

Trading Throughput for Freshness: Freshness-Aware Traffic Engineering and In-Network Freshness Control

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In addition to traditional concerns such as throughput and latency, freshness is becoming increasingly important. To stay fresh, applications stream status updates among their components. Existing studies propose the metric age of information (AoI) to gauge the freshness and design systems to achieve low AoI. Despite active research in this area, existing results are not applicable to general wired networks for two reasons. First, they focus on wireless settings where AoI is mostly affected by interference and collision while queueing is more dominant in wired settings. Second, the legacy drop-adverse flows are not taken into account in the literature. Scheduling mixed flows with distinct performance objective is not yet addressed.

In this paper, we study wired networks shared by two classes of flows, aiming for high throughput and low AoI respectively, and achieve a good trade-off between their throughput and AoI. Our approach to the problem consists of two layers: freshness-aware traffic engineering (FATE) and in-network freshness control (IFC). FATE derives sending rate/update frequency for flows via optimization, and its solution is then enforced by IFC through efficient scheduling mechanisms at each outport of in-network nodes. We also present efficient Linux implementation of IFC and demonstrate the effectiveness of FATE/IFC through extensive emulations. Our results show that it is possible to trade a little throughput (5% lower) for much shorter AoI (49 to 71% shorter) compared to state-of-the-art traffic engineering.

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1 INTRODUCTION

As we step into the era of the Internet of Things (IoT), applications increasingly depend on the network to not only carry high throughput but also deliver the information when it is *fresh* so that they can synchronize their geo-distributed components. Freshness is critical for emerging streaming and IoT applications. On cloud gaming platforms such as Google's Stadia [4], games are streamed from the servers to the players and freshness determines players' gaming experience; live-streaming services such as Facebook Live [3] and YouTube TV [6] strive to provide fresh content to their audiences. The rapid development of smart city [20, 57, 58, 68], connected vehicles [18, 28, 30, 64, 65], and IoT technologies also introduces a diversity of safety-critical applications that require consistently available fresh and up-to-date information. Given these applications, freshness as an end-to-end performance metric is outpacing more traditional measures like flow-level throughput and packet-level latency, and freshness-centric flows are expected to occupy a significant share of network traffic in the near future [22].

To evaluate freshness, *Age of Information (AoI)* has been proposed as a metric to gauge how synchronized the information source and its recipient are [43, 44]. Multiple studies design information update systems to minimize AoI through various techniques, including update frequency control

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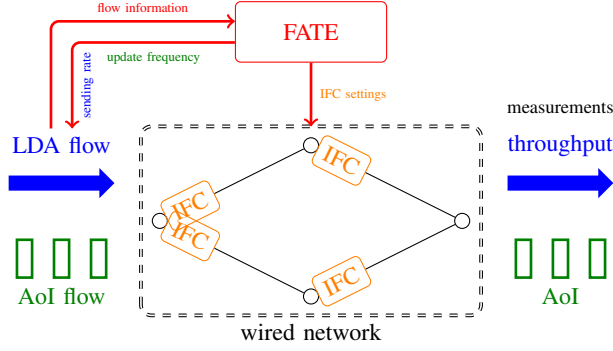


Fig. 1. We study a wired network with mixed legacy drop-adverse (LDA) flows and freshness-centric AoI flows, where LDA flows aim for high throughput while AoI flows aim for low age of information (AoI). We propose a two-layer system to achieve a good trade-off between the throughput and AoI. The freshness-aware traffic engineering (FATE) at the higher layer calculates the sending rate/update frequency for LDA/AoI flows, and the in-network freshness control (IFC) at the lower layer schedules the packets at the outputs of the network nodes to enforce the FATE solution.

[44, 60, 61, 74], active queue management [15–17, 23, 24, 56], and sending slots scheduling at base stations/interfered channels [38–40, 63, 65, 66]. We refer the reader to [51, 74] for surveys.

Despite enormous efforts on AoI minimization, existing proposals are not directly applicable to general wired networks for two reasons. First, most work in the literature focuses on wireless environments. Several papers focus on simple queueing system, single-hop base station, or probabilistic modeled network scheduling [11, 15, 17, 23, 24, 34, 38–41, 44, 45, 52, 56, 61, 63, 73, 74], and some recent attempts start investigating multi-hop scenarios and trajectory planning for graph exploration [16, 49–51, 65, 69, 70]. Wireless environment is inherently different from wired environment in that the major source of delay comes from interference and collision while queueing plays a central role in the wired environment.

Second, existing work does not take the legacy drop-adverse (LDA) flows into account. Existing work considers the networks with only AoI flows – the status update flows that aim for low AoI. While in practice, AoI flows will share the network with already-existing LDA flows that aim for either high throughput or low latency. Some recent papers study the AoI flows with minimum throughput requirements (“dual intent”) [38, 39, 50, 51]. However, that setting is still different from mixed LDA and AoI flows, which present different opportunities and challenges as the flows have distinct, instead of coherent, interests. Especially, dropping LDA packets causes performance degradation, and hence the traditional network design avoids packet drops. In contrast, dropping AoI packets could potentially improve the freshness of the AoI flows [16, 17, 45, 74]. As a result, it is possible to maximize the throughput for LDA flows while minimizing AoI for AoI flows by handling LDA and AoI packets differently. How to efficiently serve these two intents by packet management is not yet addressed in the literature.

Contributions and Organization: In this work, we study wired networks with mixed LDA and AoI flows as shown in Fig. 1, where the two classes of flows aim for distinct performance goals – high throughput and low AoI, respectively. We aim to achieve different trade-offs between LDA flows’ throughput and AoI flows’ AoI through our two-layer network design. The higher layer, the freshness-aware traffic engineering (FATE), optimizes sending rate/update frequency of the LDA/AoI flows. FATE centers on the LDA-AoI Coscheduling problem (LAC), which trades off LDA flows’ throughput for AoI flows’ AoI. LAC leverages inverted update frequency as a proxy for AoI,

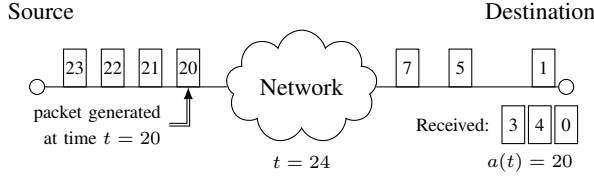


Fig. 2. The status update age $a(t)$ at time t is the elapsed time since the freshest update received at the destination at time t was generated at the source. In this example, the current time $t = 24$ and the generated time of each packet is marked accordingly. Upon the arrival of the packet generated at time $t = 1$, the freshest update received at the destination was generated at $t = 4$, and hence the status update age is $a(t) = a(24) = 24 - 4 = 20$ at time $t = 24$. Notice that receiving the outdated (or “out-of-ordered”) update (generated at $t = 1$) does not help reduce $a(24)$.

and we justify this choice by showing that a zero-queueing schedule is NP-hard to obtain and providing an upper bound on the AoI.

Given a FATE solution, the lower layer, the in-network freshness control (IFC), maintains the update frequency across the network through efficient per-port queueing management – AoI-Aware Queueing (AAQ). We propose two different in-network scheduling policies for AAQ: size-driven multiplexing (SDM) and time-division multiplexing (TDM). We provide simple and effective implementations, and we demonstrate their low overhead and good performance through experiments.

We organize the paper as follows. We first briefly review the metric of AoI and discuss the techniques to balance throughput with freshness in Section 2. Then, in Section 3, we introduce FATE, formulate LAC, and analyze the factors that affect AoI to justify LAC. Given an LAC solution, we establish the IFC scheme through two policies SDM and TDM in Section 4 and provide the efficient Linux implementation of IFC in Section 5. In Section 6, we conduct experiments to examine the overhead of IFC, the effectiveness of FATE and IFC, and the combination of IFC with other queueing management methods. With related work reviewed in Section 7, we conclude the paper in Section 8.

