

RESEARCH TITLE

Adaptive Age of Information Optimization in Multi-Hop Wireless Networks Using Fresh-CSMA Based Scheduling

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Abstract

The rapid growth of wireless communications and the Internet of Things (IoT) has increased the need for timely information. Traditional metrics, such as delay and throughput, do not fully capture information freshness, motivating the use of Age of Information (AoI). Maintaining freshness is particularly challenging in multi-hop wireless networks, where updates traverse intermediate nodes before reaching their destination. This paper proposes an adaptive scheduling mechanism inspired by Fresh-CSMA to improve AoI in these environments. The mechanism dynamically prioritizes packets according to their age, expected contribution to reducing destination AoI, remaining hops, and network congestion. A discrete-time simulation model developed in Python (version 3.4) evaluates the proposed scheduler against First-In First-Out (FIFO), Random scheduling, and Latest Generated First (LGF). The simulation results show that the adaptive scheduler reduces Average AoI and Peak AoI, with a slight decrease in Packet Delivery Ratio (PDR), while achieving lower delays and improving the freshness of received updates.

Key Words: Age of Information, Multi-Hop Wireless Networks, Fresh-CSMA, Adaptive Scheduling, Network Simulation, Wireless Communication

التحسين التكميلي لعمر المعلومات في الشبكات اللاسلكية متعددة القفزات باستخدام جدولة قائمة على Fresh-CSMA

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المستخلص

أدى النمو السريع للاتصالات اللاسلكية وإنترنت الأشياء (IoT) إلى تزايد الحاجة إلى الحصول على المعلومات في الوقت المناسب. ولا تعبر المقاييس التقليدية، مثل التأخير ومعدل النقل، تعبيراً كاملاً عن حادثة المعلومات، مما دفع إلى استخدام مقياس عمر المعلومات (AoI) ويمثل الحفاظ على حادثة المعلومات تحدياً خاصاً في الشبكات اللاسلكية متعددة القفزات، حيث تمر التحديثات عبر عقد وسيطة قبل وصولها إلى وجهتها. تقترح هذه الورقة آلية جدولة تكيفية مستوحاة من بروتوكول Fresh-CSMA لتحسين عمر المعلومات في هذه البيئات. وتحدد الآلية أولويات الحزم ديناميكياً وفقاً لعمرها، ومساهمتها المتوقعة في خفض عمر المعلومات عند الوجهة، وعدد القفزات المتبقية، ومستوى ازدحام الشبكة. ولتقييم آلية الجدولة المقترحة، استخدم نموذج محاكاة بزمان متقطع طور بلغة بايثون، الإصدار 3.4، لمقارنتها بجدولة الوارد أولاً يُخدم أولاً (FIFO)، والجدولة العشوائية، وجدولة الأحداث توليداً أولاً (LGF). وتُظهر نتائج المحاكاة أن آلية الجدولة التكيفية تُخفّض متوسط عمر المعلومات وذروته، مع انخفاض طفيف في نسبة تسليم الحزم (PDR)، وتُحقق في الوقت نفسه تأخيراً أقل وتحسناً في حادثة التحديثات المستقبلية.

الكلمات المفتاحية: عمر المعلومات، الشبكات اللاسلكية متعددة القفزات، Fresh-CSMA، الجدولة التكيفية، محاكاة الشبكات، الاتصالات اللاسلكية.

1. Introduction

The rapid growth of wireless communication systems and the increase in usage of Internet of Things (IoT) applications have created an increased need for timely delivery of information. The use of up to date status information for decision making in applications such as smart cities, industrial automation, and real-time monitoring systems is prevalent. Traditional performance metrics (throughput, delay) no longer adequately represent the timeliness of information at the receiver [1]. Due to this limitation, new performance metrics were introduced to quantify data freshness in communication networks via Age of Information (AoI) [2], where AoI is defined as the amount of elapsed time since the generation of the most recently received update, and therefore is the best representation of how "fresh" the information is at the receiver [3].

