Scheduling Algorithms for Wireless Downlink with Deadline and Retransmission Constraints

Fan Zhang*, Aoyu Gong*, Lei Deng†, and Yijin Zhang*
*School of Electronic and Optical Engineering, Nanjing University of Science and Technology, Nanjing, China
†College of Electronics and Information Engineering, Shenzhen University, Shenzhen, China
Emails: fan.zhang@njust.edu.cn, gongaoyu@gmail.com, ldeng@szu.edu.cn, yijin.zhang@gmail.com

***Abstract*—Packet scheduling for wireless downlink to multiple nodes with deadline and retransmission constraints plays an important role in supporting real-time applications. In this paper, under independent packet arrival processes for different nodes, we formulate this downlink problem as an Markov Decision Process (MDP) by considering all the packets in the queues for all the nodes and obtain a deterministic stationary ϵ-optimal scheduling policy. To reduce the exponential complexity due to possibly multiple packets in each queue, we modify this MDP by only considering the head-of-line (HoL) packets, and obtain a heuristic scheduling policy. Simulation results show that the proposed heuristic policy achieves near-optimal performance and outperforms three baselines.**

***Index Terms*—Deadline-constrained downlink, throughput, scheduling, retransmissions, Markov Decision Process**

I. Introduction

Deadline-constrained wireless communication systems have been becoming widespread nowadays. Typical examples include real-time streaming and video conferencing over cellular or WiFi networks [1], [2], 5G-enabled tactile Internet [3], wireless networked control systems [4]–[6], and wireless cyber-physical systems [7]–[9]. In such applications, each packet has a strict deadline, that is, a packet will be removed from the system if it is not successfully transmitted before the deadline [2], [10].

Deadline-constrained wireless downlink has been an active research area since the seminal work [11] by Hou, Borkar and Kumar, For the frame-synchronized traffic, they proposed an idle-time-based framework to characterize timely capacity region and further designed a throughput-optimal scheduling policy, called the largest-deficit-first (LDF) policy. After that, a serials of extensive works [12]–[15] have been conducted for such traffic. However, it requires that the traffic for each node only possibly has a new packet arrival at the beginning of every global frame and the strict deadline is equal to the frame length, which only captures limited practical scenarios. To remove this limit, Deng *et. al* in [2] proposed an Markov Decision Process (MDP)-based framework to consider general traffic patterns. They characterized the timely capacity region by a finite number of linear constraints and also proposed an MDP-based throughput-optimal scheduling policy.

However, the existing studies did not impose any restriction on retransmissions, but assumed that a packet can be transmitted as soon as it has not been transmitted successfully and its deadline has not been expired. This setting does not comply with the current standards for wireless networks. For example, the hard limit on retransmission times is termed `maxRetxThreshold` [16], [17] in 4G LTE and 5G NR standards, and the hard limits for short packets and long packets are termed `dot11ShortRetryLimit` and `dot11LongRetryLimit` [18], respectively, in WiFi standards. In addition, this hard limit is usually set to be 1 for URLLC applications [19].

In this paper, we focus on wireless downlink to multiple nodes with deadline and retransmission constraints, where the packet arrival processes for different nodes are independent. We aim to design a scheduling policy that maximizes the network throughput. Our contributions are as follows.

- First, following [2], we formulate our problem as an MDP by modeling all the packets in all the queues into the state, and obtain a deterministic stationary ϵ-optimal scheduling policy based on this MDP. To our best knowledge, we are the first to consider a retransmission constraint.
- Second, it is well-known that the MDP approach suffers from the curse of dimensionality. The exponential complexity comes from two parts in our problem: (i) the number of nodes, and (ii) the number of packets in each queue. In this work, we partially address the curse of dimensionality by reducing the exponential complexity due to part (ii). We formulate a modified MDP that only models the head-of-line (HoL) packets into the state. The intuition behind is that the information of HoL packets has a dominant impact on the system performance, and it is reasonable to take into account the impact of non-HoL packets merely relying on the packet arriving rate, but not relying on the actual arrival events. Based on this modified MDP, we propose a heuristic scheduling policy.
- Finally, we conduce extensive simulations to demonstrate that the proposed heuristic policy achieves near-optimal performance and outperforms three baselines.