2 BACKGROUND AND MOTIVATION

We start by introducing the age of information (AoI) metric for measuring freshness. Then, we explore the techniques that could balance throughput with freshness in a mixed LDA/AoI environment and discuss the corresponding challenges.

2.1 Freshness and Age of Information (AoI)

A new metric that has recently emerged to quantify freshness is the *Age of Information (AoI)* [43], which quantifies the degree of synchronization between the information source and its destinations. To synchronize the destinations, the information source streams status update packets through the network. The *status update age* $a(t)$ is then defined as the elapsed time since the freshest update received at the destinations at time t , as illustrated in Fig. 2. $a(t)$ reduces upon the receipt of a new update, which results in the saw-like waveform in Fig. 3.

Instead of directly referring to the fluctuating $a(t)$, we would quantify the degree of synchronization by the long-term time-averaged performance. Accordingly, we define AoI as the long-term time-averaged status update age, which is given by

$$\text{AoI} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T a(t) dt. \quad (1)$$

This is illustrated in Fig. 3. The existence of the above limit is typically assumed implicitly.

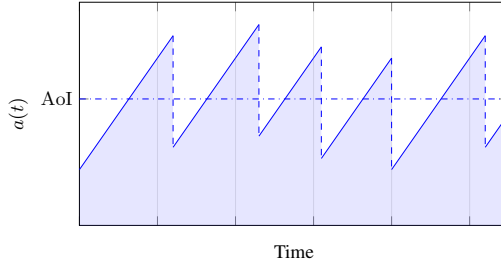


Fig. 3. Age of information (AoI) is defined as the long-term time-averaged status update age, which averages $a(t)$ (the shaded area) over time.

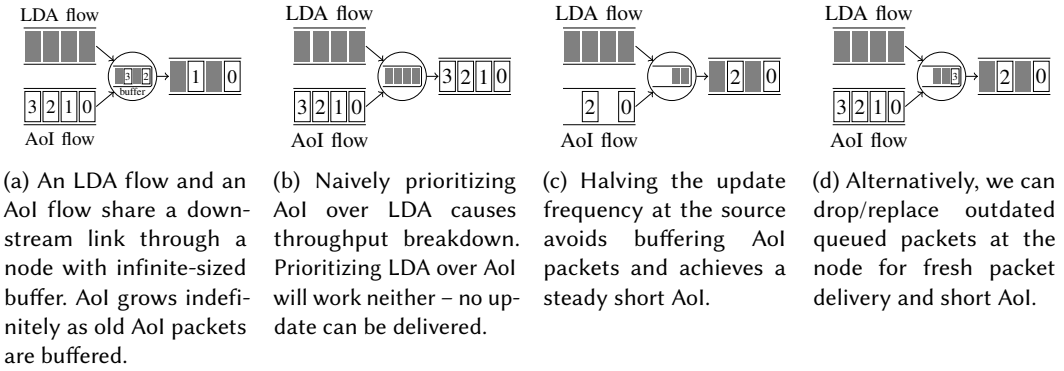


Fig. 4. Balancing the throughput of LDA flow with the AoI of the AoI flow requires techniques more sophisticated than simple prioritization. We could perform update frequency control or active packet drop to improve the AoI.

We remark that AoI/freshness is different from latency. Latency measures how fast a packet can be delivered from the source to the destination, while freshness evaluates how synchronized the source and the destination are. The former is a per-packet property, while the latter depicts an end-to-end characteristic. Although shorter latency can potentially help achieve fresher information delivery, freshness does not require a fast or even intact transmission for all packets. For example, dropping a packet hurts the latency of transmitting the packet, but it might clear the path for fresher information to arrive at the destination and thus improve the AoI.

2.2 Balancing Throughput with Freshness

We refer to the status update flows that aim for freshness the *AoI flows*. In addition to the new AoI flows, legacy network flows pursue high throughput/low latency. Since dropping packets hurts both throughput and latency, we call those legacy flows the *legacy drop-adverse (LDA) flows*. Traditional networks are designed to serve LDA flows, and hence most network techniques center around packet-drop avoidance.

Classical network design may not be beneficial for the freshness-centric AoI flows. Consider the example shown in Fig. 4(a). Three links of unit capacity connect to a node with infinite-sized buffer in the middle. An LDA flow and an AoI flow traverse through links, join at the node, and share the same downstream link. Traditional network design might share the link equally, which causes the AoI packets buffered at the node and the end-to-end AoI will grow indefinitely.

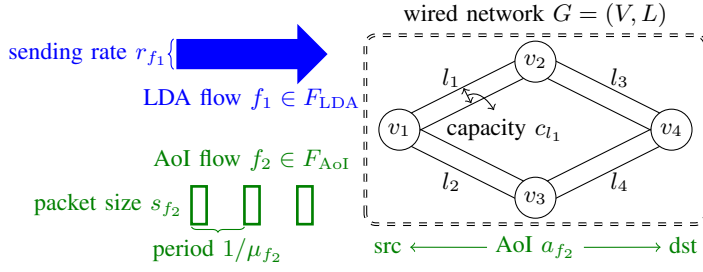


Fig. 5. We model the network by a directed graph $G = (V, L)$ shared by a set of LDA flows F_{LDA} and a set of AoI flows F_{AoI} . Freshness-aware traffic engineering (FATE) optimizes over the sending rate r_f for $f \in F_{LDA}$ and the update frequency μ_f for $f \in F_{AoI}$.

To avoid buffering AoI packets, one might want to prioritize the AoI flow over the LDA flow (Fig. 4(b)). However, that completely blocks the LDA flow and results in throughput breakdown. Therefore, to well balance throughput with AoI, we need more sophisticated approaches than naive prioritizing.

There are two techniques that can achieve a more balanced trade-off: update frequency control and active packet drop. As shown in Fig. 4(c), we can halve the update frequency of the AoI flow. As such, no AoI packet will be buffered and we achieve a smaller end-to-end AoI. Alternatively, we can also buffer and drop/replace outdated AoI packets at the intermediate node as in Fig. 4(d). Accordingly, we always send out fresh packets rather than letting packets age in the queue.

To perform these techniques, we need to address a few challenges. First, how can we come up with the right update frequency for the AoI flows? Also, in a practical network setting, buffers are of finite sizes and we might also need to determine the sending rate of the LDA flows to avoid packet drops. In addition, how should we drop the packets? Especially, we need to discard outdated packets efficiently without incurring too much processing overhead. Otherwise, burdened network nodes would suffer slow forwarding and hurt freshness. In this paper, we deal with these issues through FATE, IFC, and efficient Linux implementation that are elaborated in the following sections.

3 FRESHNESS-AWARE TRAFFIC ENGINEERING (FATE)

In this section, we establish our freshness-aware traffic engineering (FATE). FATE models LDA flows as fluids of fixed sending rate and AoI flows as sequences of status updates with fixed update frequency. Given predetermined routes, FATE performs sending rate/update frequency control over LDA/AoI flows to optimize some objective. In particular, we propose the LDA-AoI Coscheduling (LAC) problem, which balances throughput and an approximated AoI. The approximation is then justified through our analysis of the composition of AoI, which shows that a zero-queueing schedule is NP-hard to verify/obtain and that AoI can be upper-bounded.

3.1 Model

We model the network by a directed graph $G = (V, L)$ where V is the set of nodes and L the set of links. Each link $l \in L$ has a non-negative capacity c_l . Two sets of flows F_{LDA} and F_{AoI} share the network, where F_{LDA} consists of LDA flows and F_{AoI} is the set of AoI flows. Each flow $f \in F_{LDA} \cup F_{AoI}$ sends through a predetermined simple path from some source node to some destination node. We write $l \in f$ if and only if link l is on the path of flow f . We denote by r_f the throughput (sending rate) of an LDA flow $f \in F_{LDA}$ and by a_f the AoI of an AoI flow $f \in F_{AoI}$. To compute AoI, we model each AoI flow $f \in F_{AoI}$ as a periodic status update sequence with update frequency (number of updates per unit time) μ_f . Each status update is a sequence of packets with total size s_f . Without

loss of generality, we model each status update as one AoI packet of size s_f in the following context. Fig. 5 provides an illustration of the notation defined here.

