fail in the face of the actual traffic conditions, which are very heterogeneous. ML techniques, in particular, reinforcement learning, have been applied in several works to cope with this type of problem.

4.1.1. Path selection

For many applications, the data must be delivered to the destination within a limited period of time after their acquisition by the sensor, otherwise, it would become unusable and uninteresting. Path selection method based on Quality of Service (QoS) adapts the network routing traffic by processing packets differently according to a set of attributes such as security, bandwidth, delay (latency), and packet loss. The development of a routing protocol that ensures a balance between power consumption and data quality is a challenge due to the distributed and dynamic topology of WSNs, in addition to their limited resources.

In [54] a link quality monitoring scheme for Routing Protocol for Low-Power and Lossy Networks (RPL) has been proposed to maintain up-to-date information about networks route, and directly react to link quality variations and topology changes due to nodes' mobility. An RL technique has been applied to minimize the overhead caused by active probing operations. The proposed approach helps to improve packet loss rates and energy consumption, only for single-channel networks. To improve secure data transactions, a trusted routing scheme based on blockchain technology and RL has been introduced in [55] for WSNs. To enhance the trustworthiness of

where $\mathbb{E}[\cdot]$ denotes the expectation function, θ and θ' represent the parameters of the predict and the target network respectively. The network is trained with a variant of the Q-learning algorithm, using stochastic gradient descent to update the weights [48]. The Q-learning in this method aims to directly approximate the optimal action-value $Q^*(s, a) \approx Q(s, a|\theta)$.

A DRL algorithm extracts features from the environment using DL while the RL agent optimizes itself by trial and error. The DRL has been extended by incorporating other ML techniques to deal with various types of problems. Transfer learning [49] aims at transferring the learned knowledge representation between different but related domains. It improves the learning process of the target agent and allows to achieve a near-optimal performance with fewer steps. Multi-task learning [50] is about learning a single policy for a group of different related tasks. It is a particular type of transfer learning, where the source and the target tasks are considered as the same. The interrelation between tasks makes the agent learning them simultaneously in order to improve the generalization performance of all the tasks. The idea behind meta-learning, also known as learning to learn, is to rapidly learn new tasks. To achieve this goal, the agent trained through various learning algorithms. Model-Agnostic Meta-Learning (MAML) proposed by fin *et al.* [51] is a meta-learning trained by gradient descent strategy and which aims to optimize the model weights for a given neural network. To deal with some real-world scaling is-

444 the routing information, the proposed scheme takes advantage
445 of the tamper-proof (i.e., detection of unauthorized access to an
446 object), decentralization, and traceability characteristics of the
447 blockchain, while RL helped nodes to choose a more trusted
448 and efficient relay nodes. The RL algorithm in each routing
449 node dynamically learns the trusted routing information on the
450 blockchain to select reliable routing links. The results of this
451 work prove that the integration of the RL into the blockchain
452 system improves delay performance even with 50% of mali-
453 cious nodes in the routing environment. Liu *et al.* [56, 57]
454 have addressed the shortest path problem for intelligent vehi-
455 cles. The Optimized Path Algorithm Based on Reinforcement
456 Learning (OPABRL) proposed in these papers, used a combi-
457 nation of prior RL technology and searching-optimal shortest
458 path algorithm to analyze and find a relatively shorter path with
459 fewer turns. Compared to four algorithms commonly used in
460 intelligent robot trajectory planning, OPABRL outperforms all
461 methods in terms of the number of turns, the path lengths, and
462 the running time, with a probability of 98% near to the optimal
463 solution. The parameters such as packet loss, data content, the
464 distance between a forward node and the sink node, and resid-
465 ual energy are used as metrics in [58] to design an effective
466 security routing algorithm to ensure data security. Each node
467 learns the behavior of its neighbors, by updating the q-value
468 according to the collected metrics, and avoid malicious nodes
469 in the next routing strategy. The experiments in the proposed
470 schema were conducted under two different types of security at-
471 tacks which are Black-Hole and Sink-Hole attacks. The packet
472 delivery rate surpasses other existing trust-based methods with
473 2.83 to 7 times higher, depending on the percentage of mali-
474 cious nodes. On the other side, the energy consumption of the
475 proposed approach is too high compared to the others, espe-
476 cially with the black hole attack.

477 Zhao *et al.* [59] have developed a deep RL routing algorithm
478 to improve crowd management in smart cities, called DRLS, by
479 meeting the latency constraints of people’s service demands.
480 Compared to the classic link-state protocols, Open Shortest
481 Path First (OSPF) and Enhanced-OSPF (EOSPF), DRLS per-
482 formance outperforms in terms of service access delay and suc-
483 cessful service access rate, with more stable management of
484 network resources.

4.1.2. Routing based on energy efficiency

485 Low-power IoT networks rely on constrained devices, and
486 they are battery-powered. In this type of networks, packet trans-
487 mission is hop by hop, and the packets cross multiple interme-
488 diate nodes to reach the base station. The energy consumption
489 of the closest nodes to the sink is higher because they serve as
490 relay nodes. Since energy is mostly consumed by the communi-
491 cation module, several routing approaches have been proposed
492 to tackle this problem in order to increase network lifetime.

493 The authors in [60, 61] have tried to maximize the network
494 lifetime of WSNs by improving routing strategies using RL.
495 The proposed methods mainly consider the link distance, the
496 residual energy of the node and the neighbors, in the defini-
497 tion of reward function, to select the best paths. We have
498 to note that [60] implements a flat architecture, which makes
499

500 the proposed solution only intended for small networks with
501 low requirements and not suitable for large scale WSNs. A
502 multi-objective optimization function has been proposed for
503 WSNs data routing in [62], using clustering and the RL method
504 SARSA, defined as Clustering SARSA (C-SARSA). Fair dis-
505 tribution of energy and maximize vacation time of the Wire-
506 less Portable Charging Device (WPCD) are the two main ob-
507 jectives. For that, the data-generating rate, energy consumption
508 rate of receiving/sending the data, and the time of arrival, charg-
509 ing, traveling, and field have been considered. According to the
510 residual energy, each node determines its willingness, which re-
511 flects if it can participate in the determination of the data route
512 or not.

513 The routing problem in UnderWater Sensor Networks has
514 been studied by many works due to the particularity of this type
515 of network. The topology in an underwater network is more dy-
516 namic compared to WSN, where each node is independent and
517 frequently changes its position relative to other sensors with the
518 water currents. This causes instability of communication links,
519 reduces their efficiency, and increases energy consumption [63].
520 Several routing challenges face UWSN, such as high propaga-
521 tion delay, localization, clock synchronization, and radio waves
522 attenuation, especially in salt-water.

523 In [64, 65], a Q-learning algorithm has been proposed to en-
524 sure data forwarding in UWSN. These approaches consider the
525 propagation delay to the sink and the energy consumption of
526 the sensor nodes to learn the best path. Li *et al.* [66] have pro-
527 posed a novel routing protocol based on the MARL protocol for
528 Underwater Optical Wireless Sensor Network (UOWSN). The
529 MARL agent determines the next neighbor according to the link
530 quality, to reduce the latency communication and the residual
531 energy of the node, and maximize the network lifetime.

532 Kwon *et al.* [67] have formulated a distributed decision-
533 making process in multi-hop wireless ad-hoc networks using
534 a Double Deep Q-Network [68, 69]. Double DQN handles the
535 problem of overestimating Q-values by selecting the best action
536 to take according to an online network, and calculate the target
537 Q value of taking that action using a target network. Each relay
538 node adjusts its transmission power to increase or decrease the
539 wave range in a way to improve both network throughput and
540 the amount of the corresponding transmission power consump-
541 tion.

542 Path selection, in terms of QoS and distance, as well as the
543 routing strategies based on energy-efficient, are the two most
544 routing optimization problems that have been addressed by the
545 RL techniques in recent years.

4.2. Scheduling

546 Due to the heterogeneous and dynamic nature of IoT net-
547 work infrastructure, scheduling decisions became a fundamen-
548 tal problem in the development of IoT systems. Briefly, the
549 scheduling problem is to determine the sequence in which op-
550 erations will be executed at each control step or state. Smart
551 and self-configuration devices should be used to adapt sched-
552 ule decisions based on environmental changes, and satisfying
553 certain restrictions, such as hardware resources and application
554 performance. In order to improve the trade-off between energy
555

556 consumption and the QoS, RL techniques have been applied
557 in many works to adapt tasks, data transmission, and time slot
558 scheduling.

559 4.2.1. Task scheduling

560 A task scheduling process assigns each sub-task of different
561 tasks to a selected and required set of resources to support user
562 goals. Different studies have applied RL techniques to optimize
563 task scheduling process in IoT networks.

564 A cooperative RL among sensor nodes for task scheduling
565 has been proposed in [70, 71], to optimize the tradeoff between
566 energy and application performance in WSNs. Each node takes
567 into consideration the local state observations of its neighbors,
568 and shares knowledge with other agents to perform a better
569 learning process and gives better results than a single agent.
570 Wei *et al.* [72] have combined the Q-learning RL method with
571 an improved supervised learning model Support Vector Ma-
572 chine (ISVM-Q), for task scheduling in WSN nodes. The ISVM
573 model takes as input the state-action pair and computes an esti-
574 mation of the Q value. Based on this estimation, the RL agent
575 selects the optimal task to realize. The experimental results
576 show that the proposed ISVM approach improves application
577 performance while preserving network energy by putting the
578 sensor and communication modules to sleep mode when nec-
579 cessary. These results remain valid even with a higher number
580 of trigger events and with different learning rates and discount
581 factors values.

582 4.2.2. Data transmission scheduling

583 The wireless sensor nodes usually have limited available
584 power. Thus many research studies attempt to optimize data
585 transmission of collected measurements in order to extend net-
586 work lifetime and ensure stability.

