On the Performance of Back-Pressure Scheduling Schemes with Logarithmic Weight

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Abstract

Recently, significant advances have been made in wireless scheduling toward high-performance networks, leading to development of throughput-optimal scheduling schemes. Beyond throughput performance, however, scheduling with good delay performance has remained open except for a small class of network systems. In this paper, we extend the well-known back-pressure scheduling scheme by using logarithmic weight and improve the delay performance without any loss of throughput performance under multi-hop traffic. We provide rigorous throughput analysis of the proposed solution, and performance evaluations through simulations.

Index Terms

Back-pressure scheduling, logarithmic weight, multi-hop traffic, delay performance, max weight scheduling.

I. Introduction

Wireless scheduling has been extensively studied for the last decade [1]–[10]. Scheduling is a process to determine at each time the packets that will be transmitted, and the power level of the links to transmit the packets over partially shared wireless medium. Scheduling performance can improve by activating multiple links at the same time. However, due to the shared property of wireless medium, transmissions of nearby links may interfere with each other, and none of them can achieve acceptable transmission rate. Hence, scheduling tasks include finding a set of

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active links and their power levels that satisfy the underlying interference constraints. Another important task is to determine which packet has to be transmitted over each active link. The choice of packets for transmissions impacts on scheduling decisions of the future for multi-hop traffic. Due to complex interference constraints and time correlations between scheduling decisions, throughput-optimal scheduling turns out to be in general a non-linear, non-convex optimization problem.

Back-pressure scheduling scheme has been developed by Tassiulas and Ephremides in their seminal work [1], and shown to be throughput-optimal. The scheme determines its schedule by solving the MaxWeight problem with weight of queue length differential, which however turns out to be a NP-Hard problem in general [11]. Addressing high computational complexity of the MaxWeight problem, many efficient scheduling schemes have been developed for single-hop traffic. A class of low-complexity scheduling schemes called *Pick-and-Compare* have been shown to be throughput optimal [2]–[4]. They repeatedly pick a candidate schedule at random and examine its performance. In this way, they keep improving scheduling performance to optimal. *Carrier-Sensing-Multiple-Access (CSMA) based approach* has been proposed to reduce the complexity even further [5], [6]. CSMA-based schemes let the links cooperate with each other to have a stationary distribution of link activities, which is shown to be the same as that of an optimal solution.

However, the provable efficiency of the above low-complexity scheduling schemes is limited to single-hop traffic scenarios and may not hold under multi-hop traffic. With multi-hop traffic, scheduling should choose appropriate packets to transmit, which imposes additional complexity on scheduling algorithm and/or queue structure. The original *back-pressure* scheduling scheme proposed in [1] achieves optimal performance by maintaining per-flow queue structure at each link, and transmit packets from the queue whose queue length difference from the next-hop queue is the largest.

It has been shown that many low-complexity scheduling schemes for single-hop traffic can be extended to multi-hop traffic with help of *regulators* [9], [12]. Using statistical information of flows, regulator that temporarily holds incoming packets at each link can make the packet arrivals at queues as a stochastic process independent of scheduling, which plays a key role in showing efficiency of scheduling schemes that are originally designed for single-hop traffic. However, the addition of regulators often results in very large delays [13], which become a major obstacle to their implementation in practice. Recently, the MaxWeight algorithm of original back-pressure scheduling that requires intensive computations has been replaced with CSMA-based algorithm in [5]. Although this solution achieves throughput optimality with low complexity, it also suffers from large queueing delays due to long switching time between schedules [14].

There has been recent effort to improve the delay performance without any loss of throughput. Delay-optimal scheduling has been known only for limited cases such as tandem queue networks [15]. The work of [16] tackles the last packet problem of the back-pressure scheduling scheme, and improves the delay performance by replacing queue length differentials with waiting time differentials. Interesting shadow queue structure has been introduced in [17] to combine per-flow queues, and it turns out that combining queue structure also significantly improves the delay performance. In [10], the authors adopt logarithmic function to calculate link weights of the MaxWeight scheduling, and show that this log-based MaxWeight scheduling scheme has good delay property as well as achieves optimal throughput. However, log-based MaxWeight is designed only for single-hop traffic, and its effectiveness for multi-hop traffic remains unclear.

In this paper, we extend the idea of the log-based scheduling scheme to multi-hop traffic. We redefine the weight of the original back-pressure scheme using a logarithmic function, and show that the log-based back-pressure scheme achieves optimal throughput by introducing a novel Lyapunov function. Through simulations, we show that the log-based back-pressure scheme has better delay performance than the original back-pressure scheme.