3.2 LDA-AoI Coscheduling (LAC) Problem

FATE computes the sending rate/update frequency for LDA/AoI flows by solving the LDA-AoI Coscheduling (LAC) problem. LAC aims to maximize the throughput of LDA flows while minimizing the AoI by finding the best update frequency for the AoI flows. To do so, LAC optimizes the following objective

$$\max \sum_{f \in F_{\text{LDA}}} r_f - \lambda \sum_{f \in F_{\text{AoI}}} \frac{1}{2\mu_f} \quad (\text{LAC})$$

where $\lambda \geq 0$ is the trade-off factor.

As shown in Fig. 4(a), congestion would hurt AoI as the old AoI packets are buffered. Therefore, LAC strives for congestion-free sending/status update via capacity constraints as follows. Let $S_{\text{LDA}}(l)$ and $S_{\text{AoI}}(l)$ be the total LDA/AoI traffic on the link l , i.e.,

$$S_{\text{LDA}}(l) = \sum_{f \in F_{\text{LDA}}: l \in f} r_f, \quad S_{\text{AoI}}(l) = \sum_{f \in F_{\text{AoI}}: l \in f} \mu_f s_f.$$

Assuming no packet drop, the capacity constraint requires, for each $l \in L$,

$$S_{\text{LDA}}(l) + S_{\text{AoI}}(l) \leq c_l. \quad (2)$$

Together, we can formulate the LDA-AoI coscheduling (LAC) problem as

$$\begin{aligned} \max \quad & \sum_{f \in F_{\text{LDA}}} r_f - \lambda \sum_{f \in F_{\text{AoI}}} \frac{1}{2\mu_f} \\ \text{s.t.} \quad & S_{\text{LDA}}(l) + S_{\text{AoI}}(l) \leq c_l \quad \forall l \in L \\ & r_f \geq 0 \quad \forall f \in F_{\text{LDA}} \\ & \mu_f \geq 0 \quad \forall f \in F_{\text{AoI}} \end{aligned}$$

We remark that LAC can be efficiently solved in the following equivalent convex form by second order cone methods:

$$\begin{aligned} \max \quad & \sum_{f \in F_{\text{LDA}}} r_f - \frac{\lambda}{2} \sum_{f \in F_{\text{AoI}}} h_f \quad (\text{Equivalent Convex LAC}) \\ \text{s.t.} \quad & S_{\text{LDA}}(l) + S_{\text{AoI}}(l) \leq c_l \quad \forall l \in L \\ & r_f \geq 0 \quad \forall f \in F_{\text{LDA}} \\ & \mu_f \geq 0 \quad \forall f \in F_{\text{AoI}} \\ & h_f \mu_f \geq 1 \quad \forall f \in F_{\text{AoI}} \end{aligned}$$

Notice that LAC minimizes AoI via minimizing $\frac{1}{2\mu_f}$, which is an approximation to the true AoI a_f . We motivate and justify such an approximation in the following subsection.

3.3 AoI Factors and Upper Bound

Instead of minimizing AoI a_f directly, LAC minimizes the inverse of μ_f as a proxy. This choice is driven by the following two results. First, it is NP-hard to precisely determine AoI due to the queueing delay. Second, we can upper-bound AoI, and the varying term in the bound is proportional to the inverse of μ_f . We derive these results by providing a more detailed analysis of AoI herein, and the proofs for the theorems in this subsection are deferred to Appendices.

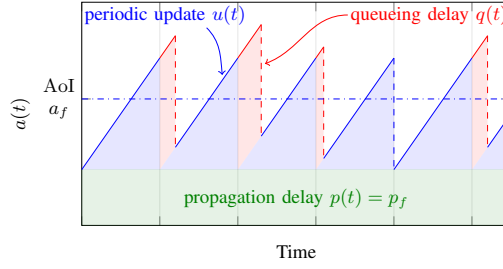


Fig. 6. Break down the cause of AoI: periodic update, propagation delay, and queueing delay.

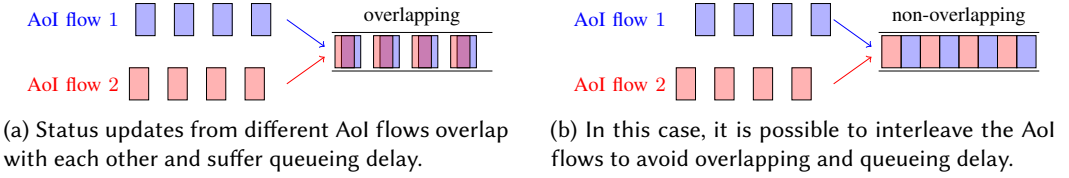


Fig. 7. Carefully interleaving the AoI flows can potentially mitigate queueing delay in some cases.

As shown in Fig. 6, the status update age $a(t)$ of a flow f can be attributed to three factors: periodic update $u(t)$, propagation delay $p(t)$, and queueing delay $q(t)$, which satisfy

$$a(t) = u(t) + p(t) + q(t).$$

The longer the update period, or the lower the update frequency μ_f , of an AoI flow leads to long AoI. The propagation delay $p(t)$ accounts for the time one status update traverses through an empty network, which is a constant p_f determined by the total link latency d_f and the packet transmission delay, i.e.,

$$p_f = d_f + \sum_{l:l \in f} \frac{s_f}{c_l}.$$

The queueing delay $q(t)$ accounts for the time when an update is not forwarded right upon its arrival at an intermediate node and becomes stale while waiting in the queue. According to (1), the AoI a_f of the flow f is

$$a_f = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T a(t) dt = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T u(t) + p(t) + q(t) dt = \frac{1}{2\mu_f} + p_f + q_f$$

where q_f is the long-term time-averaged $q(t)$. We slightly abuse the terminology to also refer to q_f as the queueing delay.

The most uncertain term in the LAC problem is the queueing delay q_f . There are three scenarios under which an update suffers queueing delay – waiting for LDA flows, previous updates, or updates from other AoI flows. To tackle these scenarios, we can prioritize AoI updates to avoid AoI flows being blocked by LDA flows. Also, if an update needs to wait for previous updates from the same flow, it suggests that the update frequency of the flow is higher than the forwarding link capacity. We should reduce the update frequency and discard old queued updates when a new update arrives.

The trickiest scenario is when AoI packets from different flows wait for one another. Though in some cases, such as in Fig. 7(a) and (b), we can carefully interleave the AoI flows to reduce the queueing delay, it is not always the case. Even if we ensure link capacity is enough to accommodate

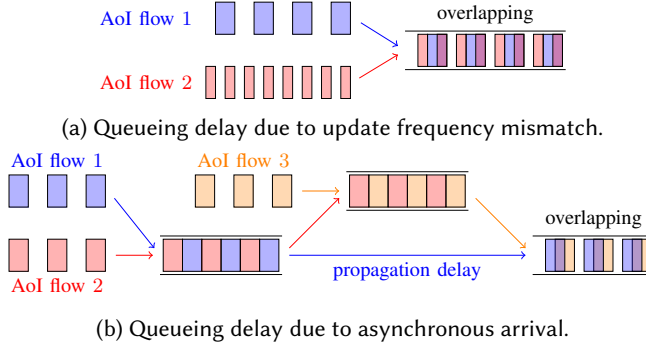


Fig. 8. It is not always possible to completely avoid queueing delay by interleaving the flows even though the links have enough capacities.

the updates in the long run through condition (2), the arrival timing could still cause transient congestion. For example, in Fig. 8(a), both AoI flows occupy half of the link capacity. Since flow 2 updates twice more frequent than flow 1, it is not possible to interleave them without congestion. Another example in Fig. 8(b) shows three AoI flows sharing different links. We can interleave flow 1 and 3 carefully to ensure they do not overlap with flow 2. However, when they meet at the rightmost link, they inevitably collide and cause queueing delay.