587 Kosunalp *et al.* [73] addressed the problem of data transmis-
588 sion scheduling by extending an ALOHA-Q strategy [74] to be
589 integrated into the Media Access Control (MAC) protocols de-
590 sign. ALOHA-Q uses slotted-ALOHA as the baseline protocol
591 for access channel with a benefit of simplicity. The Q-value of
592 each slot into the time frames represents the willingness of this
593 slot for reservation. The simulation result shows that ALOHA-
594 Q outperforms existing scheduling solutions and it can provide
595 better throughput and is more robust with an additional dynamic
596 ϵ -greedy policy.

597 The authors in [75] have addressed the transmission schedul-
598 ing optimization in a maritime communications network based
599 on Software Defined Network (SDN) architecture. A deep Q-
600 learning approach combined with a softmax classifier (S-DQN)
601 has been implemented to replace the traditional algorithm in
602 the SDN controller. The DQN was used to establish a mapping
603 relationship between the received information and the optimal
604 strategy. S-DQN aims to optimize scheduling in a heteroge-
605 neous network with a large volume of data to manage. Yang
606 et Xie [76] have attempted to solve the transmission scheduling
607 problem in Cognitive IoT (CIoT) systems with high dimension
608 state spaces. For that, an actor-critic DRL approach based on a
609 Fuzzy Normalized Radial Basis Function neural network (AC-
610 FNBRF) has been proposed to approximate the action function

611 of the actor and the value function of the critic. The perfor-
612 mance of the proposed approach has been compared with clas-
613 sical actor-critic RL, deep Q-learning, and greedy policy RL
614 algorithm. Simulations show that the proposed AC-FNBRF
615 outperforms the others with a gain that reaches 25% on power
616 consumption and 35% on transmission delay when the packet
617 arrival rates are high.

618 4.2.3. Time slot scheduling

619 Time slot scheduling algorithms dynamically allocate a unit
620 of time for a set of devices to communicate, collect or transfer
621 data to another device in order to improve throughput and min-
622 imize the total latency. RL and DRL methods are leveraged in
623 many research work to provide better scheduling.

624 Lu *et al.* [77] have integrated the Q-learning technique into
625 the exploration process of an adaptive data aggregation slot
626 scheduling. The RL approach converges to the near-optimal
627 solution, and the nodes have the capability to reach the ac-
628 tive/sleep sequence, which increases the probability of data
629 transmission and saves sensor energy. However, compared
630 to three exiting methods, namely Distributed Self-learning
631 Scheduling, Nearly Constant Approximation, and Distributed
632 delay-efficient data Aggregation Scheduling, the performance
633 of the proposed RL approach does not exceed all of them in
634 terms of average delays and residual energy.

635 A deep Q-learning has been applied in [78] for scheduling
636 in a vehicular network, to improve the QoS levels and promote
637 the environment safety without exhausting vehicular batteries.
638 The RL agents have been implemented in centralized intelli-
639 gent transportation system servers, and learn to meet multiple
640 objectives, such as reducing the latency of safety messages and
641 satisfying the download requirements for vehicles before leav-
642 ing the road. The performance of the proposed DQN algorithm
643 exceeds several existing scheduling benchmarks in terms of ve-
644 hicles' completed request percentage (10% – 25%) and mean
645 request delay (10% – 15%). In terms of network lifetime, DQN
646 outperforms all its competitors except the Greedy Power Con-
647 servation (GPC) method in some situations with large file sizes
648 or when the density of the vehicular network increases.

649 The performance of the proposed RL and DRL based ap-
650 proaches has been studied in task, data transmission, and time
651 slot scheduling.

652 4.3. Resource Allocation

653 As the number of connected objects increases, a large vol-
654 ume of data is generated by IoT environments. This explosion
655 is due to the various IoT applications developed to improve our
656 daily life, such as smart health, smart transportation, and smart
657 city. Therefore, to be able to adapt to the environment change
658 and cope with the specific requirement of applications, like re-
659 liability, security, real-time, and priority, it is necessary to rely
660 on a Resource Allocation (RA) process. The goal is to find the
661 optimal resources allocation, to a given number of activities, in
662 order to maximize the total return or minimize the total costs.

663 Xu *et al.* [79] have addressed the RA problem to maximize
664 the lifetime of WBAN using RL. The harvested energy, trans-

mission mode and power, allocated time slots, and relay selection are taken into account to make the optimal decision. The authors in [80] have proposed an extensible model for Self-Organizing MAC (SOMAC) for wireless networks, to switch between the available MAC protocols (i.e., CSMA/CA and TDMA) dynamically using RL and improve the network performance according to any metric, such as delay, throughput, packet drop rate, or even a combination of those, chosen by the network administrator.

In [81], a DRL based vehicle selection algorithm has been designed to maximize spatial-temporal coverage in mobile crowdsensing systems. A DRL resource allocation frameworks for Mobile Edge Computing (MEC) have been proposed in [82, 83]. The authors have used different DRL techniques and metrics in their modeling of these systems. For instance, [83] has applied a Monte Carlo Tree Search method based on a multi-task RL algorithm. The work has improved the traditional DNN, by splitting the last layers, to build a sublayer neural network for high-dimensional actions. The service latency performance was significantly better in the random walk scenario and the vehicle driving-based base station switching scenario, compared to the deep Q-network with percentages reaching 59% in some cases.

RL approaches, including DRL, have been adopted for resource allocation in wireless networks, internet of vehicles, and mobile edge networks.

4.4. Dynamic Spectrum Access

With the emergence of the IoT paradigm and the growing number of devices connecting and disconnecting from the network, it was necessary to develop new dynamic spectrum access solutions. The DSA is a policy that specifies how equipment can efficiently and economically share available frequencies while avoiding interference between users.

In [84], two Q-learning algorithms have been integrated into the channel selection strategy for Industrial-IoT, to determine which channels are vacant and of good quality. Both proposed RL algorithms aim to assess the future occupation of the channels and to sort and classify the candidate channel list according to the channel quality. Compared to five spectrum handoff schemes, the results showed a remarkable improvement in latency and throughput performance under diverse IIoT scenarios. A Non-Cooperative Fuzzy Game (NC-FG) framework has been adopted in [85] to address the requirement for an optimal spectrum access scheme in stochastic 5th-Generation wireless systems (5G) WSNs. To reach the Nash equilibrium solution of the NC-FG, a fuzzy-logic inspired RL algorithm has been proposed to define the robust spectrum sharing decision and adjust the channel selection probabilities accordingly. We have to note that the values of the various parameters of the implemented RL system are missing in the paper.

The problem of dynamic access control in 5G cellular networks has been studied also by Pacheco-Paramo *et al.* [86]. The authors proposed a real-time configuration selection scheme based on the DRL mechanism to dynamically adjust the access class barring rate according to the changing traffic conditions and minimize collision cases. The training results show that the

proposed solution is able to reach a 100% success access probability for both Human-to-Human and Machine-to-Machine user equipment and with a low number of transmissions. To achieve this level of performance, the training of the proposed mechanism is almost three times longer than the Q-Learning based solution. In wireless networks, Wang *et al.* [87] have implemented a DRL-based channel selection to find the policy that maximizes the expected long-term number of successful transmissions. The DSA problem has been modeled as a POMDP in an unknown dynamic environment. At each time slot, a single user selects a channel to transmit packet and receive a reward value based on the success/failure status of transmission. The authors designed an algorithm that allows the DQN to re-train a new good policy, only if the returned reward value is reduced by a given threshold. This can degrade the performance of the proposed solution, especially with dynamic IoT environments.

Research papers that employ RL and Deep RL to solve dynamic spectrum access problems focus mainly on networks where communication traffic is changing and unknown.

4.5. Energy

For battery-powered devices in IoT systems, optimizing energy consumption and improving network lifetime are fundamental challenges. The difficulty of replacing or recharging the nodes, especially in unreachable areas, motivated researchers to employ the RL technique to find a better compromise between residual energy and application constraints.

In [88] a Transmission Power Control (QL-TPC) approach has been proposed to adapt, by learning, the transmission power values in different conditions. Every RL agent is a player in a common interest game. This game theory provides a unique outcome and leads to a global benefit by minimizing transmission power with a percentage of packet reception ratio always higher than 95%. Based on traffic predictions and transmission state of neighbor nodes, an RL agent has been designed in [89] to adapt between the sleep-active node duty-cycle, by adjusting the MAC parameters and reduce the number of slots in which the radio is on. The drawback of the proposed solution is that it has a high probability of packet loss. Soni et Shrivastava [90] have picked up nodes in cluster sets using Q-learning and then collect data from cluster heads using a mobile sink. This solution has a double advantage: first, clustering saves the energy consumption of the nodes by reducing the number of hops and distance to the cluster head. The second advantage is that the mobile sink visits only the interested cluster head which sends a request to the sink for data collection.

Energy Harvesting (EH) is an alternate process to provide some energy to the nodes by deriving power from external sources (e.g., solar, thermal, wind) and extend the lifetime of the sensor network. Due to the stochastic behavior of this technology, since most of these energy sources vary over time, using EH brings new challenges to energy management of how to maximize the harvested power and energy use efficiency. Several energy management schemes using RL have been proposed.

In [91] an RL energy management (RLMAN) has been proposed using an actor-critic algorithm to select the appropriate

throughput based on the state of charge of the energy storage device. The problem of energy management is presented as a Cooperative Reinforcement Learning (CRL) in [92], where agents share information to regulate active/sleep duty cycle. In this system, each EH-node seeks to keep both its node and the next hop node alive.

Deep RL approaches have been employed to improve nodes' performances, for the large IoT energy harvested networks. In [93] an end-to-end approach has been proposed to control IoT nodes and select the value or define the interval of the duty cycles. For this, a PPO policy gradient method using neural networks as function approximators has been applied, giving better results compared to SARSA. Sharma *et al.* [94] have exploited the mean-field game combined with multi-agent Q-learning to find out the optimal power control and maximize the obtained throughput. In simulations, the authors have only focused on sum-throughput to show that the proposed approach can achieve performance close to DNN-based centralized policies, without requiring information on the state of all the nodes in the network.