II. System Model

As shown in Fig. 1, we consider a fully-connected wireless downlink network where a BS wants to transmit the packets from its queue i to node i for $i = 1, 2, \ldots, K$. The channel time is divided into time slots of equal duration. At the beginning of each slot and at each queue i, a single-slot packet arrives with probability $0 < \lambda_i \leq 1$. Each packet has a strict delivery deadline $D \geq 1$ (slots) and is allowed to be

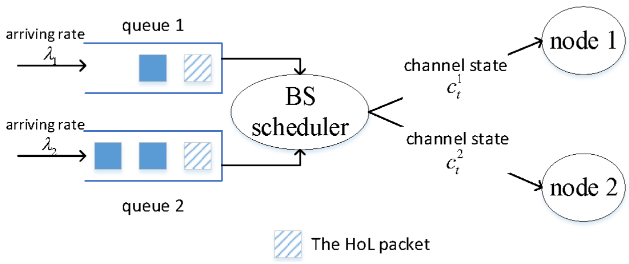

Fig. 1. A wireless downlink scenario for two nodes at slot t.

transmitted for at most $1 \leq N \leq D$ times. The packet arrival processes are assumed to be independent across all the queues. At the beginning of each slot, the BS determines which queue's HoL packet or no packet will be transmitted, according to a predefined scheduling policy.

We assume that the channel state for each node keeps unchanged during a slot, and evolves over slots independently of each other. We model it as a time homogeneous finite-state Markov chain (FSMC) with only two states $\{0, 1\}$: the good state 1 and the bad state 0. Let c_t^i represent the channel state for node i at slot t. The transition probability from $c_t^i = 0$ to $c_{t+1}^i = 1$ is $\alpha_i > 0$ and the transition probability from $c_t^i = 1$ to $c_{t+1}^i = 1$ is $\beta_i > 0$. We assume that c_t^i is known to the BS at the beginning of slot t for all node i. We further denote by $p_{c_t^i}$ the probability of successful transmission if a packet is sent to node i at slot t. Obviously, $0 \leq p_0 < p_1 \leq 1$. When a packet is sent at a slot, the BS is aware of whether this packet is transmitted successfully at the end of this slot, through an instantaneous and error-free feedback sent from the corresponding node.

With the above assumptions, a packet will be removed from its associated queue when either of the following events occurs: (i) the packet has been successfully transmitted, (ii) the packet has been transmitted for N times, and (iii) the packet has stayed at the queue for D slots. Under this consideration, our goal is to find a scheduling policy for BS to maximize the network throughput, defined as the average number of packets successfully transmitted per slot.

III. MDP Formulation and Optimal Solution

In this section, we cast our wireless downlink problem as an MDP, propose an optimization formulation based on this MDP, and apply the value iteration algorithm to solve this formulation.

A. MDP Formulation

We define a finite-dimension infinite-horizon average-reward MDP, denoted by $\boldsymbol{\mathcal{M}}$, by describing the following definitions of state, action, state transition probabilities, reward and average reward.

1) *Definition of the State:* We define the network state as

$$S_t \triangleq (c_t^1, L_t^1, n_t^1, c_t^2, L_t^2, n_t^2, \ldots, c_t^K, L_t^K, n_t^K).$$

where $c_t^i \in \{0, 1\}$ is the channel state for node i at slot t, $n_t^i \in \{1, 2, \ldots, N\}$ is the remaining allowable transmission times of the HoL packet in queue i at slot t, and L_t^i is the collection of the remaining time before expiration (called lead time) of all the packets in queue i at slot t. We adopt the convention that $n_t^i = N$ when queue i has no packet at slot t. Here, as each queue has as most D packets with the lead time not larger than D, L_t^i can be represented by a zero-one string [2], $L_t^i \triangleq b_1^i b_2^i \ldots b_D^i$ where $b_l^i = 1$ if and only if there exists a packet in queue i with lead time l. For example, when $D = 4$ and there are only two packets in queue i with the lead time 1, 3 at slot t, we have $L_t^i = 1010$. Thus, by enumerating all possible S_t, we can obtain the state space $\mathcal{S}$ for $\boldsymbol{\mathcal{M}}$ with $|\mathcal{S}| = (2N(2^D - 1) + 2)^K$.