In fact, even when a zero-queueing-delay interleaving schedule is possible, obtaining such a schedule is NP-hard by the following theorem.

Theorem 1. *Given a set of AoI flows F_{AoI} with update frequencies μ_f , status size s_f , and link capacities c_l for all $f \in F_{\text{AoI}}$ and $l \in L$, it is NP-hard to determine if there exists a zero-queueing-delay interleaving schedule.*

While it is NP-hard to determine a zero-queueing-delay schedule, it is possible to upper-bound AoI (and hence upper-bound the queueing delay) for LAC solutions by the following theorem.

Theorem 2. *Given a feasible solution to LAC, there exists a scheduling policy such that*

$$a_f \leq \frac{1 + 2|f|}{2\mu_f} + d_f$$

for all $f \in F_{\text{AoI}}$, $\mu_f > 0$, where $|f| = |\{l : l \in f\}|$ is the number of links on the path taken by f .

Since $1 + 2|f|$ and d_f are both constants, we know that the varying part of this AoI upper bound is proportional to $\frac{1}{2\mu_f}$, which is hence chosen as the proxy for AoI minimization in LAC.

4 IN-NETWORK FRESHNESS CONTROL (IFC)

Once we solve LAC, we can assign the sending rate and update frequency accordingly and the network should be congestion-free in the long run thanks to the condition (2). However, long-term freedom from congestion does not imply that the AoI will achieve its lowest value. For instance, the sending rate and update frequency might not be precisely applied at the source. Or, after going through multiple hops, queueing and stochastic processing delay could cause the update frequency of an AoI packet series to drift from the assigned value. Therefore, our mission then becomes enforcing the FATE solution into the network through in-network freshness control (IFC). We propose a new per-port queueing discipline – AoI-aware queueing (AAQ) – to do so. Below we present the design of AAQ and its core component, the scheduler.

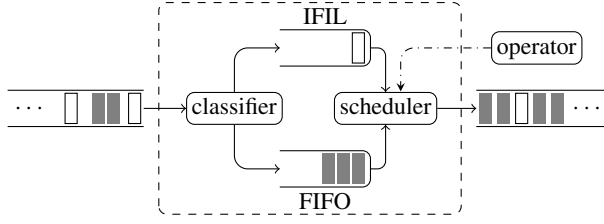


Fig. 9. To enforce an LAC solution, we introduce AoI-aware queueing (AAQ) at each out port to sort the packets before transmitting them on a link.

4.1 AoI-Aware Queueing (AAQ)

To start with, we make the following four simple observations:

- <1> Work conservation: When $S_{LDA}(l) + S_{AoI}(l) < c_l$, we should increase r_f and μ_f whenever possible.
- <2> Scheduler: We need a scheduler to allocate link capacities c_l to LDA and AoI flows according to $S_{LDA}(l)$ and $S_{AoI}(l)$ in (2).
- <3> Self queueing delay avoidance: We should replace the old AoI packet by the new one from the same AoI flow.
- <4> Cross queueing delay mitigation: AoI flows should be served in a FIFO manner.

Based on these observations, we propose a per-port queueing policy, the *AoI-Aware Queueing* (AAQ), to enforce an LAC solution. The basic idea of AAQ is to manage the output queue for each link in accordance with (2). The architecture of AAQ is shown in Fig. 9.

For the traffic arrives at an output, which is a mixture of LDA and AoI packets, AAQ sorts them into two sub-queues for LDA and AoI respectively by a classifier. Two sub-queues are governed by different queueing policies. AAQ chooses some queueing policy to maximize the throughput for the LDA sub-queue. For the AoI sub-queue, we propose the *inter-flow FIFO*, *intra-flow LIFO-W* (IFIL) based on our observations.

IFIL, as its name suggests, enqueue different flows in FIFO manner, while the packets from the same flow follows LIFO-W policy: Last-arriving packet preempts existing waiting packet in the queue (if any). Operationally, every incoming AoI packet is enqueued at the back of the queue (observation <4>). However, if there exists an AoI packet from the same flow in the queue already, the newly arrived packet preempts (replaces) the existing one (observation <3>). In brief, IFIL schedules different AoI flows in a FIFO manner, which avoids flow starvation, while keeping only the last arrived packet of each flow in the queue. This design also ensures that the number of status update packets buffered at each IFIL queue is at most $|F_{AoI}|$, since only the latest arriving packet is kept per AoI flow.

After the two sub-queues, AAQ installs a scheduler to reassemble the packets to the outgoing link (observation <2>), which we will further elaborate on in the next subsection.

4.2 Scheduler and Scheduling Policies

A core component of AAQ is the scheduler that interleaves the LDA and AoI packets according to (2) (observation <2>) while conserving work (observation <1>). To do so, whenever the link is ready to send, the scheduler first check the occupancy of LDA and AoI subqueues. If only one of them carries packets, the scheduler dequeues packets to send from the non-empty queue. When both the subqueues are occupied, the scheduler decides which subqueue to dequeue from according to a scheduling policy that enforces $S_{LDA}(l)$ and $S_{AoI}(l)$. Below we discuss the design of such a policy.

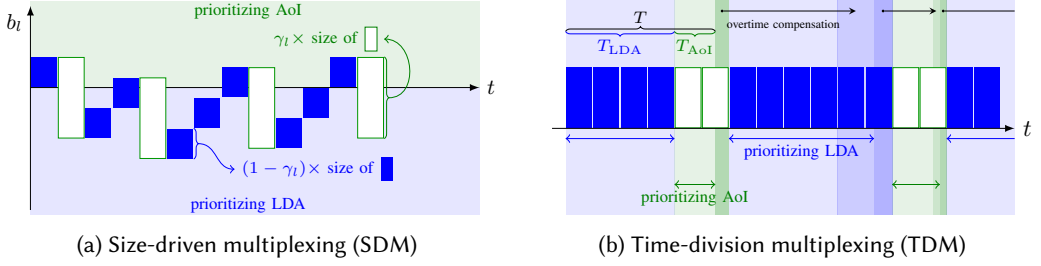


Fig. 10. An example showing the schedule fulfilled by SDM and TDM. The LDA packets are filled while the AoI packets are hollow. SDM maintains the variable b_l to prioritize LDA/AoI subqueue accordingly, while TDM partitions the predetermined time frame T to decide the prioritization periods. If a packet is still under transmission while the prioritization period ends, the overtime is compensated to the other subqueue.

To begin with, we define *AoI ratio γ_l of link l* to be the share of total traffic on link l that is from AoI flows, i.e.,

$$\gamma_l = \frac{S_{AoI}(l)}{S_{LDA}(l) + S_{AoI}(l)}$$

when $S_{LDA}(l) + S_{AoI}(l) > 0$; Otherwise, we set $\gamma_l = 1$. By definition, we have $\gamma_l \in [0, 1]$ and

when $\gamma_l = 1$, the link carries only AoI flows, while $\gamma_l = 0$ implies an LDA only link. In other words, γ_l reflects the LDA/AoI traffic distribution on link l .

To enforce the allocation $S_{LDA}(l)$ and $S_{AoI}(l)$ at each link l , we can keep track of the total LDA and AoI traffic on the link and ensure that the ratio between them is equal to $1 - \gamma_l$ to γ_l in the long run. Alternatively, given a fixed link capacity c_l , we can also ensure that the time spent on sending LDA/AoI traffic is proportional to $1 - \gamma_l$ and γ_l correspondingly. These two options lead to the following *size-driven multiplexing (SDM)* and *time-division multiplexing (TDM)* policies.