Energy optimization has been and will be continually an interesting research topic for wireless IoT networks. The existing work have shown that the application of RL and DRL approaches allowed to extend node's lifetime and improve harvested networks.

4.6. Mobility

Mobile nodes in WSNs, such as a robot or mobile sink, allows overcoming the various trade-offs related to the characteristic of these networks. To cope with the energy issue, for example, sink mobility has been exploited in many systems to extend network lifetime and solve the hotspot problem (also known as energy hole-problem), as depicted in Figure 3.

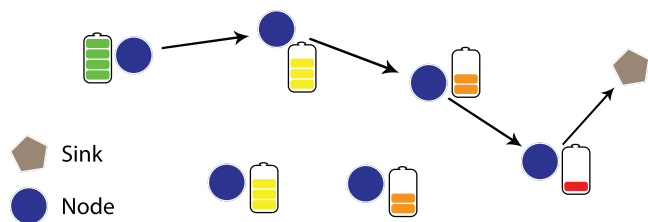


Figure 3: Illustration of the energy hole-problem.

As we have mentioned previously, several IoT devices rely on low-cost hardware, and they are not equipped with location sensors (e.g., LPS, GPS, or iBeacon). Therefore, an intelligent system must be integrated into mobile nodes in order to find the optimal trajectory to follow. With the trial-and-error strategy followed by the RL agents, the mobile nodes have the capacity to explore the network environment, make internal decisions to find the right trajectory, and adapt to dynamic networks.

Wang *et al.* [95] have addressed the problem caused by scaling-up in WSNs and propose a location update scheme of the mobile sink node to achieve more efficient network topology. First, the sink node updates its location by collecting

information from certain key nodes and searches for the best performing location to define it as the final location. Then, a Window-based Directional SARSA(λ) algorithm (WDS) is designed to build an efficient path-finding strategy for the sink node. Through two simulation scenarios, a simple path, and a longer path with traps, the WDS algorithm is always able to find the optimal route to the sink with only a 48% to fall into a trap.

The authors in [96] have developed an indoor user localization system based on BLE for smart city applications. Their solution extends the DRL to semi-supervised learning that utilizes both labeled and unlabeled data. The model collects the Received Signal Strength Indicator (RSSI) from a set of fixed Bluetooth devices with a known position to provide the current location and the distance to the target point. Simulations show an improvement that can reach 23% in target distance and at least 67% more rewards compared to the supervised DRL scheme. Liu *et al.* [97] have proposed an Ethereum blockchain-enabled data sharing scheme combined with DRL to create a safe and reliable IIoT environment. A distributed DRL based approach was integrated into each mobile terminals to move to a location and achieve the maximum amount of collected data. Blockchain technology was used to prevent attacks and network communication failure while sharing the collected data. Simulation results showed that compared to a random solution, the DRL algorithm can increase the geographical fairness ratio by 34.5%. The problem of data collection in WSNs has been addressed also in [98]. The authors propose a single mobile agent based on DRL to learn the optimal route path while improving data delivery to the sink and reduce energy consumption. The proposed method employs a DNN combined with the actor-critic architecture, where it takes as input the state of the WSN, defined by the locations of each node in the environment, and outputs the traveling path.

The employment of RL approaches, especially the Deep RL, have allowed to manage the network topology and collect data via mobile nodes.

4.7. Caching

With the rapid increase in IoT devices and the number of services over mobile networks, the amount of wireless data traffic generated is continuously increasing. However, the limit of link capacity, the long communication distance, and the high workload introduced in the network pose significant challenges to satisfy the Quality of Experience (QoE) or the QoS required by applications. Edge caching is a promising technology to tackle these network problems. The goal of caching is to reduce unnecessary end-to-end communications by keeping popular content at edge nodes close to users. Thus, the requested data can be obtained quickly from nearby edge nodes, which reduces the redundant network traffic and meet the low-latency requirement. Compared to the network in Figure 4a, the edge cache in Figure 4b allowed to reduce the number of requests required toward remote servers.

In [99], a DRL based caching policy has been proposed to solve the cache replacement problem, for IoT content, with limited cache size. Taken into consideration both the fetching cost

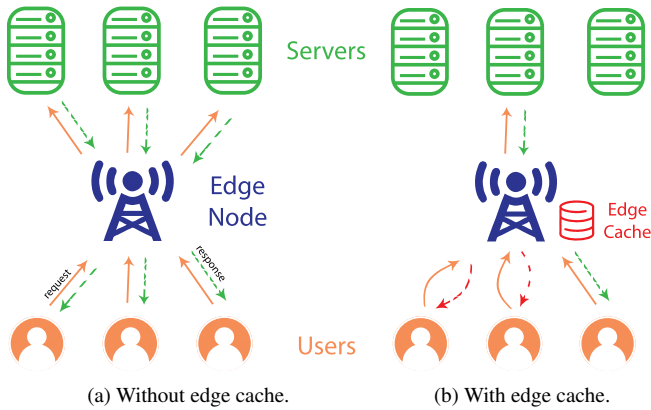


Figure 4: Illustration of the difference between standard and cache-enabled edge scenarios in IoT networks.

and the data freshness, the developed framework can make efficient decisions without assuming the data popularity or the user request pattern. The DRL based caching policy has been compared to the two caching policies Least Recently Used (LRU) and Least Fresh First (LFF). The simulation results demonstrate that the proposed policy achieves better performance in terms of cache hit ratio, data freshness, and data fetching cost with different configurations. An actor-critic DRL is applied in [100] to realize a joint optimization of the content caching, computation offloading, and resource allocation problems in fog-enabled IoT networks. Two DNNs have been employed to estimate the value function with a large state and action space in order to minimize the average transmission latency. Evaluation results show the effect of radio resource optimization and caching on decreasing end-to-end service latency. The proposed approach outperforms the performance of offloading all tasks at the edge when the computational capability increase, but it starts to degrade when the computational burden becomes heavy.

Time-varying feature, as caching issues, has been solved using deep reinforcement learning techniques.

5. Discussion and Lessons Learned

Tables 2 and 3 summarize the research in each wireless IoT issue. For each of surveyed paper, we identified the used RL and DRL models, their state spaces, action spaces, and reward functions.

Through this survey, we found that both RL and DRL algorithms are able to enhance network performance, such as lower transmission power [67, 79, 88], provide better routing decision-making as the works described in the section 4.1, and higher throughput [76, 91, 92], and these in various wireless networks, including underwater wireless sensor network [64, 65, 66], internet of vehicles [56, 78, 81], cellular network [85, 86], Wireless Body Area Networks [79], etc. Reinforcement learning models allow a wireless node to take as input its local observable environment and subsequently learn effectively from its collected data to prioritize the right experience and choose the best next decision. The Deep RL approach,

a mix between RL and DL, allows for making better decisions when facing high-dimensional problems and to solve scalability issues by using neural networks, one of the challenges, for example, in edge caching methods.

In terms of the time complexity of the proposed RL solutions, [70] proposes a constant time approach since the size of the set of tasks and the number of the neighbor nodes are fixed at initialization. But most of the other proposed algorithms, such as [54, 72, 79, 95, 101], require a quadratic time complexity with an execution time that increases exponentially as the size of the state and/or the action space increases. The authors in [76] try to decrease the Computational complexity by combining the hidden layer nodes which have similar functions. The improved deep Q-network, S-DQN [75], reduces the computation and time complexity by more than 90% to reach Q-value converge.

The cost in terms of energy consumption has been evaluated in many surveyed works. The proposed routing protocol in [60] makes a significant improvement in three situations: the first node dies, the first node isolates to the sink, and the time until the network cannot accomplish any packet delivery. With small and large scale network scenarios, the MAC protocol designed in [89] allows to extend nodes lifetime, up to 26 times, by reducing the average activated slots. The authors obtained a percentage of Packet Delivery Ratio (PDR) near that with a duty cycle at 100%. The routing method in [58] focuses more on ensuring a higher PDR when the network is facing attacks, however, it introduces high energy consumption. The RL method in [64] consumes less energy among the compared data forwarding methods in different network sizes with a percentage reaching 37.26%. This solution acquires a better value of information but achieves a PDR slightly lower. The power consumption by the actor-critic system in [76] increases with the packet arrival rate. That always remains lower than the state of art algorithms, even during the learning process. Another actor-critic solution has been proposed in [98] shows that DRL can reduce the consumed energy by the mobile agents over time as the training process progresses. The deep MCTS method applied in [83] outperforms all methods in terms of energy consumption, with different computing capability of edge servers and a varied number of mobile devices ranging from 10 to 260, while always ensuring a minimal average service latency.