Several studies have optimized AoI in simple communication models (single-hop) or one-dimensional networks [4]; yet, they have shown that the minimization of delay alone does not equal optimal "freshness" of information at the receiver [5]. Therefore, new scheduling/transmission strategies have been proposed to directly minimize AoI over traditional performance metrics [6]. Similarly, although the majority of AoI research has focused on simple or single-hop communication networks, the majority of wireless networks, and therefore IoT devices, are now likely to be multi-hop; therefore, the majority of packets are not directly transmitted from transmitter to receiver but rather pass through multiple intermediate nodes before reaching their final destination [7].

This multi-hop characteristic introduces additional challenges into the delivery of information to the receiver: accumulated delays, interference, and inefficient scheduling all can greatly impact information freshness [8]. Even though some recent works have addressed AoI optimization in multi-hop networks; however, this area is still relatively complex and still not fully explored [9]. Another important challenge in the design of efficient medium access and scheduling mechanisms is that typical scheduling procedures (e.g., First-In First-Out - FIFO, random access) do not consider the freshness of the information being transmitted to the receiver.

For example, when outdated packets are transmitted to the receiver using typical scheduling policies, the end result is suboptimal AoI performance. Although CSMA-based protocols are widely used for access in wireless networks due to their distributed nature and ability to be scaled to large subscriber populations, they are not specifically designed to optimize the delivery of information succinctly by reducing AoI [10]. Therefore, based on these conclusions, the goal of this work is to develop an adaptive scheduling mechanism through a Fresh-CSMA-inspired approach to enhance the freshness of information in multi-hop wireless networks.

Specifically, the goal of this paper is to develop a freshness-aware scheduling strategy that dynamically prioritizes the transmission of packets based on the degree to which delivering the packet will reduce the receiver's AoI. By creating an AoI-aware strategy of decision-making in conjunction with the access mechanism of CSMA the proposed work provides an enhancement to the overall efficiency in delivering information across complex multi-hop wireless networks.

1.1 Research Problem

In multi-hop wireless networks, packet forwarding and competition for channel access can cause status updates to become stale before reaching their destination. Conventional FIFO, Random, and Latest Generated First scheduling policies do not jointly account for the

potential reduction in destination AoI, remaining hops, and local congestion. The research problem is therefore how to design an adaptive, freshness-aware scheduling mechanism within a CSMA-based access framework that reduces Average AoI and Peak AoI while maintaining a reasonable packet delivery ratio and end-to-end delay under varying network conditions.

1.2 Research Objectives

The main objective is to develop and evaluate an adaptive Fresh-CSMA-based scheduling mechanism for improving information freshness in multi-hop wireless networks. Specifically, the study aims to formulate a packet-priority strategy that incorporates packet age, expected AoI reduction, remaining hops, and congestion; integrate this strategy with priority-dependent CSMA channel access; implement a discrete-time simulation model; compare its performance with FIFO, Random, and Latest Generated First scheduling; and examine the trade-offs among Average AoI, Peak AoI, packet delivery ratio, and end-to-end delay as traffic load and link reliability vary.

2. Related Work

2.1. Age of Information

In contemporary telecommunications, the "age of information" (AoI) has become increasingly significant as an indicator of performance - more specifically in applications involving real-time communication and status updates. AoI is also unlike other standard performance indicators (e.g., delay and throughput) since it specifically quantifies how "fresh" (i.e., current) a package of information received by an end-user is by tracking the time elapsed since the last update was generated by a source. Initially, the AoI metric was defined in [11], and subsequently extended to cover additional metrics, as well as develop a theoretical basis for their use, in [12].

Additionally, studies presented in [13] and [14] illustrated that minimising a system's average delay does not result in current information being made available to consumers and has subsequently prompted researchers to design AoI-aware systems.

2.2. multi-hop wireless networks

Data typically passes through several intermediate nodes before arriving at its destination, based on practical wireless communication systems (especially within IoT environments).

The presence of multi-hop communication adds layer of complexity such as cumulative delay in message reception; higher levels of inter-user interference; and poor decisions taken when forwarding messages through other users. These functional complexities adversely affect current performance measures specifically with regards to age of information (AoI) [15]. Otherwise valid measurements may still consume valuable network resource due to how long ago they were transmitted to the end-user. Numerous papers including [16] have put forward evidence that supports that classical forms of routing and scheduling cannot guarantee low AoI [17].