2) *Definition of the Action:* The action space of the BS is defined as $\mathcal{A} \triangleq \{0, 1, \ldots, K\}$. The action at slot t, denoted by A_t, requires the HoL packet in queue a to be transmitted at slot t if $A_t = a \in \mathcal{A} \setminus \{0\}$ and requires no packet to be transmitted at slot t if $A_t = 0$.

3) *Definition of the State Transition Probabilities:* We use $\Pr(S_{t+1} = s' | S_t = s, A_t = a)$ to represent the transition probability from the state $S_t = s$ to $S_{t+1} = s'$ if the action $A_t = a$ is taken at slot t. Its calculation depends on (i) the FSMCs for the channel states (ii) the packet arrival events at the end of slot t and (iii) the packet removal events at the end of slot t due to successful transmission under some channel state, deadline expiration or achieving the maximal allowable transmission times. As these events are independent of the slot index t, $\Pr(S_{t+1} = s' | S_t = s, A_t = a)$ is time-homogeneous for every case, and can be simply written as $\Pr(s'|s, a)$. Thus, by examining the impact of these events for each $s, s' \in \mathcal{S}$ and each $a \in \mathcal{A}$, we can obtain all $\Pr(s'|s, a)$s for $\boldsymbol{\mathcal{M}}$.

For example, considering a two-node downlink scenario with $D = 4, N = 2$, assume that

$$s = (1, 1101, 2, 0, 0011, 1).$$

If the BS transmits the HoL packet of queue 1 at the sate s, then we have

$$\Pr\big((1, 1010, 2, 1, 0111, 1)|s, 1\big) = p_1(1 - \lambda_1)\beta_1\lambda_2\alpha_2.$$

4) *Definition of the Reward:* The reward that is gained when action a is taken at state s, denoted by $r(s, a)$, is defined as the probability that a packet is successfully transmitted under state s and action a, i.e.,

$$r(s, a) \triangleq \begin{cases} 0, & \text{if } a = 0 \text{ or } L^a = 00\cdots0, \\ p_{c^a}, & \text{otherwise,} \end{cases}$$

where $s = (c^1, L^1, n^1, \ldots, c^K, L^K, n^K)$.

5) *Definition of the Average Reward:* The long-term average reward, denoted by $\overline{r}$, is defined as:

$$\overline{r} \triangleq \liminf_{T \to \infty} \frac{1}{T} \sum_{t=1}^{T} \mathbb{E}[r(S_t, A_t)]. \quad (1)$$

From the formulation of $\mathcal{M}$, we see that the network throughput is exactly to the average reward $\bar{r}$ defined in (1). Hence, we aim to obtain the optimal scheduling policy that maximizes (1). Then, the optimization problem can be expressed as follows:

$$\arg\max_{\chi\in\mathbf{\Pi}} \liminf_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T}\mathbb{E}_{\chi}[r(S_t, A_t)] \tag{2}$$

where $\mathbf{\Pi}$ denotes the set of all possible policies for $\mathcal{M}$.

B. Optimal Solution

It is easy to check that $\mathcal{M}$ consists of a single recurrent class plus a possibly empty set of transient states for every deterministic stationary policy, and thus $\mathcal{M}$ is *unichain*. Furthermore, there exists a state $s \in \mathcal{S}$, for any deterministic Markov policy, it is possible to go from every $s' \in \mathcal{S}$ to s with positive probability. With these two properties, by [20, Theorem 8.5.3], we can use the following value iteration algorithm to obtain a deterministic stationary ϵ-optimal solution to (2) for an arbitrarily small positive number ϵ, denoted by χ^{ϵ}.