The goal of an RL agent is to learn the policy which maximizes the reward it obtains in the future. A Single-Agent Reinforcement Learning (SARL) approach is based on using only one agent in a defined environment that makes all the decisions. In the IoT network, the SARL can be deployed in the base stations or monitoring nodes (e.g., sink node), and the RL agent interacts according to the state of the whole network. The network can also have several agents deployed in one or multiple nodes but each focuses on optimizing only its own environment, for example, battery level, the channels available for this node, the neighbor nodes. When adopting more than one agent that interacts with each other and their environment, the system is called MARL. The MARL accelerate the training in distributed solutions that can be efficient than centralized SARL since each RL agent combines both its own experience and that of the other

Table 2: A summary of applied RL methods and models with their associated objectives.

| Obj. | Ref. | RL Method | State | Action | Reward | Network |
|------------|----------|-----------------------|--|---|--|-----------------------------|
| Routing | [54] | Multi-armed bandit | Link quality | Selects the set to probe | Trends in link quality variations | WSN with mobile nodes |
| | [55] | SARSA | Current position of packets (i.e., routing node) | Select a routing node | Delivered tokens | WSN |
| | [56, 57] | Q-learning | Grid map: obstacle or non-obstacle | Select a path | Related to path length and number of turns | IoV |
| | [58] | Q-learning | Behaviors of neighboring nodes | Select neighbor node | Forwarded data packet | WSN |
| | [60] | Custom Q-value | Current position of packets (i.e., sensor node) | Select a neighboring node | Related to neighboring residual energy, distance to the neighbor, and hop count between neighbor node and sink | WSN |
| | [61] | – | – | Select a route | – | WSN |
| | [62] | SARSA | The ratio of the remaining energy to the drain rate of the energy | Select a forwarding ratio of route request packet | Energy drain rate | WPCD |
| | [64] | Q-learning | Transmission status in previous time slot | Select a node | Related to information timeliness and residual energy | UOWSN with passive mobility |
| | [65] | Q-learning | Position of the sensor node | Select an accessible node | Transmission distance | UWSN |
| | [66] | Q-learning (Modified) | {Busy, Idle} | Select neighbors of each node | Residual energy and link quality | UOWSN |
| Scheduling | [70] | Q-learning | [State of sensing area, state of transmitting queue, state of receiving queue] | {Sleep, Track, Transmit, Receive, Process} | Task completion success | WSN |
| | [71] | SARSA (Modified) | {Idle, Awareness, Tracking} | {Detect Targets, Track Targets, Send Message, Predict Trajectory, Intersect Trajectory, Goto Sleep} | Related to residual energy, maximum energy level, and number of field-of-view detected target's positions | WSN |
| | [72] | Q-learning | [Sensing area, Transmitting queue, Receiving queue] | {Sleep, Sense, Send, Receive, Aggregate} | Related to scheduling energy consumption and applicability predicates | WSN |
| | [73] | Q-learning | List of nodes | Select a slot | Transmission success | WSN |
| | [77] | Q-learning | Selected active slots in the previous frame | Select an active slot for the current frame | Transmission and acknowledgment success | WSN |
| RA | [79] | Q-learning | Data and energy queue lengths | Select a transmission mode, a time slot allocation, a relay selection, and a power allocation | Related to transmission rate and consumed transmission power | EH-WBAN |
| | [80] | Q-learning | Available MAC protocols | Select a MAC protocol | Related to the percentage gain of a network performance metric | Wireless Network |
| DSA | [84] | Q-learning | Bandwidths: occupied or unoccupied | Select a set of channels | Probability of sensing a vacant channel | IIoT |
| | [85] | – | Spectrum sharing decision | Adjust channel selection probabilities | – | 5G WSN |

– Not mentioned

(Continued on next page)

Table 2: A summary of applied RL methods and models with their associated objectives (*Continued*).

| Obj. | Ref. | RL Method | State | Action | Reward | Network |
|----------|------|------------------|--|--|---|----------------------|
| Energy | [88] | Q-learning | Link status | Select a transmission power levels | Related to Packet Reception Ratio and Power levels | WSN |
| | [89] | Q-learning | Slot information of the current node and its neighborhood | Active or sleep mode | Related to the amount of successfully transmitted, received, and overheard received packets | WSN |
| | [90] | Q-learning | Neighbouring cluster head which can be selected | Select a neighbouring node | Link cost | WSN with mobile sink |
| | [91] | Actor-Critic | [Residual energy required to operate, Energy storage capacity] | Select the throughput F_{min} and F_{max} | Related to normalized residual energy and throughput | EH-WSN |
| | [92] | Q-learning | [Residual energy, Throughput] | [Stay sleep, Turn on collection, Turn on processing, Turn on transmission] | Takes different values for each possible outcome | EH-WSN |
| Mobility | [95] | SARSA (Modified) | Location of the sink | {Turn left, Turn right, Forward, Backward} | +1 if final location, 0 otherwise | WSN with mobile sink |

971 agents. In the surveyed papers, we note that only 20% of the RL
972 based approaches use MARL, and only one paper [94] in DRL
973 approaches. This can be explained by the fact that the MARL
974 approach requires an efficient and regular synchronization sys-
975 tem, which can cause overloads on IoT networks and reduce the
976 performance and the lifetime of the nodes. In addition, Deep
977 learning requires much more computational performance than
978 the standard RL. This would make the deployment of such an
979 algorithm in a distributed network with low power nodes more
980 difficult and less efficient regarding resources consumption.

981 Simulation and emulation are well-established techniques to
982 imitate the operation of a real-world process or system over
983 time [102]. They are applied by researchers and developers
984 during the testing and validation phases of new approaches.
985 This is the case with machine learning technologies that re-
986 quire a large amount of resources and time for the training
987 and testing phases. MATLAB [103, 104], Cooja [105], OM-
988 NET++ [106], and Network Simulator (NS-2/3) [107, 108] are
989 the most network simulator that the authors use to evaluate the
990 application of their RL approaches in IoT networks. To evalu-
991 ate DRL based approaches, the authors turn more towards
992 tools using python as a programming language, such as Ten-
993 sorFlow [109] and OpenAi-Gym [110], which offer several li-
994 braries for ML and DL. In addition to the simulation results,
995 the authors in [54, 67, 73, 80, 88, 89] have evaluated the per-
996 formance of their approaches in real-world experiments. This
997 gives more realistic results of the proposed approaches perfor-
998 mances for IoT networks.

999 The availability of a global view of the network or the col-
1000 lection of all the necessary information from the environment
1001 is not always guaranteed in IoT environments. Two surveyed

1002 papers [88, 87] have addressed the problems of partial observa-
1003 tions about the overall environment by the RL agent.

1004 The authors in [88] rely on a decentralized system where each
1005 agent is independent but simultaneously influences a common
1006 environment. Thus, a multi-agent Decentralized POMDP (Dec-
1007 POMDP) is considered in a wireless system with more than
1008 one transmitter node, where each one relies on its local infor-
1009 mation. Otherwise, each agent needs to know and keep track
1010 of action decision and reward value per transmitted packet of
1011 all other agents. To avoid network overhead and reduce com-
1012 plexity, such information is not exchanged between the agents.
1013 Based on stochastic games, indirect collaboration among the
1014 nodes is obtained through the application of the common inter-
1015 est in game theory since they aim to improve the total reward
1016 by helping each other.

1017 In [87], the DSA problem has been formulated as a POMDP
1018 with unknown system dynamics. The problem has been formu-
1019 lated as follows: a wireless network is considered with mul-
1020 tiple nodes, dynamically choosing one of N channels to sense
1021 and transmit a packet. The difficulty comes from the fact that
1022 the full state of all channels can not be all observable since the
1023 node can only sense one channel at the beginning of each time
1024 slot. However, based on the previous sensing decisions and ob-
1025 servations, the RL agent infers a distribution on the state of the
1026 system. Considering the advantage of the model-free over the
1027 model-based in this type of problems, a Q-learning was applied
1028 by considering the belief space and converting the dynamic
1029 multi-channel access into a simple MDP. The state-space size
1030 grows exponentially as it becomes large, which requires using
1031 deep Q-learning instead of the Q values table.

1032 It is evident that from 2016 to February 2020, most re-

Table 3: A summary of applied DRL methods and models with their associated objectives.

| Obj. | Ref. | DRL Method | State | Action | Reward | Network |
|------------|------|--|--|--|---|----------------------------|
| Routing | [59] | Deep Q-learning | Location of requests | Select a route requests | Related to request access success, resource usage balance degree, and data transmission delay | Smart city network |
| | [67] | Double Deep Q-Network | Number of relay nodes | Transmission range | Related to throughput improvement and transmission power consumption | Wireless ad-hoc Network |
| Scheduling | [75] | Deep Q-learning | [Channel state, Cache state] | Dispatch or not a data packet to a relay ship for caches state, channels state, and energy consumption | Related to signal-noise ratio, terminals' cache state, and energy consumption | Maritime Wireless Networks |
| | [76] | Actor-Critic | [Channel status, Channel access priority level, Channel quality, Traffic load of the selected channel] | {Transmit power consumption, Spectrum management, Transmission modulation selection} | Related to transmission rate, throughput, power consumption, and transmission delay | CIoT |
| | [78] | Deep Q-learning | Underlying network characteristics | Select an intelligent transportation system server or a vehicle | Sum of IoT-GWs' power consumption, waiting time of the vehicles to receive any service, delay of completed service requests, penalty for incomplete service request and early cut-off of one of the IoT-GWs | IoV |
| RA | [81] | Deep Q-learning | Covered times | List of selected vehicles | Cost of the sensing tasks | IoV |
| | [82] | Deep Q-learning | Data rate of user equipment and computation resource of vehicular edge server and fixed edge server | Determine the setting of vehicular edge server and fixed edge server | Vehicle edge computing operator's utility | Vehicle Edge Network |
| | [83] | Monte Carlo tree search | [Computing capability state, radio bandwidth resource state, task request state] | [Bandwidth, Offloading ratio, Computation resource] | Related to the end node in the search path | Mobile Edge Network |
| DSA | [86] | Deep Q-learning / Double Deep Q-learning | Received preambles success and barring rate | Select barring rate value | Avoid or reach a defined limit | 5G |
| | [87] | Deep Q-learning with Experience Replay | Channels' state : good or bad | Select a channel | Transmission success | Wireless Network |

(Continued on next page)

Table 3: A summary of applied DRL methods and models with their associated objectives (*Continued*).