The rest of the paper is organized as follows. The system model is provided in Section II. In Section III, we describe the log-based back-pressure scheme and analyze its throughput performance. The proposed scheme is evaluated through simulations in Section IV, and the conclusion follows in Section V.

II. System Model

We consider a network graph $G(V, E)$ with the set V of nodes and the set E of directed links. A directed link $l = (a, b)$ is established from node a to node b if node a can transmit data packets directly to node b when there is no other active transmission. Let c_l denote its transmission rate. We assume a time-slotted system with a single frequency channel, under which two or more simultaneous transmissions may suffer from significant interference from each other, and cannot transmit data packets successfully.

Let $s \in \{0,1\}^{|E|}$, where $|\cdot|$ is the cardinality of the set, denote a vector that represents a schedule in a time slot. If $s_l = 1$, link l will be active and transmit data packets during the time slot, and if $s_l = 0$, link l will be inactive and remain silent. We say that a schedule s is *feasible* if all active links in s satisfy the signal-to-interference-plus-noise (SINR) constraints. If a feasible schedule s is scheduled in a time slot, each link l in the schedule can transmit data at rate c_l. Assuming that transmission power of each node is fixed, there are a finite number of feasible schedules. We denote the set of all feasible schedules by $\mathcal{S}$, and the associated set of achievable link rate vectors by $\mathcal{C}$.

We consider multi-hop traffic flows. A flow f injects packets at a source node and and requests to deliver the injected packets to a destination node via hop-by-hop communications. The route of a flow is a sequence of nodes or links from the source to the destination, and is assumed to be fixed and cycle-free. Let $[H_l^f]$ denote the routing matrix with $H_l^f = 1$ if the route of flow f passes through link l, and with $H_l^f = 0$ otherwise. In the route of flow f, we denote the previous and the next hop of link l by l_f^- and l_f^+, respectively. Each link l has a separate queue for each flow f. Let $Q_l^f(t)$ denote the queue length of link l for flow f in time slot t, and let $X_l^f(t)$ denote the number of packets transmitted from $Q_l^f(t)$ to $Q_{l_f^+}^f$ during time slot t. The queue will evolve as

$$Q_l^f(t) = \left[Q_l^f(t-1) + X_{l_f^-}^f(t) - X_l^f(t) \right]^+, \qquad (1)$$

where $[\cdot]^+ = \max\{0, \cdot\}$. If link l is the first hop from the source, we set $X_{l_f^-}^f(t) = A^f(t)$, where $A^f(t)$ denotes the number of exogenous packet arrivals for flow f during time t and has mean rate $E[A^f(t)] = \lambda_f$. Let $\mathcal{F}$ denote the set of all flows, and let $\vec{\lambda}$ denote the arrival rate vector, i.e., $\vec{\lambda} = [\lambda_1, \lambda_2, \ldots, \lambda_{|\mathcal{F}|}]$.

The network is said to be *stable* if an associated Markov chain is ergodic. The stability region Λ of the network is the set of arrival rate vectors that a scheduling scheme can stabilize the network, and can be written [18] as

$$\Lambda = \left\{ \vec{\lambda} \mid \sum_{f \in \mathcal{F}} H_l^f \lambda_f \le \phi_l \text{ for all } l \in E, \text{ for some } \vec{\phi} \in Co(\mathcal{C}) \right\}, \qquad (2)$$

where $Co(\mathcal{C})$ denote the convex hull of the set $\mathcal{C}$. A scheduling scheme is said to be *throughput-optimal* if it stabilizes any arrival rate $\vec{\lambda}$ strictly inside Λ.

In [1], the authors have developed a throughput-optimal scheduler, so-called back-pressure scheme. The back-pressure scheme finds a feasible schedule that maximizes the queue-differential weighted rate sum in each time slot t, i.e.,

$$\underset{s \in \mathcal{S}}{\operatorname{argmax}} \sum_{l \in E} (Q_l^f(t) - Q_{l_f^+}^f(t)) s_l c_l. \tag{3}$$

It has been shown that the network remains stable under the back-pressure scheme for any arrival rate λ within Λ. In this work, we investigate the performance of back-pressure scheme with a different weight. We show that the new scheme is also throughput-optimal and improves delay performance over the original back-pressure scheme in certain network scenarios.