Algorithm 1 The Value Iteration Algorithm to find χ^{ϵ}

1: **Initialization:** Set $v^{(0)}(s) = 0$ for each $s \in \mathcal{S}$, specify $\epsilon > 0$ and set $k = 0$.

2: **Evaluation:** For each $s \in \mathcal{S}$, compute $v^{(k+1)}(s)$ by

$$v^{(k+1)}(s) = \max_{a\in\mathcal{A}}\left[r(s,a) + \sum_{s'\in\mathcal{S}} \Pr(s'|s,a)v^{(k)}(s')\right].$$

3: **Stopping Rule:**
If

$$\max_{s\in\mathcal{S}}\left(v^{(k+1)}(s)-v^{(k)}(s)\right)-\min_{s\in\mathcal{S}}\left(v^{(k+1)}(s)-v^{(k)}(s)\right) < \epsilon,$$

obtain the decision rule:

$$dec(s) \in \arg\max_{a\in\mathcal{A}}\left[r(s,a) + \sum_{s'\in\mathcal{S}} \Pr(s'|s,a)v^{(k)}(s')\right],$$

and obtain the corresponding policy as χ^{ϵ}.
Otherwise, increase k by one and return to step 2.

When $K = 2$, $\alpha_1 = \alpha_2 = 0.7$, $\beta_1 = \beta_2 = 0.7$, $p_0 = 0.3$, $p_1 = 0.6$, four numerical experiments of applying Algorithm 1 to find $\chi^{10^{-5}}$ are illustrated in Fig. 1. It can be seen that 20, 23, 28 and 30 iterations are needed, respectively.

IV. Modified MDP Formulation and Heuristic Design

Section III has designed the optimal scheduling policy χ^* based the MDP formulation $\mathcal{M}$. However, it involves a state space $\mathcal{S}$ with $|\mathcal{S}| = (2N(2^D-1)+2)^K$, and thus suffers from high complexity, which is undesirable in practice. To overcome this weakness, we modify $\mathcal{M}$ to $\mathcal{M}'$ by only considering the lead time of the HoL packet in each queue to define the network state, and then propose a heuristic design for scheduling policy based on $\mathcal{M}'$.

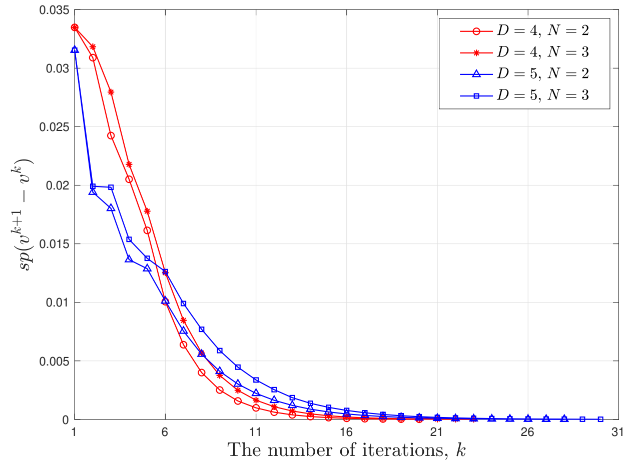

Fig. 2. Four iteration procedures for the case of two nodes.

A. Modified MDP Formulation

We define $\mathcal{M}'$ by describing the following definitions of state, action, state transition probabilities, reward and average reward.

1) *Definition of the State:* We define the network state as

$$S'_t \triangleq (c_t^1, l_t^1, n_t^1, c_t^2, l_t^2, n_t^2, \ldots, c_t^K, l_t^K, n_t^K).$$

where $c_t^i \in \{0,1\}$ and $n_t^i \in \{1,2,\ldots,N\}$ have the same physical meanings as in $\mathcal{M}$, and $l_t^i \in \{0,1,2,\ldots,D\}$. Here $l_t^i = 0$ means no packet in queue i at slot t, and $l_t^i \in \{1,2,\ldots,D\}$ is the lead time of the HoL packet in queue i at slot t. We adopt the convention that $n_t^i = N$ when $l_t^i = 0$. Thus, by enumerating all possible S'_t, we can obtain the state space $\mathcal{S}'$ for $\mathcal{M}'$ with $|\mathcal{S}'| = (2ND+2)^K$, which has a significant reduction compared with $|\mathcal{S}| = (2N(2^D-1)+2)^K$.