| Obj. | Ref. | DRL Method | State | Action | Reward | Network |
|----------|-------|------------------------------|--|--|---|------------------------|
| Energy | [93] | Proximal Policy Optimization | [Level of the energy buffer, Distance from energy neutrality, Harvested energy, Weather forecast of the day] | Select a duty cycles value | Distance to energy neutrality | IoT |
| | | | [Level of the energy buffer, Harvested energy, Weather forecast of the whole episode, Previous duty cycle] | Select the maximum duty cycle | Level of the energy buffer | |
| | [94] | Deep Q-learning | Energy arrivals and channel states to the access point of the node | Transmit energy | Sum throughput | EH network |
| Mobility | [96] | Deep Q-learning | [Vector of RSSI values, Current location, Distance to the target] | {West, East, North, South, NW, NE, SW, SE} | Positive if distance to the target point is less than a threshold, negative otherwise | IoT |
| | [97] | Actor-Critic | {[Data distribution, Location of Mobile terminal, Past trajectories]} | Moving direction and distance | Energy-efficiency | IIoT |
| | [98] | Actor-Critic | Coordinates of the source nodes | Mobile node movement | Negative of the consumed energy | WSN with mobile agents |
| Caching | [99] | Actor-Critic | Values of information about cached/arrived data items | Replace or not the data cached | Sum utility of requested data items | IoT |
| | [100] | Actor-Critic | [Size of input data, computation requirement, popularity of requesting, storage flag, link quality] | [Assign BSs to requesting service, requesting decision, computation tasks location, computational resource blocks] | Related to the time cost function for computation offloading requests and for content delivery requests | Fog computing network |

1033 searchers in these studies have given considerable interest to
1034 apply RL and DRL according to the requirements of the appli-
1035 cation and the target set. We note that most research focuses on
1036 applying the RL technique in routing, scheduling, and energy.
1037 While in resource allocation, mobility, and caching, researchers
1038 are more focusing on applying the DRL technique. In these
1039 types of applications, agents are located in unconstrained de-
1040 vices, such as at the edge router and crowdSensing servers, and
1041 which can be easily extended with more computation resources.

1042 The majority of RL approaches are using Q-learning as a
1043 method for training their agents, and few of them are using
1044 SARSA method. This can be explained by the fact that SARSA
1045 takes into consideration the performance of the agent during the
1046 learning process, whereas with Q-learning, authors only care
1047 about learning the optimal solution towards which they will
1048 eventually move. We also note that the actor-critic method is
1049 mainly used with DRL approaches due to the difficulty of train-
1050 ing an agent in many cases. This is due to the interaction insta-
1051 bility, during the learning process, between the actor and critic,

as one of the weaknesses of the methods based on the value
function.

1052
1053
1054 As shown in Figure 5, nearly a third of the research covers
1055 the routing issue. RL algorithms show good results since they
1056 are flexible, robust against node failures, and it can maintain
1057 data delivery even if the topology changes. The management of
1058 energy consumption and harvesting still represents a significant
1059 research challenge, with the main objective to extend the life-
1060 time of the IoT network. Depending on the network character-
1061 istics and application constraints, the definition of the network
1062 lifetime differs. The three major definitions are [111]: (i) the
1063 time until the first node death; (ii) the time until the first node
1064 becomes disjoint; (iii) the time until all nodes die or failure to
1065 reach the base station. Various other definitions have been pro-
1066 posed and reported in the literature, where the researchers are
1067 using thresholds such as the percentage of dead nodes, packet
1068 delivery rate, remaining energy.

Some miscellaneous issues have been solved using RL tech-
niques for wireless IoT networks, but they are not well cov-

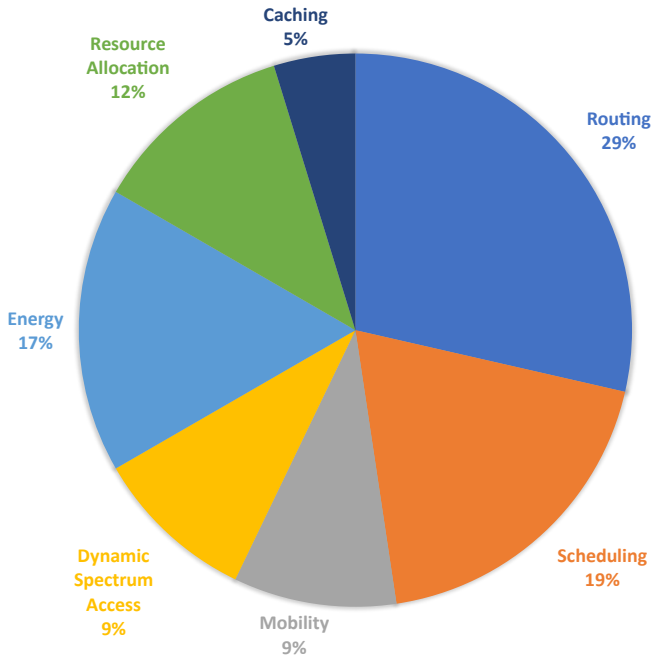


Figure 5: Percentage of research papers according to the IoT issues addressed by RL and DRL techniques.

ered during the period of the surveyed papers. In terms of IoT security, a DQN-based detection algorithm has been proposed by Liang *et al.* [101] for virtual IP watermarks, to ensure the safety of low-level hardware in the intelligent manufacturing of IoT environments and real-time detection for virtual intellectual property watermarks. For the deployment and topology control issue, Renold *et al.* [112] have developed a Multi-agent Reinforcement Learning-based Self-Configuration and Self-Optimization (MRL-SCSO) protocol for effective self-organization of unattended WSNs. To maintain a reliable topology, the neighbor with the maximum reward value is selected as the next forwarder.

6. Challenges

The different surveyed papers show that RL and DRL techniques are able to solve multiple issues in IoT environments by making them more autonomous decision-making. However, the application of RL and DRL techniques still has certain challenges:

- The identification of the RL method to be applied in a specific IoT issue can be a difficult task. We observe from the surveyed papers, that the majority of work use the Temporal-Difference [113] learning methods (e.g., SARSA, Q-learning). This poses another challenge since the performance of these methods is affected by multiple parameters such as the learning rate and the discount factor. Each of these parameters can take a real number (\mathbb{R}) of an infinity of value between $[0, 1]$. In DRL, the task of tuning the parameters of the applied techniques becomes more difficult since it is affected by the number and type of neural hidden layers as well as the loss function.

- The RL research studies try to identify all the possible scenarios that an RL agent may face to define the "optimal" reward function that achieves the goal quickly and efficiently. Sometimes agents encounter new scenarios where the defined reward function can lead to unwanted behavior. One of the solutions proposed for this problem is to recover the reward function by learning from demonstration, known as Inverse RL [114, 115, 116].

- Unlike supervised and unsupervised learning, RL et DRL methods have no separate training steps. They always learn by a trial-and-error process, as long as the agent did not reach a final state. In this case, the performance of the agent varies according to the historical data (i.e., the encountered environment states and the executed actions), and the followed exploration strategy. The offline RL [117] strategy can accelerate this process by collecting a large dataset from past interactions and train the agent for many epochs before deploying the RL or DRL model into the real environment. On top of that, the sequential steps of the trial-and-error process can extend the convergence time. The Advantage Actor-Critic (A2C) [118] and Asynchronous Advantage Actor-Critic (A3C) [119], two variants of the actor-critic algorithm, can handle this by exploring more state-action space in less time. The principal difference is that several independent agents are trained in parallel with a different copy of the RL environment and then update the global network.

- The problem of supporting network mobility remains not well studied in many surveyed works. A wireless network may include one or more mobile nodes, which makes its structure dynamic and can be relatively unstable. In fact, if the RL mechanisms do not explicitly support network mobility, dysfunction, or degradation in performance can affect the system. To address non-stationary property in wireless networks, the author in [80] intends to use Deep RL algorithms rather than the standard RL proposed in the paper. To study the impact of mobile WSNs in the data collection problem with a mobile agent, the authors in [98] try to dynamically adjust the network structure while always ensuring a lower energy consumption. The evaluation of sensor nodes under different mobility scenarios has been also mentioned as a future work in [64, 92] to study their influences on performances.

- Resource constraints, in particular energy-saving, is a fundamental issue in developing wireless sensor systems with the goal to extend the network life-time. Thus, the employed RL and DRL techniques should minimize algorithms' complexity in terms of memory space and reduce their execution time when running them on IoT devices. Low-power and lightweight RL and DRL frameworks, such as ElegantRL [120] and TensorFlow Lite [121] have been designed to run on sensor and mobile devices with mostly equivalent features as heavy solutions, while optimizing performance and reducing binary file size. Another interesting feature to optimize and reduce the required re-

sources is the deployment model of the RL agents. Compared to centralized approaches, which rely on a single network node, decentralized approaches share the learning computation load among various wireless nodes. Using distributed approaches enables RL agents to avoid the overhead of running tasks by observing and predicting only its own environment.

7. Conclusion

This survey presented recent publications that applied both RL and DRL techniques in wireless IoT environments. First, an overview of wireless networks, MDP, RL, and DRL techniques is provided. Then, we presented a taxonomy based on IoT networking and application problems, including routing, scheduling, resource allocation, dynamic spectrum access, energy, mobility, and edge caching. Additionally, we summarized for each paper the used method, the state space, the action space, and the reward function. Afterwards, we studied the proposed contributions in terms of time complexity, energy consumption, designed systems, and evaluation methods, followed by statistical analysis. Finally, we identified the remaining challenges and open issues for applying RL and DRL techniques in IoT. It is important to emphasize that these techniques are valuable to solve many issues in IoT networking and communication operations, but more work is required to cover more management operations such as monitoring, configuration and the security of these environments.