III. Log Back-Pressure Algorithm

Our work is motivated by [10], where the authors show that the maximum weight scheduling with weight of logarithmic queue length achieves the maximum throughput for single-hop traffic and has good delay performance. We extend the ideas to multi-hop traffic, show that the extended scheme can achieve the stability region Λ, and evaluate its delay performance through simulations.

A. Algorithm description

In this section, we describe our scheduling scheme with logarithmic weight, denoted by log-back-pressure.

Log-Back-Pressure:

- At each time slot t, each link l calculates the weight w_l as

$$w_l = \max_{f \in \mathcal{F}} \left(\log(1 + Q_l^f(t)) - \log(1 + Q_{l_f^+}^f(t)) \right), \tag{4}$$

  where $Q_{l_f^+}^f(t)$ denotes the queue length at the next hop. If the receiver of link l is the destination, then we set $Q_{l_f^+}^f(t) = 0$ for all t.
- The scheme finds a feasible schedule that maximizes the weighted rate sum

$$s^* \in \underset{s \in \mathcal{S}}{\operatorname{argmax}} \sum_{l \in E} w_l s_l c_l. \tag{5}$$

- During the time slot, each link l in the selected schedule s^* transmit data packets from the queue of flow f^* that yields the weight w_l, i.e.,

$$f^* \in \underset{f \in \mathcal{F}}{\operatorname{argmax}} \left(\log(1 + Q_l^f(t)) - \log(1 + Q_{l_f^+}^f(t)) \right). \tag{6}$$

The algorithm is similar to the original back-pressure scheme, except that the link weight is a function of logarithmic queue lengths. In the following, we show that our log-back-pressure scheme is throughput-optimal for multi-hop traffic, using a novel Lyapunov function.

B. Throughput optimality

We consider a Markov chain, where each state is described by queue lengths. If we can find a Lyapunov function whose drift is negative for sufficiently large queue lengths, then the Markov chain will be ergodic, and the queue lengths remain finite, which implies that the system is stable under the scheduling scheme. We first find an appropriate Lyapunov function and show that its drift is negative under the log-back-pressure scheme.

We define the Lyapunov function $V(t)$ as

$$V(t) := \sum_{l \in E} \sum_{f \in \mathcal{F}} Q_l^f(t) \log(1 + Q_l^f(t)). \tag{7}$$

Let $c_{max} = \max_{l \in E} c_l$, and suppose that $c_{max} \geq 1$. Also let $\Delta Q_l^f(t) := Q_l^f(t+1)\log(1 + Q_l^f(t+1)) - Q_l^f(t)\log(1 + Q_l^f(t))$. From (1), if $Q_l^f(t) \leq c_{max}$, there exists a constant C_1 such that $|\Delta Q_l^f(t)| \leq C_1$ with high probability. If $Q_l^f(t) > c_{max}$, we have $Q_l^f(t+1) = Q_l^f(t) + X_{l_f^-}^f(t) - X_l^f(t)$, and from $\log(1 + Q_l^f(t) + X_{l_f^-}^f(t) - X_l^f(t)) \leq \log(1 + Q_l^f(t)) + \log\left(1 + (X_{l_f^-}^f(t) - X_l^f(t))/(1 + Q_l^f(t))\right)$, we can obtain the following equations, which are simplified by dropping t.

$$\begin{aligned} \Delta Q_l^f &= (X_{l_f^-}^f - X_l^f)\log(1 + Q_l^f) \\ &\quad + (Q_l^f + X_{l_f^-}^f - X_l^f)\log(1 + (X_{l_f^-}^f - X_l^f)/(1 + Q_l^f)) \\ &\leq (X_{l_f^-}^f - X_l^f)\log(1 + Q_l^f) + C_2, \end{aligned}$$

where the inequality holds since $\log(1+x) \leq |x|$ and $Q_l^f(X_{l_f^-}^f - X_l^f)/(1+Q_l^f) + (X_{l_f^-}^f - X_l^f)^2/(1+Q_l^f) \leq 2c_{max} + 4c_{max}^2/(1 + c_{max}) = 6c_{max} =: C_2$. From the Lyapunov function, we can derive $\Delta V(t) := V(t+1) - V(t)$ as

$$\begin{aligned} \Delta V(t) &= \sum_{l \in E} \sum_{f \in \mathcal{F}} \Delta Q_l^f(t) = \sum_{l: Q_l^f(t) \leq c_{max}} \sum_{f \in \mathcal{F}} \Delta Q_l^f(t) + \sum_{l: Q_l^f(t) \geq c_{max}} \sum_{f \in \mathcal{F}} \Delta Q_l^f(t) \\ &\leq 2C_1 \cdot |E| \cdot |\mathcal{F}| \\ &\quad + \sum_{l \in E} \sum_{f \in \mathcal{F}} (\log(1 + Q_l^f))(X_{l_f^-}^f - X_l^f) + C_2. \end{aligned} \tag{8}$$