Size-Driven Multiplexing (SDM): We maintain a budget variable b_l , initialized as 0, for each link l . Whenever a LDA packet of size s is sent over link l , we increment b_l by $\gamma_l s$. Instead, when an AoI status update of size s is sent, we decrement b_l by $(1 - \gamma_l)s$. The scheduling policy is then when $b_l > 0$, we prioritize AoI subqueue. Otherwise, we prioritize LDA subqueue. In the long run, SDM ensures the total LDA/AoI traffic sent through link l achieves the desired AoI ratio γ_l .

Time-Division Multiplexing (TDM): Given some fixed time frame T , we partition it into two sub-time frames T_{LDA} and T_{AoI} where

$$T_{LDA} = (1 - \gamma_l)T = \frac{S_{LDA}}{S_{AoI} + S_{LDA}}T, \quad T_{AoI} = \gamma_l T = \frac{S_{AoI}}{S_{AoI} + S_{LDA}}T.$$

We take turns to prioritize LDA/AoI subqueues according to T_{LDA} and T_{AoI} : We prioritize LDA subqueue for T_{LDA} then prioritize AoI subqueue for T_{AoI} . By the end of each turn, if a packet/status update is still under transmission, we compensate the overtime proportionally to the other subqueue. As such, the ratio of the sending time for LDA/AoI traffic through link l approaches $\frac{1 - \gamma_l}{\gamma_l}$ in the long run. Correspondingly, the AoI ratio approaches to γ_l .

We use the example in Fig. 10 to compare SDM with TDM. As shown in the figure, SDM can usually spread AoI packets more evenly than TDM, which could be beneficial as it avoids AoI packet clusters, but it could also lead to a prolonged AoI if the spread update frequency is slightly longer than the incoming update frequency. In that case, TDM, by setting the prioritization periods to directly match the update frequency, could be more useful. However, a key drawback of TDM is that it needs to constantly access system time, which can incur significant overhead. For that, SDM is computationally more favorable than TDM. The advantage of TDM is that it does not need the

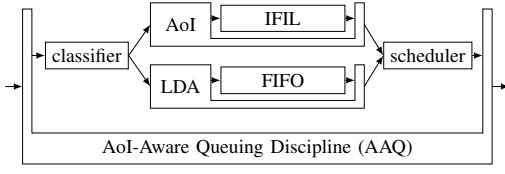


Fig. 11. Architecture of AoI-aware queueing discipline (AAQ).

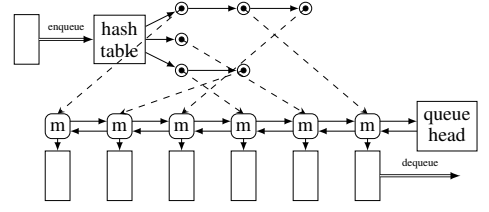


Fig. 12. Architecture of hashed IFIL. The rectangles are the packets and the boxes marked by m are the meta-data of the packets.

packet size information. All operations of TDM can be done by only monitoring the link status, which allows one to fully decouple the subqueues from the scheduler.

With SDM or TDM installed at each output, the system operator can solve LAC to derive the corresponding AoI ratios γ_l for all link l , and assign the γ_l value to the queueing policy governing the link l .

5 IMPLEMENTATION

We demonstrate the feasibility of our proposed IFC scheme by implementing AAQ and IFIL as Linux kernel modules. We remark that this is not the only way to potentially implement IFC. For instance, one could instead use servers as classifiers and schedulers. We have also successfully implemented IFC in DPDK [2] to demonstrate the potential of a smartNIC deployment. However, DPDK is vendor-specific and its deployment in a virtualized environment (such as cloud-based content-delivery networks) is highly involved. Therefore, we also implement IFC as Linux kernel modules so that it is easy for embedded and commodity Linux systems, such as connected vehicles, networked robotic systems, and public clouds, to import our design without further modification.

AAQ: As shown in Fig. 11, we pack the classifier and the scheduler into the AAQ module. The classifier is a function that categorizes packets based on their header. In our implementation, the classifier distinguishes packets using their layer 4 protocol number as we deem UDP traffic the AoI traffic in the experiments. One can adopt other classifiers according to their definition of AoI traffic. For instance, one can also design a special layer 3 protocol for AoI traffic, and the corresponding classifier filters traffic according to the layer 3 protocol number.

AAQ has two subqueues (or “classes” as in Linux traffic control terminology) for LDA and AoI flows. By default, we employ FIFO for the LDA subqueue and IFIL for the AoI subqueue. We can change the queueing disciplines of the subqueues to handle the flows differently. The scheduler can prioritize these two subqueues according to its scheduling policy, e.g., SDM or TDM. Each time the scheduling policy is invoked, it examines the subqueues and returns one-bit Boolean value to indicate which subqueue the scheduler should dequeue from.

IFIL: To enforce IFIL, outdated packets within the queue need a way of quickly being replaced with fresher arrivals. We could do so by linearly searching through the queue, but this introduces significant overhead. Instead, we store the packets in the queue as a doubly-linked list of their meta-data and maintain a hash table to locate the packet from each flow. The architecture is shown in Fig. 12. Since we keep only one packet per flow in the IFIL queue, we can pre-allocate the memory for the hash items to reduce overhead due to memory allocation. We remark that the total number

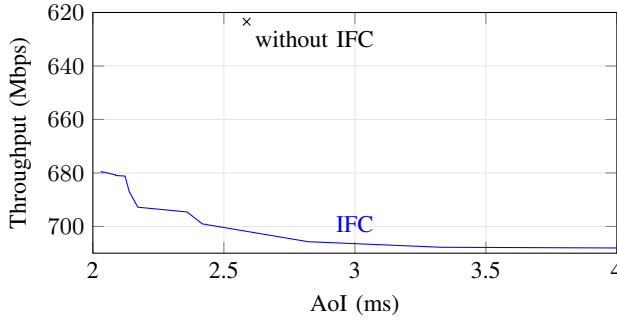


Fig. 13. The throughput/AoI trade-off of a one-link (physical, 1 Gbps) example. The results show that our Linux kernel implementation can sustain at least a 1-Gbps link, providing the IFC benefits without incurring significant overhead.

of hash items and meta-data is bounded by the length of the queue. Under moderate queue size, e.g., 10^4 to 10^5 packets, the whole data structure (hash items and meta-data) could easily fit in the cache.

Effectiveness: To demonstrate that our Linux kernel implementation is effective with acceptable overhead, we physically connect two carefully time-synchronized computers by a 1-Gbps link, pump mixed LDA/AoI traffic through it, and measure the throughput/AoI trade-offs in Fig. 13. The results show that our Linux kernel implementation can serve at least a 1-Gbps link without incurring significant overhead. We remark that time-synchronization is only needed because we want to measure the AoI accurately. In practice, we don't need the computers to be time-synchronized to perform IFC. To gather accurate AoI measurements over multiple computers, we emulate the network and use 100 Mbps virtual links in Section 6 to avoid challenging multi-computer time-synchronization. But given Fig. 13, we expect the results extend to physical links of 1 Gbps or higher bandwidth.

6 EVALUATION

We evaluate FATE and IFC through extensive emulations, reported on in this section. We start with the setup in Section 6.1 and then address the following questions:

- Section 6.2: What is the overhead of performing IFC? How much does our design reduce the overhead?
- Section 6.3: How does FATE perform in comparison to other existing traffic engineering objectives? How does the trade-off factor λ in LAC affect the performance?
- Section 6.4: How does IFC perform in comparison to other existing active queue management (AQM)/TCP variants?
- Section 6.5: Can IFC be combined with existing methods? How much improvement does this provide?