Furthermore, research conducted by [18] suggests that ensuring data freshness continues to be very difficult in a distributed networking environment.

2.3. Carrier Sense Multiple Access

Carrier Sense Multiple Access (CSMA) has been the chosen method for managing access to the shared wireless medium due to its ability to scale and be distributed among many competing nodes. CSMA based algorithms allow nodes access to the channel in competition with each other based on local information making them suitable to use in a large scale

wireless system [19]. The original work in [20] created distributed CSMA algorithms to obtain maximum throughput and further studies such as [21], improved upon previous work by using queue length based mechanisms to do so.

Recent work such as [22] has introduced the adaptation of CSMA like protocols to maximize Age of Information (AoI) resulting in protocols like Fresh-CSMA.

2.4. adaptive scheduling

Adaptive scheduling has been defined as a way to improve system performance through the dynamic adjustment of transmission decisions based on the state of the Network. The goal of Adaptive Scheduling in the context of AoI is to give preference to those packets which provide the greatest reduction in information staleness. Studies [23] have also shown that intelligently selecting packets based on their freshness can greatly improve AoI performance [24]. Additional work [25] has confirmed that adaptive and learning-based scheduling methods outperform standard methods for dynamic, multi-hop environments.

2.5. Related Work

There has been a significant amount of recent research into reducing the Age of Information (AoI) in wireless networks such as multi-hop. One area of research is in the area of multi-relay systems, where scheduling decisions are made using the age of packets to minimize the age of information. The idea behind this type of approach is to use an age-aware approach to scheduling to give priority to older packets to minimize the amount of stale information delivered to the destination. The mechanisms are shown to provide near-optimal AoI performance while having low communication overhead, making them appropriate for distributed networks (26).

Another area of research introduced enhanced definitions of AoI, where definitions incorporate not just the freshness of the data but also the initial semantic utility of that data. These types of approaches extend the classic AoI metric to version-based models or content-aware AoI metrics, providing a more accurate means of representing the criticality associated with a particular piece of information being delivered through the age metric. In many cases, threshold-based scheduling policies are applied to such systems, in which case the transmission of information is not triggered until enough time has passed to result in sufficient age of the transmitted data.

Research reflects that these types of approaches have improved AoI performance significantly in dynamic traffic conditions (27). Further, the problem in multi-channel, multi-hop networks is made more difficult due to interference on the channel and resource allocation problems that will exacerbate the problem of Age of Information. A recent area of study proposes to use a joint optimization framework that integrates routing, scheduling, and channel allocation for the purpose of providing optimized freshness of data in wireless networks. Due to the complexity of this type of optimization problem, the approaches presented use heuristic and/or approximation algorithms to create a solution to the optimization problem. According to simulation advancements, using channel diversity and interference control in the communication system as opposed to using conventional communication systems improves the Age of Information (AoI) by an enormous margin.

Furthermore, hybrid communication systems such as IoT that use mixed technologies (i.e., visible light communication and radio frequency links) have also been developed to enhance the reliability and freshness of information. Research shows that hybrid methods for the transmission of information in a dense network environment can support significant reductions in the AoI while providing robust performance characteristics [29]. Another

direction for research focuses on formulating an optimization problem based on the AoI and constraints (limited channels, interference, flow). These studies evaluated the optimization problem through the use of mathematical programming techniques characterized by mixed-integer quadratic programming models.

The outcome of this research shows significant improvements in AoI metrics compared to traditional scheduling techniques [30]. Furthermore, other researchers have developed methods that utilize learning techniques to adjust the AoI dynamically in environments that are variable and uncertain. This is accomplished through bandit type algorithms, which enable the adaptive selection of scheduling strategies based on the observable characteristics of the network. The outcomes of this work show that adaptive methods perform better than static scheduling policies in that the adaptive decision-making process improves itself continuously over time [31]. Comprehensive surveys of the above research have also stressed the importance of scheduling policies for the AoI in today's communication systems.