2) *Definition of the Action:* The definitions of action space and action are the same as in $\mathcal{M}$.

3) *Definition of the State Transition Probabilities:* We use $\Pr(S'_{t+1} = s'|S'_t = s, A_t = a)$ to represent the transition probability from the state $S'_t = s$ to $S'_{t+1} = s'$ if the action $A_t = a$ is taken at slot t. As the sate S'_t only considers the lead time of the HoL packet in each queue, we need to evaluate the impact of lead times of all non-HoL packets merely relying on the packet arriving rate, but not relying on the actual packet arrival events as in $\mathcal{M}$. This idea complicates the calculation of transition probabilities and introduces additional randomness for modeling the system evolution, but is beneficial to reduce the state space. We checked that $\Pr(S'_{t+1} = s'|S'_t = s, A_t = a)$ is always time-homogeneous, too, and can be simply written as $\Pr'(s'|s,a)$. When action a is taken, as the state transition for an arbitrary queue will not be influenced by that of other queues, $\Pr'(s'|s,a)$ can be decomposed as

$$\Pr'(s'|s,a) = \Pr(c^{i'}|c^i)\prod_{i=1}^{K}\Pr'((l^{i'}, n^{i'})|(l^i, n^i), a).$$

We further consider the following five cases.

Case 1: When $l^i = 0$, a packet will arrive at the empty queue i with probability λ_i, so we have

$$\begin{aligned}
&\Pr'((0,N)|(0,N),a) = 1-\lambda_i, && \forall a \in \mathcal{A},\\
&\Pr'((D,N)|(0,N),a) = \lambda_i, && \forall a \in \mathcal{A}.
\end{aligned}$$

Case 2: When $l^i = 1$, the HoL packet in queue i will be removed no matter whether it is transmitted at the current slot, so we have

$$\begin{aligned}
&\Pr'((0,N)|(1,n^i),a) = (1-\lambda_i)^D, && \forall a \in \mathcal{A},\\
&\Pr'((l^{i'},N)|(1,n^i),a) = (1-\lambda_i)^{l^{i'}-1}\lambda_i, && \text{for } l^{i'} \geq 1\\
& && \forall a \in \mathcal{A}.
\end{aligned}$$

Here $(1-\lambda_i)^D$ represents the probability that no packet arrived in queue i since the arrival of the HoL packet and $(1-\lambda_i)^{l^{i'}-1}\lambda_i$ represents the probability that a packet arrived $l^{i'}$ slots later than the arrival of the HoL packet.

Case 3: When $1 < l^i \leq D$, $n^i = 1, a = i$, the HoL packet in queue i will be removed no matter whether the transmission is successful, so we have

$$\begin{aligned}
&\Pr'((0,N)|(l^i,1),i) = (1-\lambda_i)^{D-l^i+1},\\
&\Pr'((l^{i'},N)|(l^i,1),i) = (1-\lambda_i)^{l^{i'}-l^i}\lambda_i, \ \text{for } l^{i'} \geq l^i.
\end{aligned}$$

Here $(1-\lambda_i)^{D-l^i+1}$ represents the probability that no packet arrived in queue i during $D-l^i+1$ slots since the arrival of the HoL packet, and $(1-\lambda_i)^{l^{i'}-l^i}\lambda_i$ represents the probability that a packet arrived $l^{i'}-l^i+1$ slots later than the arrival of the HoL packet.