6.1 Setup

We emulate FATE/IFC in Mininet [5]. Mininet allows us to measure AoI using the same system clock. We also consider more practical evaluations over real wide-area networks, but synchronization issues make it hard to gather AoI measurements accurately. We remark that the AoI measurements

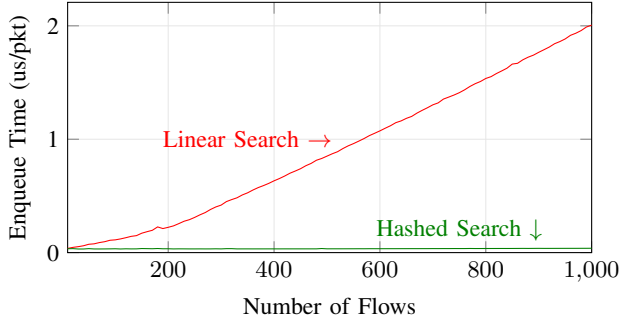


Fig. 14. The overhead of IFIL is small with hashed design, about 34.61 ns per packet. In exchange, we get huge AoI improvement.

are essential for performance quantification and discussion, but in practice, freshness difference can be experienced directly and so there is no need to measure it.

Network topologies: We emulate network topologies from Microsoft’s SWAN [31], Internet2 and Google’s B4 [32, 36].

Existing AQM/TCP Methods: In addition to IFC with SDM/TDM, we compare against the existing AQM/TCP variants including FIFO (First-In First-Out), LIFO (Last-In First-Out), RED [35], FQ-CoDel [62], BBR [19], and DCTCP [8]. We directly use Linux `tc pfifo`, `red`, `fq_codel`, `tcp bbr`, and `dctcp` as their implementations using default Linux parameter settings. For pure AQM methods, we pair them with default Linux TCP (CUBIC).

Traffic Characteristics: In the following experiments, we generate 100 random traffic patterns with mixed LDA and AoI flows. The LDA and AoI flows are generated by picking each source-destination pair with probability 0.1 (It is possible for an LDA and an AoI flow to share the same source and destination). We then average the measurements over all generated patterns and plot the average as the final result.

Evaluation Metrics: For each generated traffic pattern, we measure the total throughput of the LDA flows and the total AoI of the AoI flows.

6.2 Overhead of IFIL and Schedulers

Since IFC is designed to achieve low AoI, we have to ensure that the overhead is low when adopting it in the system. In particular, we are interested in the overhead of two components: the IFIL queue and the scheduler.

We first examine the overhead of the IFIL queue. When a packet arrives at a IFIL queue, it replaces the packet of the same flow, if there exists one, which requires searching through the queue. The naive method would be to search linearly through the queue, which can be inefficient when the queue stores a large number of flows. Instead, we propose hashed implementation in our design. In Fig. 14, we quantify the overhead by pumping packets from a number of flows into the queue and measuring the enqueue time. Fig. 14 shows that the proposed hashed implementation significantly outperforms linear search. The overhead of the hashed implementation is around 34.61 ns, while the linear search overhead grows linearly. Notice that IFIL keeps only one packet per flow, meaning that we only need to keep a small number (number of flows) of hashed items and packet meta-data to perform hashing, which could fit it the cache.

Another overhead we need to consider is the scheduler overhead. For comparison, we prepare two fully loaded FIFO queues as the AoI and LDA queues and adopt the scheduler to dequeue packets from the two queues. The scheduler dequeues according to the scheduling policy, and we

measure the dequeue overhead in terms of the time. If we keep dequeuing packets from non-empty queues without scheduling, the overhead is 3.79 ns (per packet). On the other hand, the dequeue overhead for SDM and TDM are 7.07 and 21.98 ns, respectively, regardless of the AoI ratio. This validates the fact that both SDM and TDM have very low overhead, though TDM requires more time since it inquiries system time per packet arrival.

6.3 Comparison Against Other Traffic Engineering Objectives

In addition to FATE that balances sending rate/update frequency through LAC and the trade-off factor λ , other traffic engineering objectives exist in favor of different trade-offs. In this subsection, we compare FATE with existing traffic engineering objectives and their corresponding rate allocations below. We enforce FATE solution through IFC with SDM or TDM, and the existing schemes run with traditional FIFO queues.

Traditional traffic engineering solves multi-commodity flow (MCF) problem to maximize the overall throughput:

$$\max \sum_{f \in F_{LDA}} r_f + \sum_{f \in F_{AoI}} \mu_f s_f \quad (\text{Max Throughput})$$

subject to the constraint set of LAC. Without taking AoI into account, Max Throughput achieves good throughput for all flows while not ensuring short AoI for AoI flows. Instead of maximizing the overall throughput, assuming all LDA packets are of the same s_{LDA} , we can also solve MCF to minimize AoI (proxy) by considering the objective

$$\min \sum_{f \in F_{LDA}} \frac{s_{LDA}}{2r_f} + \sum_{f \in F_{AoI}} \frac{1}{2\mu_f}. \quad (\text{Min AoI})$$

Unlike Max Throughput, Min AoI would prefer short AoI for all flows. Some recent papers [50, 51] tries to minimize AoI for AoI flows while maximizing their throughput, which lead to the two-objective optimization: ¹

$$\min \sum_{f \in F_{AoI}} \frac{1}{2\mu_f} \text{ and } \max \sum_{f \in F_{AoI}} \mu_f s_f. \quad (\text{Lou 2020})$$

The algorithm in [50, 51] approaches these two objectives iteratively. It first initializes the target total throughput v as 0. Then, it finds the routing by minimizing AoI with total throughput greater than v . Under the resulting routing, it calculates the max achievable throughput and updates v accordingly. The procedure is repeated until a Pareto optimum is reached. In our setting, the routing is fixed and hence the optimum will be obtained after one iteration.

In Fig. 15, we examine the how the trade-off factor λ influences total throughput and total AoI on the left two plots and what trade-offs different methods achieve on the right under the topologies B4 and SWAN. As expected, we can see that total throughput and total AoI both decrease when the trade-off factor λ increases. Comparing against other methods (under $\lambda = 0.125$), Max Throughput achieves up to 5% more throughput while the AoI is 49 to 71% longer than LAC. Min AoI achieves the best AoI, which is 10 to 13% shorter than LAC, while the maintaining a relatively good throughput. It is because a low AoI would also lead to high throughput for the LDA flows. Even through, LAC can choose to trade slightly more AoI for even higher throughput – 7 to 12% higher than Min AoI –

¹[50, 51] optimize not only the update frequencies but also the routes for the AoI flows. Accordingly, AoI is given by

$$\frac{1}{2\mu_f} + \sum_{l: l \in f} \frac{s_f}{c_l}.$$

Here we predetermine the routes and hence the second term is a constant and omitted from the objective.