List of Abbreviations

| | | |
|------|----------------|--|
| 1183 | <i>5G</i> | 5th-Generation wireless systems |
| 1184 | <i>A2C</i> | Advantage Actor-Critic |
| 1185 | <i>A3C</i> | Asynchronous Advantage Actor-Critic |
| 1186 | <i>AIoT</i> | Autonomous Internet of Things |
| 1187 | <i>ANN</i> | Artificial Neural Network |
| 1188 | <i>BLE</i> | Bluetooth Low Energy |
| 1189 | <i>CIoT</i> | Cognitive Internet of Things |
| 1190 | <i>CNN</i> | Convolutional Neural Network |
| 1191 | <i>CRL</i> | Cooperative Reinforcement Learning |
| 1192 | <i>CSMA/CA</i> | Carrier Sense Multiple Access with Collision Avoidance |
| 1193 | | |
| 1194 | <i>DL</i> | Deep Learning |
| 1195 | <i>DNN</i> | Deep Neural Network |
| 1196 | <i>DQN</i> | Deep Q-Network |
| 1197 | <i>DRL</i> | Deep Reinforcement Learning |
| 1198 | <i>DSA</i> | Dynamic Spectrum Access |
| 1199 | <i>EH</i> | Energy Harvesting |
| 1200 | <i>EOSPF</i> | Enhanced Open Shortest Path First |
| 1201 | <i>GPS</i> | Global Positioning System |
| 1202 | <i>IIoT</i> | Industrial Internet of Things |
| 1203 | <i>IoT</i> | Internet of Things |
| 1204 | <i>IoV</i> | Internet of Vehicles |
| 1205 | <i>IP</i> | Internet Protocol |
| 1206 | <i>LPS</i> | Local Positioning System |
| 1207 | <i>M2M</i> | Machine-to-Machine |

| | | |
|------------------|---|------|
| <i>MAC</i> | Media Access Control | 1208 |
| <i>MARL</i> | Multi Agent Reinforcement Learning | 1209 |
| <i>MCTS</i> | Monte Carlo Tree Search | 1210 |
| <i>MDP</i> | Markov Decision Process | 1211 |
| <i>MEC</i> | Mobile Edge Computing | 1212 |
| <i>ML</i> | Machine Learning | 1213 |
| <i>OSPF</i> | Open Shortest Path First | 1214 |
| <i>PDR</i> | Packet Delivery Ratio | 1215 |
| <i>POMDP</i> | Partially Observable Markov Decision Process | 1216 |
| <i>PPO</i> | Proximal Policy Optimization | 1217 |
| <i>QoE</i> | Quality of Experience | 1218 |
| <i>QoS</i> | Quality of Service | 1219 |
| <i>RA</i> | Resource Allocation | 1220 |
| <i>REINFORCE</i> | REward Increment = Nonnegative Factor x Offset Reinforcement x Characteristic Eligibility | 1221 |
| | | 1222 |
| <i>RL</i> | Reinforcement Learning | 1223 |
| <i>RPL</i> | Routing Protocol for Low-Power and Lossy Networks | 1224 |
| | | 1225 |
| <i>RSSI</i> | Received Signal Strength Indicator | 1226 |
| <i>SARL</i> | Single-Agent Reinforcement Learning | 1227 |
| <i>SARSA</i> | State-Action-Reward-State-Action | 1228 |
| <i>SDN</i> | Software Defined Network | 1229 |
| <i>TDMA</i> | Time Division Multiple Access | 1230 |
| <i>TRPO</i> | Trust Region Policy Optimization | 1231 |
| <i>UOWSN</i> | Underwater Optical Wireless Sensor Network | 1232 |
| <i>UWB</i> | Ultra Wide-Band | 1233 |
| <i>UWSN</i> | Underwater Wireless Sensor Network | 1234 |
| <i>VANET</i> | Vehicular Ad-Hoc Network | 1235 |
| <i>WBAN</i> | Wireless Body Area Networks | 1236 |
| <i>WPCD</i> | Wireless Portable Charging Device | 1237 |
| <i>WSN</i> | Wireless Sensor Network | 1238 |

References

- [1] J. Ding, M. Nemati, C. Ranaweera, J. Choi, Iot connectivity technologies and applications: A survey, *IEEE Access* (2020). 1240
- [2] R. Porkodi, V. Bhuvanawari, The internet of things (iot) applications and communication enabling technology standards: An overview, in: 2014 International conference on intelligent computing applications, IEEE, 2014, pp. 324–329. 1241
- [3] S. R. Islam, D. Kwak, M. H. Kabir, M. Hossain, K.-S. Kwak, The internet of things for health care: a comprehensive survey, *IEEE access* 3 (2015) 678–708. 1242
- [4] M. R. Jabbarpour, A. Nabaei, H. Zarrabi, Intelligent guardrails: an iot application for vehicle traffic congestion reduction in smart city, in: 2016 IEEE International Conference on Internet of Things (IThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData), IEEE, 2016, pp. 7–13. 1243
- [5] M. Abbasi, M. H. Yaghmaee, F. Rahnama, Internet of things in agriculture: A survey, in: 2019 3rd International Conference on Internet of Things and Applications (IoT), IEEE, 2019, pp. 1–12. 1244
- [6] U. Z. A. Hamid, H. Zamzuri, D. K. Limbu, Internet of vehicle (ioV) applications in expediting the implementation of smart highway of autonomous vehicle: A survey, in: *Performability in Internet of Things*, Springer, 2019, pp. 137–157. 1245
- [7] T. M. Mitchell, et al., *Machine learning*. 1997, 432, McGraw-Hill, 1997. 1246
- [8] A. Thessen, Adoption of machine learning techniques in ecology and earth science, *One Ecosystem* 1 (2016) e8621. 1247
- [9] M. Vakili, M. Ghamsari, M. Rezaei, Performance analysis and comparison of machine and deep learning algorithms for iot data classification, arXiv preprint arXiv:2001.09636 (2020). 1248