Note that since $\vec{\lambda}$ is strictly inside Λ and all routes are fixed, we can find a static stationary scheduling $\{\phi_l^f\}$ such that $\phi_l^f > \lambda^f$ for all links l and all flows f [19]. Then by scheduling the k-th queue of flow f from the source for additional $\frac{k\epsilon}{|\mathcal{F}|\cdot|E|}$ time, where $\epsilon = \min_{l\in E, f\in\mathcal{F}}(\phi_l^f - \lambda^f)$, we can find another static stationary scheduling such that the service rate π_l^f is slightly greater than the service rate at link $\pi_{l_f^-}^f$ for all links l and flows f, i.e., $\pi_l^f - \pi_{l_f^+}^f \geq \frac{\epsilon}{|\mathcal{F}|\cdot|E|}$ [20]. Hence, we can obtain that

$$\sum_{l\in E}\sum_{f\in\mathcal{F}}(\log(1+Q_l^f))(\pi_{l_f^-}^f - \pi_l^f) < 0, \tag{9}$$

when $V(t) > 0$, for this particular static scheduling policy.

Now let $C_3 := 2C_1\cdot|E|\cdot|\mathcal{F}| + C_2$. From (8), we have

$$\begin{aligned}
\Delta V(t) &\leq \sum_{l\in E}\sum_{f\in\mathcal{F}}(\log(1+Q_l^f))(X_{l_f^-}^f - X_l^f) + C_3 \\
&\leq \sum_{l\in E}\sum_{f\in\mathcal{F}}(\log(1+Q_l^f))(\pi_{l_f^-}^f - \pi_l^f) \\
&\quad - \sum_{l\in E}\sum_{f\in\mathcal{F}}(\log(1+Q_l^f))(\pi_{l_f^-}^f - \pi_l^f) \\
&\quad + \sum_{l\in E}\sum_{f\in\mathcal{F}}(\log(1+Q_l^f))(X_{l_f^-}^f - X_l^f) + C_3 \\
&= \sum_{l\in E}\sum_{f\in\mathcal{F}}(\log(1+Q_l^f))(\pi_{l_f^-}^f - \pi_l^f) \\
&\quad + \sum_{l\in E}\sum_{f\in\mathcal{F}}\pi_l^f\left(\log(1+Q_l^f) - \log(1+Q_{l_f^+}^f)\right) \\
&\quad - \sum_{l\in E}\sum_{f\in\mathcal{F}}X_l^f\left(\log(1+Q_l^f) - \log(1+Q_{l_f^+}^f)\right) + C_3,
\end{aligned} \tag{10}$$

where the last equality can be obtained by rearranging the variables. From (4), (5), and (6), the log-back-pressure selects the feasible schedule $\{X_l^f\}$ that maximizes the third term of the last equation, and thus the last two terms must be non-positive. Note that the first term is negative from (9) whenever $\sum_{l\in E}\sum_{f\in\mathcal{F}}Q_l^f > 0$, and thus we can conclude that $\Delta V(t) < 0$ for sufficiently large queue lengths.

Hence, for any arrival rate strictly within Λ, the Lyapunov function has a negative drift, which implies that the associated Markov chain is ergodic. Therefore, the network is stable under the log-back-pressure scheme.

IV. Performance Evaluation

In this section, we evaluate delay performance of the back-pressure schemes through preliminary simulations. We consider a grid network topology with 16 nodes and 24 links as shown in Fig. 1. (Similar networks have been used in [7], [8].) Each node is numbered from 0 to 15, and between two adjacent nodes, two links are established for each direction. Links can transmit either one, two, or three packets per time slot, which is denoted by the number of lines between nodes in the figure. Although the back-pressure schemes can be applied to the SINR-based interference model, we consider a simplified graph-based interference model in our simulations. In particular, we use the *primary interference model*, under which two links that share a node cannot transmit at the same time.

We generate four multi-hop flows as shown in Fig. 1. At each time slot, each flow injects a data packet at its source node with probability p, where the arrival process is independent across time slots and flows. Note that we avoid any symmetry in our simulation settings of the flow routes and the link capacities. We simulate three different scheduling schemes: original back-pressure, log-back-pressure, and MaxWeight. The MaxWeight scheme sets the weight of a link to the largest queue length in the link (in contrast, the back-pressure scheme uses the largest queue differential as the weight), and finds a feasible schedule that maximizes the weighted rate sum. The MaxWeight scheme is known to be throughput-optimal for single-hop traffic, but may not achieve the optimal performance under multi-hop traffic. We run simulations for 10^5 time slots, and measure total queue lengths, and average packet delays.