Case 4: When $1 < l^i \leq D$, $1 < n^i \leq N, a = i$, the HoL packet in queue i will be removed if it is successfully transmitted, so we have

$$\begin{aligned}
\Pr'((0,N)|(l^i,n^i),i) &= p_{c^i}(1-\lambda_i)^{D-l^i+1},\\
\Pr'((l^{i'},N)|(l^i,n^i),i) &= p_{c^i}(1-\lambda_i)^{l^{i'}-l^i}\lambda_i\\
&\qquad \text{for } l^{i'} \geq l^i,\\
\Pr'((l^i-1,n_i-1)|(l^i,n^i),i) &= 1-p_{c^i}.
\end{aligned}$$

Case 5: When $1 < l^i \leq D$, $1 \leq n^i \leq N$, $a \in \mathcal{A}\setminus\{i\}$, the HoL packet will continue to stay at queue i, so we have

$$\Pr'((l^i-1,n^i)|(l^i,n^i),a \in \mathcal{A}\setminus\{i\}) = 1.$$

4) <u>*Definition of the Reward:*</u> The reward that is gained when action a is taken at state s, denoted by $r'(s,a)$, is defined as the probability that a packet is successfully transmitted under state s and action a, i.e.,

$$r'(s,a) \triangleq \begin{cases} 0, & \text{if } a = 0 \text{ or } l^a = 0,\\ p_{c^a}, & \text{otherwise,}\end{cases}$$

where $s = (c^1, l^1, r^1, \ldots, c^K, l^K, r^K)$.

5) <u>*Definition of the Average Reward:*</u> The long-term average reward, denoted by $\overline{r}'$, is defined as:

$$\overline{r}' \triangleq \liminf_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} \mathbb{E}[r'(S'_t, A_t)]. \tag{3}$$

From the formulation of $\boldsymbol{\mathcal{M}}'$, we see that $\overline{r}'$ defined in (3) provides an evaluation for the network throughput. We aim to obtain the optimal policy that maximizes (3), i.e.,

$$\arg\max_{\chi\in\boldsymbol{\Pi}'} \liminf_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} \mathbb{E}_\chi[r'(S'_t, A_t)] \tag{4}$$

where $\boldsymbol{\Pi}'$ denotes the set of all possible policies for $\boldsymbol{\mathcal{M}}'$.

B. Heuristic Policy

With the similar argument in Section III.B, by [20, Theorem 8.5.3], we can apply the value iteration algorithm to obtain a deterministic stationary ϵ-optimal solution to (4) for an arbitrarily small positive number ϵ, denoted by $\chi^\epsilon_{\text{heu}}$. The details are omitted here, as we only need to replace $\mathcal{S}$ by $\mathcal{S}'$ and replace $\Pr(s'|s,a)$ by $\Pr'(s'|s,a)$ in Algorithm 1. Compared with χ^ϵ, $\chi^\epsilon_{\text{heu}}$ is obtained based on a reduced state space and thus can be viewed as a heuristic solution to (2).

V. Performance Evaluation

In this section, we use simulation to compare the network throughput of ϵ-optimal policy, heuristic policy and three baselines, which are described as follows.

- *Random Policy:* All HoL packets have the equal opportunity to be transmitted.
- *Smallest-HoL-Lead-Time-First (SHLF) Policy:* The HoL packet with the smallest lead time will be transmitted.
- *Shortest-Queue-First (SQF) Policy:* The HoL packet in the shortest queue will be transmitted.

Each simulation result is obtained from 10 simulation runs with 10^7 slots in each run. The channel transition probabilities are set to be $\alpha_1 = \alpha_2 = \beta_1 = \beta_2 = 0.7$, the probabilities of successful transmission are set to be $p_0 = 0.3$, $p_1 = 0.6$, and the arriving rates are set to be $\lambda_1 = \lambda_2 = \lambda$.

Fig. 3 shows that the network throughput of the heuristic policy $\chi^{10^{-5}}_{\text{heu}}$ for two nodes is almost equal to the that of 10^{-5}-optimal policy $\chi^{10^{-5}}$ in all the cases. The throughput becomes higher as the deadline D, the arriving rate λ or the maximal allowable transmission times N increases. In particular, we see that the throughput increase more slowly with λ when λ is large, as more packets are removed due to deadline expirations and thus *cannot* contribute to the throughput. The similar phenomenon occurs for large N, especially when λ is large or D is small. This is because that almost all packets are removed when they have been transmitted for far less than N times, due to deadline expirations or successful transmissions.