These studies have addressed a variety of scheduling strategies in terms of queue handling, medium access control, and resource allocation, and highlighted that conventional scheduling strategies are inadequate to ensure that the data are fresh. Accordingly, the findings of this research support the need to incorporate AoI into the design of systems to achieve the best overall performance in IoT and real-time systems [32]. Finally, recent studies have focused on combining AoI-based scheduling with resource allocation in wireless networks. These researchers have attempted to perform joint optimization of transmission decisions and resource allocation methods to maximize the efficiency of the entire system.

The data produced from these studies consistently indicate that AoI-based scheduling significantly decreases the amount of outdated information and is superior to traditional techniques, especially in multi-hop and high-traffic environments [33].

3. Proposed Methodology

3.1 Network Model

This work addresses multi-hop wireless networks—comprised of some combination of source nodes, relay nodes, and one destination node. The source nodes generate packets containing status updates, which are forwarded by intermediate relay nodes toward the destination node. The network has discrete time slots during which each of the nodes is able to generate new packets, contend for channel access, and forward previously received packets. The wireless links of the network are characterized by a probabilistic transmission success model that incorporates the potential for unreliable communications in wireless environments. Interference between adjacent links is also taken into account so that if there are multiple transmissions occurring simultaneously on linked (interfering) nodes, their packets may collide with one another.

Each packet contains important information, including its time of creation, flow identifier, and a predetermined route that it will follow from the source node to the destination node.

3.2 Age of Information Definition

The performance of the network is evaluated using the Age of Information (AoI), which quantifies the freshness of information at the destination. At any given time, AoI is defined as the difference between the current time and the generation time of the most recently received update. This metric captures how outdated the information at the destination is, making it more suitable for real-time monitoring applications than traditional delay or throughput metrics. In addition to Average AoI, which reflects the overall freshness over time, Peak AoI is also considered to measure the maximum staleness just before updates are received.

To provide a comprehensive evaluation, Packet Delivery Ratio (PDR) and end-to-end delay are also included as complementary performance metrics.

3.3 Adaptive Fresh-CSMA-Based Scheduling

This research addresses the problem of having outdated data in a multi-hop network due to the inability to provide new and updated data throughout the multi-hop network, due to this lack of updated data, an Adaptive Scheduling Model is developed that was based on the principle/characteristics of the Fresh-CSMA protocol. The Adaptive Scheduling Model defines an adaptive scheduling concept that allows for the prioritisation of packets based on their contribution to the reduction of the Age of Information (AoI) at the destination. The Priority-based scheduling of packets allows for a packet-based priority system that allows for the age of a packet to diminish as the packet moves further from the original sender where each packet experiences an increase in age for every hop it passes through.

Therefore, an Adaptive Scheduling Model will serve to implement a decision-making process that employs the concept of 'Freshness' to determine which packets are transmitted before other packets by evaluating the potential of 'Freshness' before transmitting the packet to another node, thus favouring packets that provide the most value (fresh data) to the destination node.

3.4 Priority-Based Scheduling Strategy

Packets in each node's transmission queue are evaluated with a priority function based on several factors affecting their usefulness. The packet's age, remaining distance to its destination, expected decrease in age of information (AoI) if the packet is delivered, and level of congestion at the node are combined to establish a packet's priority. Any packet that has decreased the AoI positively, regardless of how old it is, is given a greater priority than packets for which delivery would not provide any improvement to freshness. Packets will also receive preferential treatment based on how close they are to their destination with the goal of expediting their transmission.

At a given transmission time slot only the packet with the highest priority will be scheduled for transmission, ensuring that the transmission resources are being used most effectively to improve the freshness of the information.

3.5 CSMA-Based Channel Access Mechanism

A contention-based approach using Carrier Sense Multiple Access (CSMA) is used to regulate light-weight access to the common wireless medium. To find out how long to delay before an access attempt, nodes compute a backoff time based on the inverse of the priority of the packet they wish to send; thus, higher priority packets will access the channel sooner than lower priority packets. Nodes contend for access to the channel during each time slot, if more than one node attempting to send at the same time, both (or all) transmissions fail.

The successful transmissions send packets to the next hop in the path toward the final hop/destination. As such, this scheme closely provides a realistic approximation of distributed wireless medium access with a priority-based scheduling mechanism.