- 1268 [10] R. S. Sutton, A. G. Barto, Reinforcement learning: An introduction, MIT press, 2017. 1339
- 1269 [11] Y. LeCun, Y. Bengio, G. Hinton, Deep learning, nature 521 (2015) 436–444. 1340
- 1270 [12] J. Schmidhuber, Deep learning in neural networks: An overview, Neural networks 61 (2015) 85–117. 1341
- 1271 [13] B. Yegnanarayana, Artificial neural networks, PHI Learning Pvt. Ltd., 2009. 1342
- 1272 [14] H. A. Al-Rawi, M. A. Ng, K.-L. A. Yau, Application of reinforcement learning to routing in distributed wireless networks: a review, Artificial Intelligence Review 43 (2015) 381–416. 1343
- 1273 [15] I. Althamary, C.-W. Huang, P. Lin, A survey on multi-agent reinforcement learning methods for vehicular networks, in: 2019 15th International Wireless Communications & Mobile Computing Conference (IWCMC), IEEE, 2019, pp. 1154–1159. 1344
- 1274 [16] Y. Wang, Z. Ye, P. Wan, J. Zhao, A survey of dynamic spectrum allocation based on reinforcement learning algorithms in cognitive radio networks, Artificial Intelligence Review 51 (2019) 493–506. 1345
- 1275 [17] N. C. Luong, D. T. Hoang, S. Gong, D. Niyato, P. Wang, Y.-C. Liang, D. I. Kim, Applications of deep reinforcement learning in communications and networking: A survey, IEEE Communications Surveys & Tutorials 21 (2019) 3133–3174. 1346
- 1276 [18] L. Lei, Y. Tan, K. Zheng, S. Liu, K. Zhang, X. Shen, Deep reinforcement learning for autonomous internet of things: Model, applications and challenges, IEEE Communications Surveys & Tutorials (2020). 1347
- 1277 [19] T. T. Nguyen, N. D. Nguyen, S. Nahavandi, Deep reinforcement learning for multiagent systems: A review of challenges, solutions, and applications, IEEE transactions on cybernetics (2020). 1348
- 1278 [20] L. Cui, S. Yang, F. Chen, Z. Ming, N. Lu, J. Qin, A survey on application of machine learning for internet of things, International Journal of Machine Learning and Cybernetics 9 (2018) 1399–1417. 1349
- 1279 [21] K. A. da Costa, J. P. Papa, C. O. Lisboa, R. Munoz, V. H. C. de Albuquerque, Internet of things: A survey on machine learning-based intrusion detection approaches, Computer Networks 151 (2019) 147–157. 1350
- 1280 [22] D. P. Kumar, T. Amgoth, C. S. R. Annavarapu, Machine learning algorithms for wireless sensor networks: A survey, Information Fusion 49 (2019) 1–25. 1351
- 1281 [23] IEEE standard for local and metropolitan area networks - part 15.6: Wireless body area networks, IEEE Std 802.15.6-2012 (2012). 1352
- 1282 [24] M. Patel, J. Wang, Applications, challenges, and prospective in emerging body area networking technologies, IEEE Wireless communications 17 (2010) 80–88. 1353
- 1283 [25] A. Gkikopouli, G. Nikolakopoulos, S. Manesis, A survey on underwater wireless sensor networks and applications, in: 2012 20th Mediterranean conference on control & automation (MED), IEEE, 2012, pp. 1147–1154. 1354
- 1284 [26] H. Kaushal, G. Kaddoum, Underwater optical wireless communication, IEEE access 4 (2016) 1518–1547. 1355
- 1285 [27] S. Al-Sultan, M. M. Al-Doori, A. H. Al-Bayatti, H. Zedan, A comprehensive survey on vehicular ad hoc network, Journal of network and computer applications 37 (2014) 380–392. 1356
- 1286 [28] F. Yang, S. Wang, J. Li, Z. Liu, Q. Sun, An overview of internet of vehicles, China communications 11 (2014) 1–15. 1357
- 1287 [29] D. Jiang, L. Delgrossi, Ieee 802.11 p: Towards an international standard for wireless access in vehicular environments, in: VTC Spring 2008-IEEE Vehicular Technology Conference, IEEE, 2008, pp. 2036–2040. 1358
- 1288 [30] A. Gilchrist, Industry 4.0: the industrial internet of things, Springer, 2016. 1359
- 1289 [31] M. T. Spaan, Partially observable markov decision processes, in: Reinforcement Learning, Springer, 2012, pp. 387–414. 1360
- 1290 [32] S. Racanière, T. Weber, D. Reichert, L. Buesing, A. Guez, D. J. Rezende, A. P. Badia, O. Vinyals, N. Heess, Y. Li, et al., Imagination-augmented agents for deep reinforcement learning, in: Advances in neural information processing systems, 2017, pp. 5690–5701. 1361
- 1291 [33] A. Nagabandi, G. Kahn, R. S. Fearing, S. Levine, Neural network dynamics for model-based deep reinforcement learning with model-free fine-tuning, in: 2018 IEEE International Conference on Robotics and Automation (ICRA), IEEE, 2018, pp. 7559–7566. 1362
- 1292 [34] D. Silver, T. Hubert, J. Schrittwieser, I. Antonoglou, M. Lai, A. Guez, M. Lanctot, L. Sifre, D. Kumaran, T. Graepel, et al., A general reinforcement learning algorithm that masters chess, shogi, and go through self-play, Science 362 (2018) 1140–1144. 1363
- 1293 [35] C. B. Browne, E. Powley, D. Whitehouse, S. M. Lucas, P. I. Cowling, P. Rohlfshagen, S. Tavener, D. Perez, S. Samothrakis, S. Colton, A survey of Monte Carlo tree search methods, IEEE Transactions on Computational Intelligence and AI in games 4 (2012) 1–43. 1364
- 1294 [36] M. H. Kalos, P. A. Whitlock, Monte carlo methods, John Wiley & Sons, 2009. 1344
- 1295 [37] G. A. Rummery, M. Niranjan, On-line Q-learning using connectionist systems, volume 37, University of Cambridge, Department of Engineering Cambridge, UK, 1994. 1345
- 1296 [38] C. J. Watkins, P. Dayan, Q-learning, Machine learning 8 (1992) 279–292. 1346
- 1297 [39] R. S. Sutton, D. A. McAllester, S. P. Singh, Y. Mansour, Policy gradient methods for reinforcement learning with function approximation, in: Advances in neural information processing systems, 2000, pp. 1057–1063. 1347
- 1298 [40] R. J. Williams, Simple statistical gradient-following algorithms for connectionist reinforcement learning, Machine learning 8 (1992) 229–256. 1348
- 1299 [41] J. Schulman, S. Levine, P. Abbeel, M. Jordan, P. Moritz, Trust region policy optimization, in: International conference on machine learning, 2015, pp. 1889–1897. 1349
- 1300 [42] J. Schulman, F. Wolski, P. Dhariwal, A. Radford, O. Klimov, Proximal policy optimization algorithms, arXiv preprint arXiv:1707.06347 (2017). 1350
- 1301 [43] V. R. Konda, J. N. Tsitsiklis, Actor-critic algorithms, in: Advances in neural information processing systems, 2000, pp. 1008–1014. 1351
- 1302 [44] I. Grondman, L. Busoniu, G. A. Lopes, R. Babuska, A survey of actor-critic reinforcement learning: Standard and natural policy gradients, IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews) 42 (2012) 1291–1307. 1352
- 1303 [45] K. Arulkumaran, M. P. Deisenroth, M. Brundage, A. A. Bharath, Deep reinforcement learning: A brief survey, IEEE Signal Processing Magazine 34 (2017) 26–38. 1353
- 1304 [46] L. Deng, D. Yu, et al., Deep learning: methods and applications, Foundations and Trends® in Signal Processing 7 (2014) 197–387. 1354
- 1305 [47] V. Mnih, K. Kavukcuoglu, D. Silver, A. A. Rusu, J. Veness, M. G. Belle-mare, A. Graves, M. Riedmiller, A. K. Fidjeland, G. Ostrovski, et al., Human-level control through deep reinforcement learning, Nature 518 (2015) 529–533. 1355
- 1306 [48] V. Mnih, K. Kavukcuoglu, D. Silver, A. Graves, I. Antonoglou, D. Wierstra, M. Riedmiller, Playing atari with deep reinforcement learning, arXiv preprint arXiv:1312.5602 (2013). 1356
- 1307 [49] S. J. Pan, Q. Yang, A survey on transfer learning, IEEE Transactions on knowledge and data engineering 22 (2009) 1345–1359. 1357
- 1308 [50] R. Caruana, Multitask learning, Machine learning 28 (1997) 41–75. 1358
- 1309 [51] C. Finn, P. Abbeel, S. Levine, Model-agnostic meta-learning for fast adaptation of deep networks, arXiv preprint arXiv:1703.03400 (2017). 1359
- 1310 [52] L. Ericsson, More than 50 billion connected devices, White Paper 14 (2011) 124. 1360
- 1311 [53] J. Chase, The evolution of the internet of things, Texas Instruments 1 (2013) 1–7. 1361
- 1312 [54] E. Ancillotti, C. Vallati, R. Bruno, E. Mingozzi, A reinforcement learning-based link quality estimation strategy for RPL and its impact on topology management, Computer Communications 112 (2017) 1–13. 1362
- 1313 [55] J. Yang, S. He, Y. Xu, L. Chen, J. Ren, A trusted routing scheme using blockchain and reinforcement learning for wireless sensor networks, Sensors 19 (2019) 970. 1363
- 1314 [56] X.-h. Liu, D.-g. Zhang, T. Zhang, Y.-y. Cui, Novel approach of the best path selection based on prior knowledge reinforcement learning, in: 2019 IEEE International Conference on Smart Internet of Things (SmartIoT), IEEE, 2019, pp. 148–154. 1364
- 1315 [57] X.-h. Liu, D.-g. Zhang, T. Zhang, Y.-y. Cui, New method of the best path selection with length priority based on reinforcement learning strategy, in: 2019 28th International Conference on Computer Communication and Networks (ICCCN), IEEE, 2019, pp. 1–6. 1365
- 1316 [58] G. Liu, X. Wang, X. Li, J. Hao, Z. Feng, ESRQ: An efficient secure routing method in wireless sensor networks based on Q-learning, in: 2018 17th IEEE International Conference On Trust, Security And Privacy In Computing And Communications/12th IEEE International Conference On Big Data Science And Engineering (TrustCom/BigDataSE), IEEE, 1366