Fig. 2 shows the total queue lengths. It shows that all schemes have a rapid queue length increase around the boundary of the stability region, i.e., around $p = 0.44$, and thus achieve optimal throughput. Under light traffic loads, all schemes achieve similar performance. However, under heavy traffic loads, the results show that the log-back-pressure scheme outperforms the others. Under the log-back-pressure scheme, as queue lengths increase, the difference between their logarithmic values gets smaller relatively. This implies that the weight differences become smaller. Note that if all links have the same weight, the scheduler will choose the schedule with the largest number of links to maximize the weighted sum. Thus roughly, the log-back-pressure scheme under heavy traffic loads likely chooses a schedule that includes more links, which contributes to improve the delay performance.

Fig. 3 illustrates average packet delays of each scheduling scheme. The overall results are very similar to those of the queue lengths. However, it shows that the performance gaps are enlarged. For example, when the load is 0.5, the queue length of the log-back-pressure scheme is 69% of that of the back-pressure scheme, but the average packet delay is only 55%. This result suggests that the log-back-pressure scheme is effective on reducing the packet delays.

V. Conclusion

In this paper, we develop back-pressure scheduling scheme with logarithmic weight. Introducing a novel Lyapunov function, we show that the proposed scheduling scheme achieves optimal throughput with multi-hop traffic loads. We evaluate our scheme through preliminary simulations in a grid network topology under the primary interference model. The results not only confirm the throughput optimality of our proposed scheme, but also show that it outperforms the original back-pressure scheme in terms of delay. This suggests that the logarithmic weight can substantially improve the delay performance in certain network scenarios.

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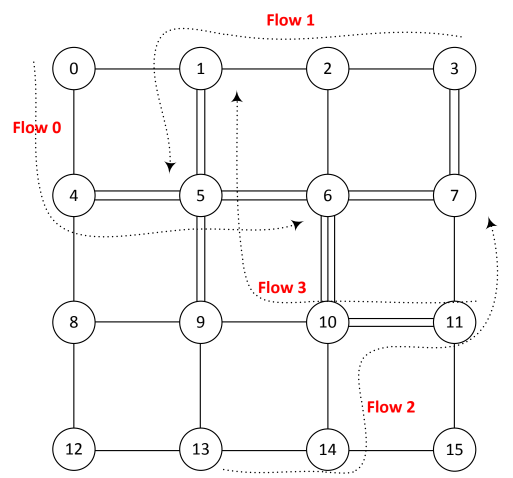

Fig. 1. Grid topology with four multi-hop traffic.

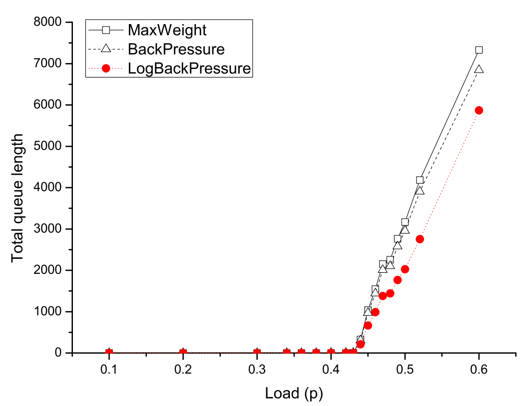

Fig. 2. Queue lengths of scheduling schemes with varying traffic loads.

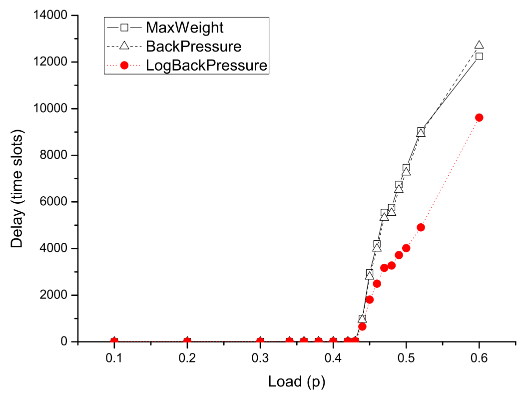

Fig. 3. Average packet delays of scheduling schemes with varying traffic loads.