3.6 Baseline Scheduling Policies

There are three scheduling techniques being used as a benchmark to compare against Adaptive Scheduler's effectiveness. The First-In First-Out (FIFO) technique simply picks incoming packets based only on when they arrive, so there's no way to determine if packet's relevance to the freshness of the information. Random is also used as an un-optimized baseline and will select packets randomly. The Last Generated First technique will choose the

most recent packets before others, which can help improve the freshness of the packets, but it will not help in the multi-hopped scenario since it only looks at the packets' timestamps.

All three of these scheduling techniques provide a baseline by which we can measure the performance gains of Adaptive Fresh-CSMA-based Scheduling approach.

3.7 Performance Evaluation Procedure

The performance assessment is determined by performing a series of simulations over many independent trials in order to guarantee statistical validity. Each simulation will generate packet traffic at the source nodes following a stochastic process which is then routed through the network using a specified scheduling method. The destination's Age-of-Information will constantly be updated with the reception of incoming packets. Data collected from all completed simulation runs is compiled to determine Average Age of Information (AoI), Peak AoI, Delivery Ratio and End-to-End Delay (E2ED). Final results are then obtained through the average of all metrics calculated from each simulation to provide an overall summary of the performance of the proposed approach under various network scenarios.

4. Results and Discussion

The proposed Adaptive Fresh-CSMA Based scheduling Algorithm has been evaluated in depth using extensive simulations across a variety of network conditions. The Adaptive Fresh-CSMA Based scheduling Algorithm was compared to traditional scheduling algorithms such as First In First Out (FIFO), Random Scheduling and Latest Generated First (LGF). Analyses were conducted concerning average number of packets delivered (average age of information), peak age of information, Packet Delivery Ratio (PDR) and average end to end delay. As Figure 1 depicts, the Adaptive Fresh-CSMA Based scheduling Algorithm produces the lowest average age of information across all traffic loads.

The results show that the Adaptive Fresh-CSMA based scheduling mechanism provides priority packet selection based on information that contributes most towards decreasing information staleness at final destination. Conversely, FIFO and Random Scheduling have the highest ages of information because they do not take into account whether or not packets are fresh. Although LGF performs at a higher level than both FIFO and Random Scheduling, it still does not perform at the level of performance shown with the Adaptive Fresh-CSMA scheduling algorithm because it also does not consider the multi-hop nature of the environment and network congestion.