- 2018, pp. 149–155.
- [59] L. Zhao, J. Wang, J. Liu, N. Kato, Routing for crowd management in smart cities: A deep reinforcement learning perspective, *IEEE Communications Magazine* 57 (2019) 88–93.
- [60] W. Guo, C. Yan, T. Lu, Optimizing the lifetime of wireless sensor networks via reinforcement-learning-based routing, *International Journal of Distributed Sensor Networks* 15 (2019) 1550147719833541.
- [61] Y. Akbari, S. Tabatabaei, A new method to find a high reliable route in IoT by using reinforcement learning and fuzzy logic, *Wireless Personal Communications* (2020) 1–17.
- [62] N. Aslam, K. Xia, M. U. Hadi, Optimal wireless charging inclusive of intellectual routing based on SARSA learning in renewable wireless sensor networks, *IEEE Sensors Journal* 19 (2019) 8340–8351.
- [63] A. Mateen, M. Awais, N. Javaid, F. Ishmanov, M. K. Afzal, S. Kazmi, Geographic and opportunistic recovery with depth and power transmission adjustment for energy-efficiency and void hole alleviation in UWSNs, *Sensors* 19 (2019) 709.
- [64] H. Chang, J. Feng, C. Duan, Reinforcement learning-based data forwarding in underwater wireless sensor networks with passive mobility, *Sensors* 19 (2019) 256.
- [65] S. Wang, Y. Shin, Efficient routing protocol based on reinforcement learning for magnetic induction underwater sensor networks, *IEEE Access* 7 (2019) 82027–82037.
- [66] X. Li, X. Hu, W. Li, H. Hu, A multi-agent reinforcement learning routing protocol for underwater optical sensor networks, in: *ICC 2019-2019 IEEE International Conference on Communications (ICC)*, IEEE, 2019, pp. 1–7.
- [67] M. Kwon, J. Lee, H. Park, Intelligent IoT connectivity: deep reinforcement learning approach, *IEEE Sensors Journal* (2019).
- [68] H. V. Hasselt, Double Q-learning, in: *Advances in neural information processing systems*, 2010, pp. 2613–2621.
- [69] H. Van Hasselt, A. Guez, D. Silver, Deep reinforcement learning with double Q-learning, in: *Thirtieth AAAI conference on artificial intelligence*, 2016.
- [70] Z. Wei, Y. Zhang, X. Xu, L. Shi, L. Feng, A task scheduling algorithm based on q-learning and shared value function for WSNs, *Computer Networks* 126 (2017) 141–149.
- [71] M. I. Khan, K. Xia, A. Ali, N. Aslam, Energy-aware task scheduling by a true online reinforcement learning in wireless sensor networks., *IJNS* 25 (2017) 244–258.
- [72] Z. Wei, F. Liu, Y. Zhang, J. Xu, J. Ji, Z. Lyu, A Q-learning algorithm for task scheduling based on improved SVM in wireless sensor networks, *Computer Networks* 161 (2019) 138–149.
- [73] S. Kosunalp, Y. Chu, P. D. Mitchell, D. Grace, T. Clarke, Use of Q-learning approaches for practical medium access control in wireless sensor networks, *Engineering Applications of Artificial Intelligence* 55 (2016) 146–154.
- [74] Y. Chu, P. D. Mitchell, D. Grace, ALOHA and Q-learning based medium access control for wireless sensor networks, in: *2012 International Symposium on Wireless Communication Systems (ISWCS)*, IEEE, 2012, pp. 511–515.
- [75] T. Yang, J. Li, H. Feng, N. Cheng, W. Guan, A novel transmission scheduling based on deep reinforcement learning in software-defined maritime communication networks, *IEEE Transactions on Cognitive Communications and Networking* 5 (2019) 1155–1166.
- [76] H. Yang, X. Xie, An actor-critic deep reinforcement learning approach for transmission scheduling in cognitive internet of things systems, *IEEE Systems Journal* (2019).
- [77] Y. Lu, T. Zhang, E. He, I.-S. Comşa, Self-learning-based data aggregation scheduling policy in wireless sensor networks, *Journal of Sensors* 2018 (2018).
- [78] R. F. Atallah, C. M. Assi, M. J. Khabbaz, Scheduling the operation of a connected vehicular network using deep reinforcement learning, *IEEE Transactions on Intelligent Transportation Systems* 20 (2018) 1669–1682.
- [79] Y.-H. Xu, J.-W. Xie, Y.-G. Zhang, M. Hua, W. Zhou, Reinforcement learning (RL)-based energy efficient resource allocation for energy harvesting-powered wireless body area network, *Sensors* 20 (2020) 44.
- [80] A. Gomes, D. F. Macedo, L. F. Vieira, Automatic MAC protocol selection in wireless networks based on reinforcement learning, *Computer Communications* 149 (2020) 312–323.
- [81] C. Wang, X. Gaimu, C. Li, H. Zou, W. Wang, Smart mobile crowd-sensing with urban vehicles: A deep reinforcement learning perspective, *IEEE Access* 7 (2019) 37334–37341.
- [82] Y. Liu, H. Yu, S. Xie, Y. Zhang, Deep reinforcement learning for offloading and resource allocation in vehicle edge computing and networks, *IEEE Transactions on Vehicular Technology* 68 (2019) 11158–11168.
- [83] J. Chen, S. Chen, Q. Wang, B. Cao, G. Feng, J. Hu, iRAF: A deep reinforcement learning approach for collaborative mobile edge computing IoT networks, *IEEE Internet of Things Journal* 6 (2019) 7011–7024.
- [84] S. S. Oyewobi, G. P. Hancke, A. M. Abu-Mahfouz, A. J. Onumanyi, An effective spectrum handoff based on reinforcement learning for target channel selection in the industrial internet of things, *Sensors* 19 (2019) 1395.
- [85] C. Fan, S. Bao, Y. Tao, B. Li, C. Zhao, Fuzzy reinforcement learning for robust spectrum access in dynamic shared networks, *IEEE Access* 7 (2019) 125827–125839.
- [86] D. Pacheco-Paramo, L. Tello-Oquendo, V. Pla, J. Martinez-Bauset, Deep reinforcement learning mechanism for dynamic access control in wireless networks handling mMTC, *Ad Hoc Networks* 94 (2019) 101939.
- [87] S. Wang, H. Liu, P. H. Gomes, B. Krishnamachari, Deep reinforcement learning for dynamic multichannel access in wireless networks, *IEEE Transactions on Cognitive Communications and Networking* 4 (2018) 257–265.
- [88] M. Chincoli, A. Liotta, Self-learning power control in wireless sensor networks, *Sensors* 18 (2018) 375.
- [89] C. Savaglio, P. Pace, G. Aloia, A. Liotta, G. Fortino, Lightweight reinforcement learning for energy efficient communications in wireless sensor networks, *IEEE Access* 7 (2019) 29355–29364.
- [90] S. Soni, M. Shrivastava, Novel learning algorithms for efficient mobile sink data collection using reinforcement learning in wireless sensor network, *Wireless Communications and Mobile Computing* 2018 (2018).
- [91] F. A. Aoudia, M. Gautier, O. Berder, Learning to survive: Achieving energy neutrality in wireless sensor networks using reinforcement learning, in: *2017 IEEE International Conference on Communications (ICC)*, IEEE, 2017, pp. 1–6.
- [92] Y. Wu, K. Yang, Cooperative reinforcement learning based throughput optimization in energy harvesting wireless sensor networks, in: *2018 27th Wireless and Optical Communication Conference (WOCC)*, IEEE, 2018, pp. 1–6.
- [93] A. Murad, F. A. Kraemer, K. Bach, G. Taylor, Autonomous management of energy-harvesting IoT nodes using deep reinforcement learning, in: *2019 IEEE 13th International Conference on Self-Adaptive and Self-Organizing Systems (SASO)*, IEEE, 2019, pp. 43–51.
- [94] M. K. Sharma, A. Zappone, M. Debbah, M. Assaad, Multi-agent deep reinforcement learning based power control for large energy harvesting networks, in: *Proc. 17th Int. Symp. Model. Optim. Mobile Ad Hoc Wireless Netw. (WiOpt)*, 2019, pp. 1–7.
- [95] X. Wang, Q. Zhou, C. Qu, G. Chen, J. Xia, Location updating scheme of sink node based on topology balance and reinforcement learning in WSN, *IEEE Access* 7 (2019) 100066–100080.
- [96] M. Mohammadi, A. Al-Fuqaha, M. Guizani, J.-S. Oh, Semisupervised deep reinforcement learning in support of IoT and smart city services, *IEEE Internet of Things Journal* 5 (2017) 624–635.
- [97] C. H. Liu, Q. Lin, S. Wèn, Blockchain-enabled data collection and sharing for industrial IoT with deep reinforcement learning, *IEEE Transactions on Industrial Informatics* 15 (2018) 3516–3526.
- [98] J. Lu, L. Feng, J. Yang, M. M. Hassan, A. Alelaiwi, I. Humar, Artificial agent: The fusion of artificial intelligence and a mobile agent for energy-efficient traffic control in wireless sensor networks, *Future Generation Computer Systems* 95 (2019) 45–51.
- [99] H. Zhu, Y. Cao, X. Wei, W. Wang, T. Jiang, S. Jin, Caching transient data for internet of things: A deep reinforcement learning approach, *IEEE Internet of Things Journal* 6 (2018) 2074–2083.
- [100] Y. Wei, F. R. Yu, M. Song, Z. Han, Joint optimization of caching, computing, and radio resources for fog-enabled IoT using natural actor-critic deep reinforcement learning, *IEEE Internet of Things Journal* 6 (2018) 2061–2073.
- [101] W. Liang, W. Huang, J. Long, K. Zhang, K.-C. Li, D. Zhang, Deep reinforcement learning for resource protection and real-time detection in IoT environment, *IEEE Internet of Things Journal* (2020).
- [102] J. Banks, Introduction to simulation, in: *Proceedings of the 31st confer-*

- ence on Winter simulation: Simulation—a bridge to the future-Volume 1, 1999, pp. 7–13.
- [103] Mathworks - solutions - MATLAB & simulink, [Accessed on July 2020]. URL: <https://fr.mathworks.com/solutions.html>.
- [104] Products and services - MATLAB & simulink, [Accessed on July 2020]. URL: <https://www.mathworks.com/products.html>.
- [105] F. Osterlind, A. Dunkels, J. Eriksson, N. Finne, T. Voigt, Cross-level sensor network simulation with cooja, in: Proceedings. 2006 31st IEEE Conference on Local Computer Networks, IEEE, 2006, pp. 641–648.
- [106] OMNeT++ discrete event simulator, [Accessed on July 2020]. URL: <https://omnetpp.org/>.
- [107] The network simulator - NS-2, [Accessed on July 2020]. URL: <https://www.isi.edu/nsnam/ns/>.
- [108] NS-3 — a discrete-event network simulator for internet systems, [Accessed on July 2020]. URL: <https://www.nsnam.org/>.
- [109] M. Abadi, P. Barham, J. Chen, Z. Chen, A. Davis, J. Dean, M. Devin, S. Ghemawat, G. Irving, M. Isard, et al., Tensorflow: A system for large-scale machine learning, in: 12th {USENIX} symposium on operating systems design and implementation ({OSDI} 16), 2016, pp. 265–283.
- [110] Gym: A toolkit for developing and comparing reinforcement learning algorithms, [Accessed on July 2020]. URL: <https://gym.openai.com/>.
- [111] N. H. Mak, W. K. Seah, How long is the lifetime of a wireless sensor network ?, in: 2009 International Conference on Advanced Information Networking and Applications, IEEE, 2009, pp. 763–770.
- [112] A. P. Renold, S. Chandrakala, MRL-SCSO: Multi-agent reinforcement learning-based self-configuration and self-optimization protocol for unattended wireless sensor networks, Wireless Personal Communications 96 (2017) 5061–5079.
- [113] R. S. Sutton, Learning to predict by the methods of temporal differences, Machine learning 3 (1988) 9–44.
- [114] A. Y. Ng, S. J. Russell, et al., Algorithms for inverse reinforcement learning., in: Icml, volume 1, 2000, p. 2.
- [115] P. Abbeel, A. Y. Ng, Apprenticeship learning via inverse reinforcement learning, in: Proceedings of the twenty-first international conference on Machine learning, 2004, p. 1.
- [116] D. Hadfield-Menell, S. Milli, P. Abbeel, S. J. Russell, A. Dragan, Inverse reward design, in: Advances in neural information processing systems, 2017, pp. 6765–6774.
- [117] S. Levine, A. Kumar, G. Tucker, J. Fu, Offline reinforcement learning: Tutorial, review, and perspectives on open problems, arXiv preprint arXiv:2005.01643 (2020).
- [118] Y. Wu, E. Mansimov, S. Liao, A. Radford, J. Schulman, Openai baselines: ACKTR and A2C, 2017. URL: <https://openai.com/blog/baselines-acktr-a2c/>.
- [119] V. Mnih, A. P. Badia, M. Mirza, A. Graves, T. Lillicrap, T. Harley, D. Silver, K. Kavukcuoglu, Asynchronous methods for deep reinforcement learning, in: International conference on machine learning, 2016, pp. 1928–1937.
- [120] ElegantRL: Lightweight, efficient and stable deep reinforcement learning implementation using pytorch, [Accessed on May 2021]. URL: <https://github.com/AI4Finance-LLC/ElegantRL>.
- [121] Tensorflow lite — ml for mobile and edge devices, [Accessed on May 2021]. URL: <https://www.tensorflow.org/lite>.