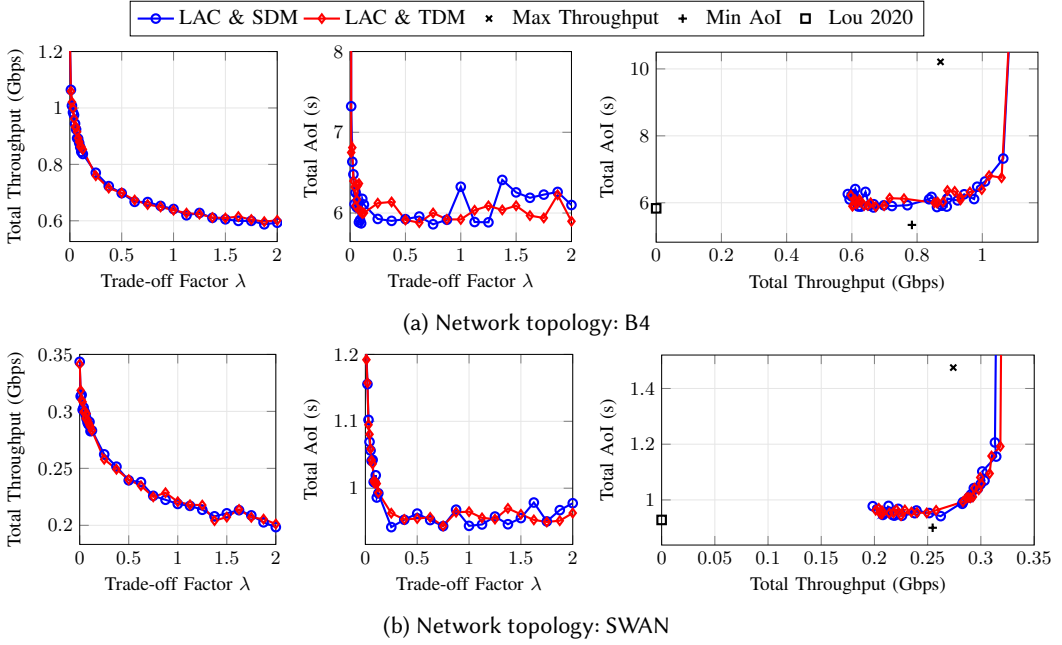


Fig. 15. We compare the rate allocation by FATE with other rate allocations from different traffic engineering objectives (Max Throughput, Min AoI, and Lou 2020) under two different network topologies. FATE solves LAC to trade throughput for AoI according to λ , and we plot the decreasing of throughput/AoI against λ on the left. Enforcing LAC solution via either SDM or TDM as the IFC gives similar performance. On the right we examine the AoI-throughput trade-off. LAC can achieve shorter AoI than traditional throughput-only scheme, while achieving higher throughput than AoI emphasized schemes.

by setting smaller λ . On the other hand, Lou 2020 also achieves small AoI (about 5% shorter than LAC), but it focuses only on AoI flows' AoI and hence LDA flows are allocated zero sending rates.

6.4 Comparison Against Other AQM/TCP Variants

After we assign the sending rate/update frequency according to the FATE solution, IFC takes over and performs packet scheduling at the nodes. In the following, we assign sending rate/update frequencies derived from LAC (under $\lambda = 0.125$) and compare the performance achieved by IFC against other existing AQM/TCP variants, including FIFO, RED, FQ-CoDel, BBR, and DCTCP. The results are shown in Fig. 16.

Fig. 16 shows that IFC, FIFO, and BBR achieve the highest throughput with the lowest AoI. RED drops packets more aggressively to maintain a short queue, which leads to a very short AoI (33 to 38% shorter than IFC). On the other hand, aggressive packet drop significantly hurts the throughput, which degrades to 47 to 60% lower. In comparison, DCTCP and BBR maintain short queues through sending rate control and hence the throughput is higher than RED while keeping AoI low. Between the two TCP protocols, BBR saturates the existing bandwidth better than DCTCP. DCTCP achieves about 33% shorter AoI with 19 to 30% lower throughput. FQ-CoDel tries to allocate bandwidth to LDA and AoI flows more evenly, which obtains slightly higher throughput than RED but suffers long AoI significantly, which is 21 to 26 \times longer than IFC.

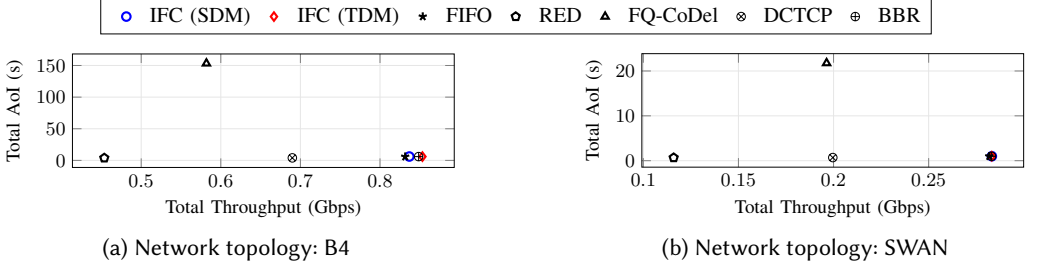


Fig. 16. Under the same rate/update frequency, IFC can achieve shorter AoI and higher throughput than some state-of-the-art queueing management methods by scheduling and enforcing different queueing policies to LDA and AoI flows at each node in the network.

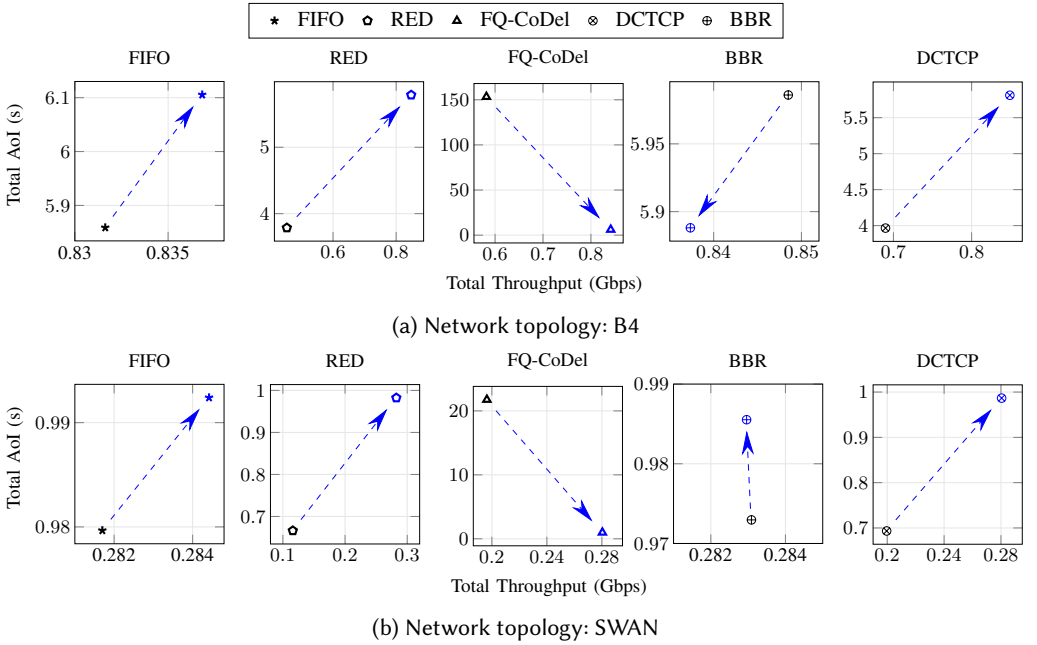


Fig. 17. In the default design of IFC, we use FIFO for the LDA flows. We can use different queueing discipline for LDA flows. Under the same rate allocation, we compare the performance of some queueing disciplines (black) with their combination with IFC (blue). After combining with IFC, we have better performance (towards the bottom/right) or achieve different AoI-throughput trade-offs (towards the top right) under both networks.

6.5 Combination with Other Methods

A key benefit of IFC is that it can easily be combined with other methods to improve their performance. Specifically, we can replace the FIFO queue in IFC with a different queueing discipline in order to handle LDA flows differently. In Fig. 17, we examine the performance improvements of FIFO, RED, FQ-CoDel, DCTCP, BBR and after combining them with IFC (with scheduler SDM) under different network topologies.

We draw an arrow to show the performance of the method before and after combined with IFC. It is better if the arrow goes down or to the right. After combination, IFC achieves better performance than fair queueing based FQ-CoDel (42 to 44% more throughput with 22 to 25× shorter

AoI). It trades AoI for throughput when combining with low queue length methods RED (about 50% longer AoI for 1.9 to 2.4× larger throughput) and DCTCP (42 to 46% longer AoI for 23 to 40% more throughput). After combining with FIFO and BBR, IFC performs well when the network is much more congested as in B4. In SWAN, the network is less congested and hence FIFO and BBR performs similar to IFC.