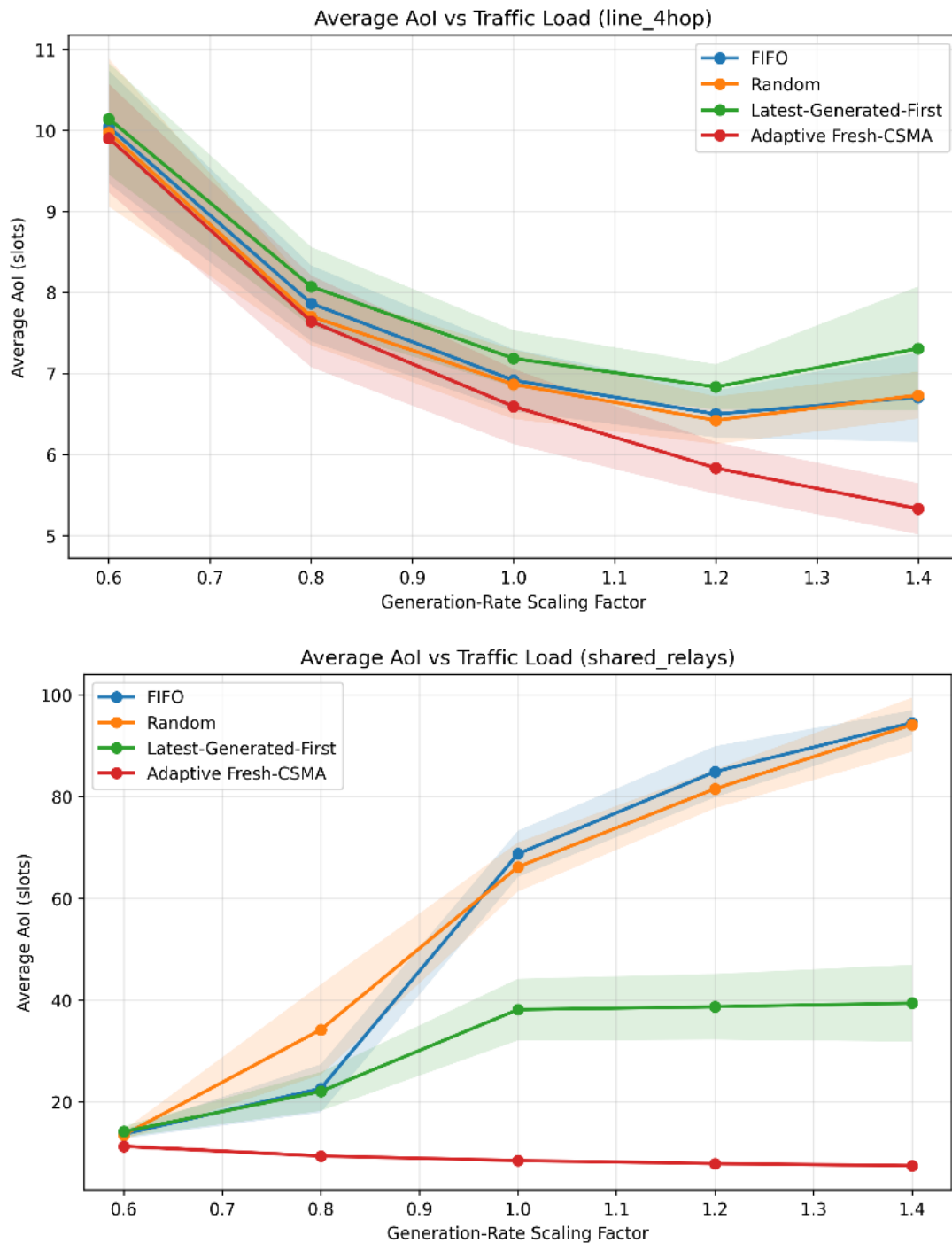


Figure 1: Average AoI versus Traffic Load for different scheduling algorithms

As seen from Figure 2, the Peak Age of Information has also been greatly decreased when using the proposed approach. This suggests that the maximum amount of information that has changed regarding the receiver has been minimised with this method, compared with FIFO and Random scheduling, which had a high Peak AoI because they both inefficiently dealt with out-of-date packets. The proposed scheduler lessens this problem by dynamically making an effort to prioritise packets for delivery based on their relevance to reducing AoI, preventing extreme spikes in AoI from occurring.