Fig. 4 shows that the heuristic policy $\chi^{10^{-5}}_{\text{heu}}$ for three nodes significantly outperforms three baselines in all the cases. The gap becomes larger as λ increases. This is because that heavier traffic would lead to more urgent scheduling scenarios where the packet information is more useful to increase the

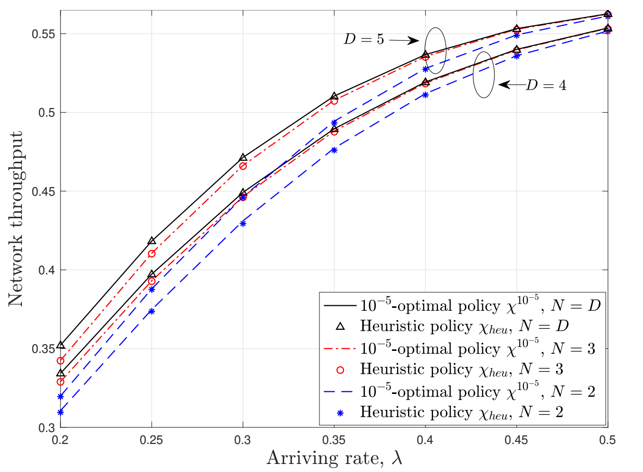

Fig. 3. A comparison for 10^{-5}-optimal policy and heuristic policy when $K = 2$.

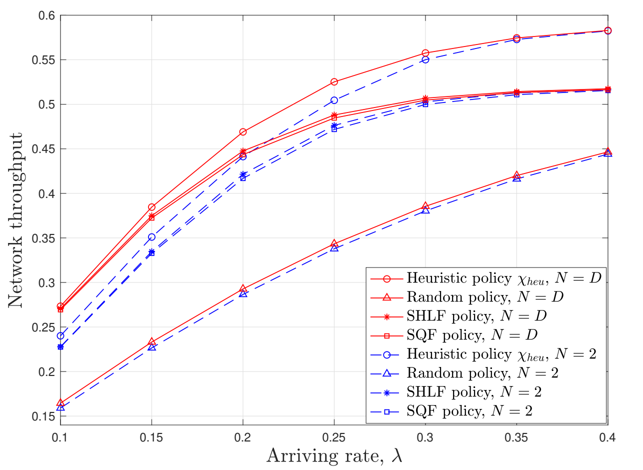

Fig. 4. A comparison for the proposed heuristic policy and three baseline policies when $K = 3$ and $D = 5$.

throughput. In addition, we see that the SHLF policy performs slightly better than the SQF policy in all the cases, which implies that the lead time of HoL packets is slightly more important than the queue length for scheduling. As expected, the random policy performs very poorly, as it makes the scheduling decisions without utilizing system information.

VI. Conclusions

In this paper, under independent packet arrival processes for different nodes, we have investigated the scheduling problem for wireless downlink with deadline and retransmission constraints. We proposed an MDP-based framework to formulate such a problem, and obtained a deterministic stationary ϵ-optimal scheduling policy. Furthermore, we proposed another MDP formulation with reduced state space to obtain a heuristic policy with near-optimal performance. Our ongoing work is to further reduce the exponential complexity caused by the number of nodes and to consider partial observation of channel states for modeling.

Acknowledgements

This work was supported in part the National Natural Science Foundation of China under Grants 62071236, 61902256, and in part by the Fundamental Research Funds for the Central Universities of China, No. 30920021127.

References

[1] M. Xing, S. Xiang, and L. Cai, "A real-time adaptive algorithm for video streaming over multiple wireless access networks," *IEEE Journal on Selected Areas in communications*, vol. 32, no. 4, pp. 795–805, 2014.