7 RELATED WORK

Data freshness is a key requirement to achieve safety and stability in many communities, including connected vehicles/satellites [14, 18, 28, 30, 64, 65], real-time database [7, 42, 46], robotics [1, 13, 48, 67], and power systems [20, 29, 53, 57, 58, 68]. State-of-the-art designs use networks for connectivity only and strive for freshness at the end systems by active probing [25, 33, 46], dedicated links [29, 53], or local decision [30].

The goal of improving freshness of flows in a network has also captured the interest of the information theory community over the past decade since the initial work of [43, 44] introduced the concept of the AoI. So far, most research papers in this area focus on theoretical analysis and consider the updates generated by a stochastic source going through different queueing systems, including one-queue systems ($M/M/1$, $M/D/1$, $D/M/1$ [44], $M/M/1/1$, $M/M/1/2^*$ [23, 24], $M/G/1$, $M/G/1/1$ [34], and multiple sources [73]), multihop networks [16, 17, 50, 51, 63, 65], and stochastic network models [41, 45, 52]. Some recent efforts [27, 37, 59] start investigating practical protocols for fresh AoI. This literature has provided many insights for design. For example, when multiple sources are present, [56] proposes to keep only the freshest update in the queue and simulation results demonstrate that the approach can effectively reduce the queueing delay. Another example is that the zero-wait policy, a.k.a., the work-conservation policy, is usually not AoI optimal [60, 61, 72]. Instead, a “lazy” policy performs better [72]. We refer the reader to [51, 74] for more comprehensive surveys on the prior work on AoI.

One recent set of papers that is related to ours focuses on analytic studies of the interplay between freshness and traditional measures, like throughput and energy. For example, [15, 38, 39, 50, 51] focus on scheduling and queueing disciplines for flows that care about a combination of freshness and throughput. [11, 21] study the energy cost of maintaining freshness. We remark that the problems investigated in these papers are different from ours in that they impose constraints to maintain throughput/energy level for the AoI flows. In contrast, in our work, the AoI flows are interested in AoI *only*, and a separate class of flows (LDA flows) is interested in throughput.

Our two-layer approach to freshness can be attributed to two main ideas: active queue management and heterogeneous flow scheduling. Active queue management methods control the queue size through packet drop or explicit congestion notification. They aim to avoid congestion [26, 35] and bufferbloat [54, 55, 62]. Although those methods also drop packets, they do not consider the heterogeneity of flows, neither do they differentiate packets from the same flow according to their properties such as freshness.

On the other hand, heterogeneous flow scheduling systems acknowledge the variety of objectives among flows and exploit their differences to get better performance. For instance, HULL [9] deals with throughput and ultra-low latency applications. pFabric [10] and PIAS [12] reduce flow completion time by differentiating short and long flows. D³ [71] satisfies deadlines of alive flows by quenching the flows past due. NetStitcher [47] improves average utilization by manipulating bulk traffic. All of the systems above leverage the diversity of the flows to achieve their design goals, and our design joins this line of research as the first to address the trade-off between throughput and freshness.

8 CONCLUSION

We investigate the trade-offs between LDA flows' throughput and AoI flows' AoI in wired networks. Our approach to the problem consists of two layers, the freshness-aware traffic engineering (FATE) at the higher layer and the in-network freshness control (IFC) at the lower layer. We formulate the LDA-AoI Coscheduling (LAC) problem to derive the desired sending rate/update frequency to maximize the throughput of LDA flows and an approximated AoI of the AoI flows. We justify our approximation by showing the NP-hardness of zero-queueing schedule and providing an upper bound on AoI. The LAC solution is then enforced by IFC through AoI-Aware Queueing (AAQ). We propose two scheduling policies for AAQ – the size-driven multiplexing (SDM) and time-division multiplexing (TDM), and we provide efficient Linux IFC implementations. Through extensive emulations, we show that our IFC implementation has low overhead and we can potentially trade a little throughput (5%) for much shorter AoI (49 to 71% shorter) comparing to traditional throughput-based objective. Also, we can combine IFC with existing AQM/TCP variants to achieve better performance or different AoI-throughput trade-offs.

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A NP-HARDNESS TO DETERMINE A ZERO-QUEUEING-DELAY SCHEDULE

We prove Theorem 1 by reducing 3-SAT to it. Since 3-SAT is NP-complete, we conclude that obtaining a zero-queueing-delay scheduling is NP-hard. Below we construct such a reduction.

We express a 3-SAT instance ϕ in the form of

$$\phi = C_1 \wedge C_2 \wedge \cdots \wedge C_n$$

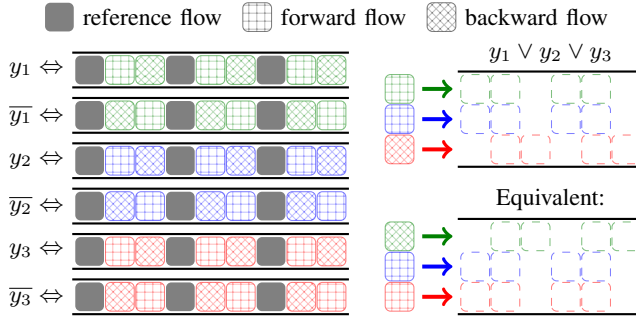


Fig. 18. We show that a zero-queueing-delay schedule is NP-hard to obtain by reducing 3-SAT, an NP-complete problem, to it. For each literal y_k in the 3-SAT instance, we create a unit-capacity throttling link and two AoI flows, the forward and the backward flow, through it. We send a reference flow through all throttling links. Without queueing, there are two possible ways the flows could share the throttling link, and we associate the two configurations to y_k and \bar{y}_k . Leveraging the forward and backward flows, we create a link with capacity 2 for each clause such that a zero-queueing-delay schedule would not exceed the link capacity. As such, a satisfiable 3-SAT instance corresponds to a zero-queueing-delay schedule.

where $C_k = y_{k,1} \vee y_{k,2} \vee y_{k,3}$ is a clause with literals $y_{k,1}$, $y_{k,2}$, and $y_{k,3}$. Each literal $y_{k,j}$ belongs to either the given set Y of literals or its complement \bar{Y} .

As shown in Fig. 18, for each literal $y \in Y$, we construct one unit-capacity throttling link for two AoI flows, the forward flow and the backward flow, with update frequency $\frac{1}{3}$ and size 1. We assign a reference AoI flow through all these throttling links so that there are two possible zero-queueing-delay configurations. We associate the configurations to y and \bar{y} respectively. Each clause corresponds to a link of capacity 2, each carries 3 AoI flows according to the literals. Two of them are forward flows and one is backward flow. We insert propagation delay appropriately so that the clause is satisfied if and only if the link capacity is not exceeded. There are three equivalent ways to choose the forward/backward flows, and we simply choose one of them.

In this way, all the clauses are satisfiable if and only if the queueing delay is zero. Therefore, a zero-queueing-delay schedule is equivalent to a feasible solution to 3-SAT, which concludes the proof.

B AOI UPPER BOUND

Below we prove Theorem 2 by constructing a scheduling policy with the desired upper-bounded a_f . We first assume all link latency is zero. For each $f \in F_{\text{AoI}}$ with $\mu_f > 0$, we allocate capacity $\frac{c_l \mu_f s_f}{S_{\text{LDA}} + S_{\text{AoI}}}$ to send the flow. As such, since a feasible solution to LAC satisfies (2), each packet is sent within

$$\frac{s_f(S_{\text{LDA}} + S_{\text{AoI}})}{c_l \mu_f s_f} \leq \frac{s_f}{\mu_f s_f} = \frac{1}{\mu_f}$$

upon arrival. In other words, it takes at most $\frac{1}{\mu_f}$ to go through each link on the path of f . Therefore, we have

$$a_f \leq \frac{1}{2\mu_f} + |f| \cdot \frac{1}{\mu_f} = \frac{1 + 2|f|}{2\mu_f}.$$

For non-zero link latency, we add d_f to the right hand side of the inequality, which leads to the desired result.