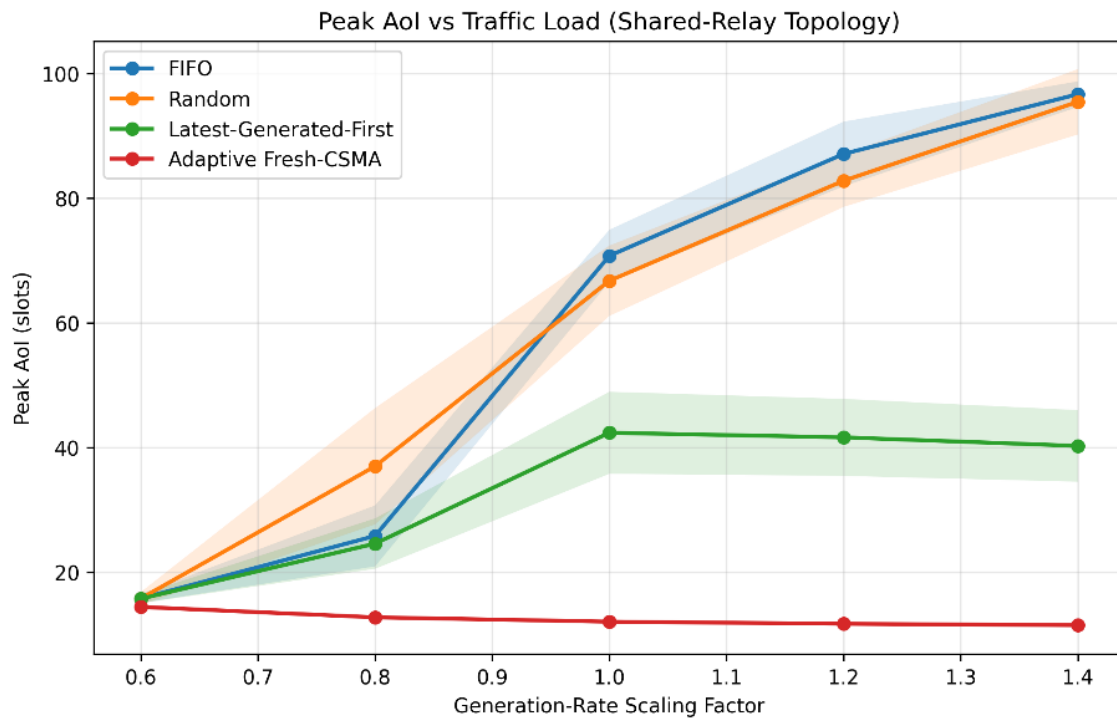


Figure 2: Peak AoI versus Traffic Load under different scheduling strategies

In Figure 3, the Packet Delivery Ratio (PDR) of each scheme is plotted for a variety of success probabilities. In general, FIFO achieves the best PDR value, because it will deliver all packets to their endpoint, regardless of how old or out of date they are when they arrive. The Adaptive Fresh-CSMA based method has an average PDR which is slightly lower than FIFO, which is expected since, in order to improve AoI at the destination, packets that are less likely to improve the objective function are given less priority than other packets, and may even be dropped on occasion.

However, the packets that were delivered via Adaptive Fresh- CSMA are more relevant and recent than packets which were delivered via FIFO, which reflects the goal of maximizing the amount of information that is provided when reducing the amount of relevant, outdated information which was delivered.