[2] L. Deng, C.-C. Wang, M. Chen, and S. Zhao, "Timely wireless flows with general traffic patterns: Capacity region and scheduling algorithms," *IEEE/ACM Transactions on Networking*, vol. 25, no. 6, pp. 3473–3486, 2017.

[3] M. Simsek, A. Aijaz, M. Dohler, J. Sachs, and G. Fettweis, "5G-enabled tactile Internet," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 3, pp. 460–473, 2016.

[4] J. Baillieul and P. J. Antsaklis, "Control and communication challenges in networked real-time systems," *Proceedings of the IEEE*, vol. 95, no. 1, pp. 9–28, 2007.

[5] B. Demirel, Z. Zou, P. Soldati, and M. Johansson, "Modular design of jointly optimal controllers and forwarding policies for wireless control," *IEEE Transactions on Automatic Control*, vol. 59, no. 12, pp. 3252–3265, 2014.

[6] L. Deng, C. Tan, and W. S. Wong, "On stability condition of wireless networked control systems under joint design of control policy and network scheduling policy," in *Proc. IEEE CDC*, 2018, pp. 2041–2047.

[7] F. De Pellegrini, D. Miorandi, S. Vitturi, and A. Zanella, "On the use of wireless networks at low level of factory automation systems," *IEEE Transactions on Industrial Informatics*, vol. 2, no. 2, pp. 129–143, 2006.

[8] B. Holfeld, D. Wieruch, T. Wirth, L. Thiele, S. A. Ashraf, J. Huschke, I. Aktas, and J. Ansari, "Wireless communication for factory automation: An opportunity for lte and 5g systems," *IEEE Communications Magazine*, vol. 54, no. 6, pp. 36–43, 2016.

[9] L. Kong, X. Chen, X. Liu, Q. Xiang, Y. Gao, N. B. Baruch, and G. Chen, "Adasharing: Adaptive data sharing in collaborative robots," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 12, pp. 9569–9579, 2017.

[10] Y. H. Bae, "Queueing analysis of deadline-constrained broadcasting in wireless networks," *IEEE Communications Letters*, vol. 19, no. 10, pp. 1782–1785, 2015.

[11] I.-H. Hou, V. Borkar, and P. R. Kumar, "A theory of QoS for wireless," in *Proc. IEEE INFOCOM*, 2009, pp. 486–494.

[12] I. Hou and P. Kumar, "Admission control and scheduling for QoS guarantees for variable-bit-rate applications on wireless channels," in *Proc. ACM MobiHoc*, 2009, pp. 175–184.

[13] I.-H. Hou, "Scheduling heterogeneous real-time traffic over fading wireless channels," *IEEE/ACM Transactions on Networking*, vol. 22, no. 5, pp. 1631–1644, 2013.

[14] S. Lashgari and A. S. Avestimehr, "Timely throughput of heterogeneous wireless networks: Fundamental limits and algorithms," *IEEE transactions on information theory*, vol. 59, no. 12, pp. 8414–8433, 2013.

[15] X. Kang, W. Wang, J. J. Jaramillo, and L. Ying, "On the performance of largest-deficit-first for scheduling real-time traffic in wireless networks," *IEEE/ACM Transactions on Networking*, vol. 24, no. 1, pp. 72–84, 2014.

[16] 3GPP TS 36.322, "Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Link Control (RLC) protocol specification (Release 16)," 2020.

[17] 3GPP TS 38.322, "NR; Radio Link Control (RLC) protocol specification (Release 16)," 2020.

[18] IEEE 802.11ac-2013, "IEEE Standard for Information technology–Telecommunications and information exchange between systems–Local and metropolitan area networks–Specific requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications–Amendment 4: Enhancements for Very High Throu," 2013.

[19] S. E. Elayoubi, P. Brown, M. Deghel, and A. Galindo-Serrano, "Radio resource allocation and retransmission schemes for URLLC over 5G networks," *IEEE Journal on Selected Areas in Communications*, vol. 37, no. 4, pp. 896–904, 2019.

[20] M. L. Puterman, *Markov decision processes: discrete stochastic dynamic programming*. John Wiley & Sons, 2014.