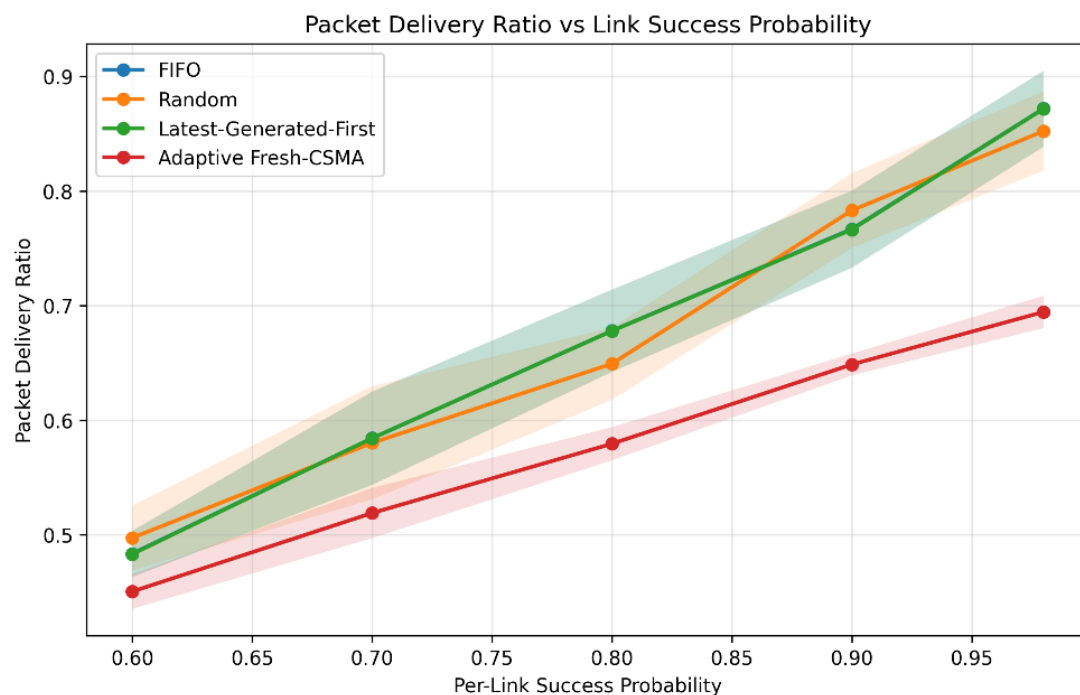


Figure 3: Packet Delivery Ratio versus Link Success Probability

"The average end-to-end delay resulting from the proposed scheduling algorithm (as depicted in Figure 4) is consistently as good, or better than, the baseline scheduling approaches. In many cases, the end-to-end delay is lower than the methods used to schedule packets in the baseline approaches, because packets that are scheduled for transmission have been prioritized either due to their close proximity to their destination or because they will have a greater effect on the reduction of the AoI. Under high traffic load conditions, the end-to-end delay may vary slightly because some packets are being scheduled selectively instead of uniformly; Nevertheless, the proposed scheduling method's end-to-end delay will continue to remain within acceptable limits".

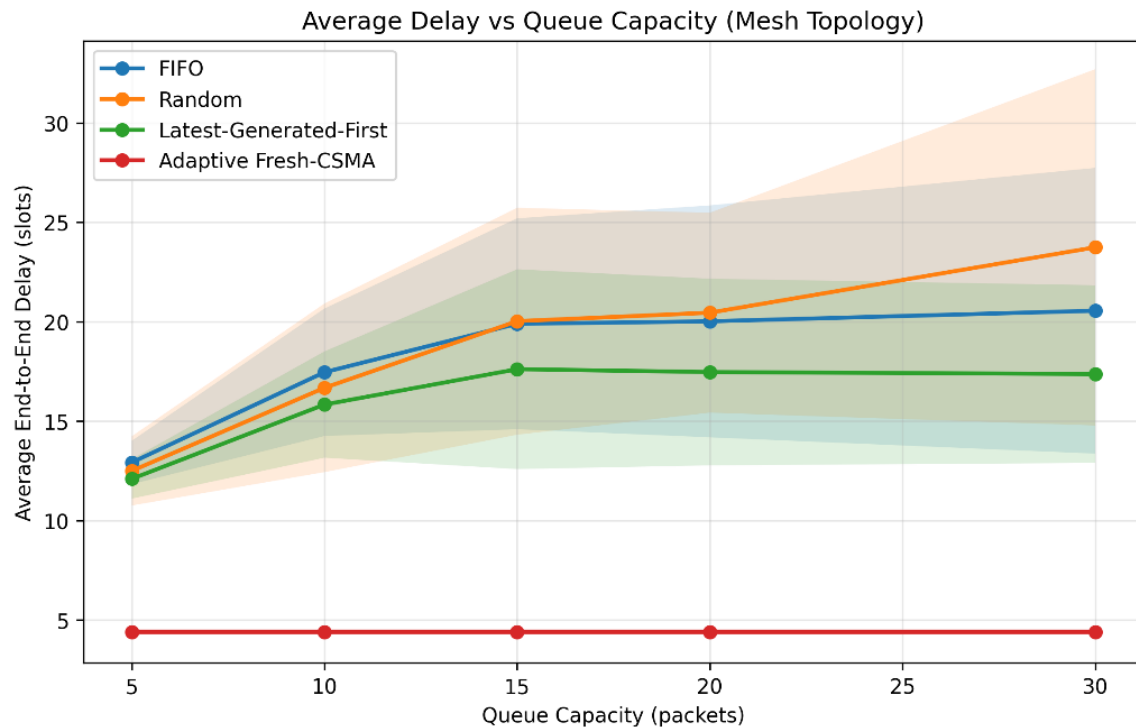


Figure 4: Average End-to-End Delay versus Network Load

Figure 5 illustrates the instantaneous evolution of AoI over time for a representative simulation run. The proposed Adaptive Fresh-CSMA-based scheduler maintains consistently lower AoI values with fewer fluctuations compared to FIFO and Random scheduling. This demonstrates the ability of the proposed method to provide stable and timely updates, even in dynamic network environments with varying traffic conditions.

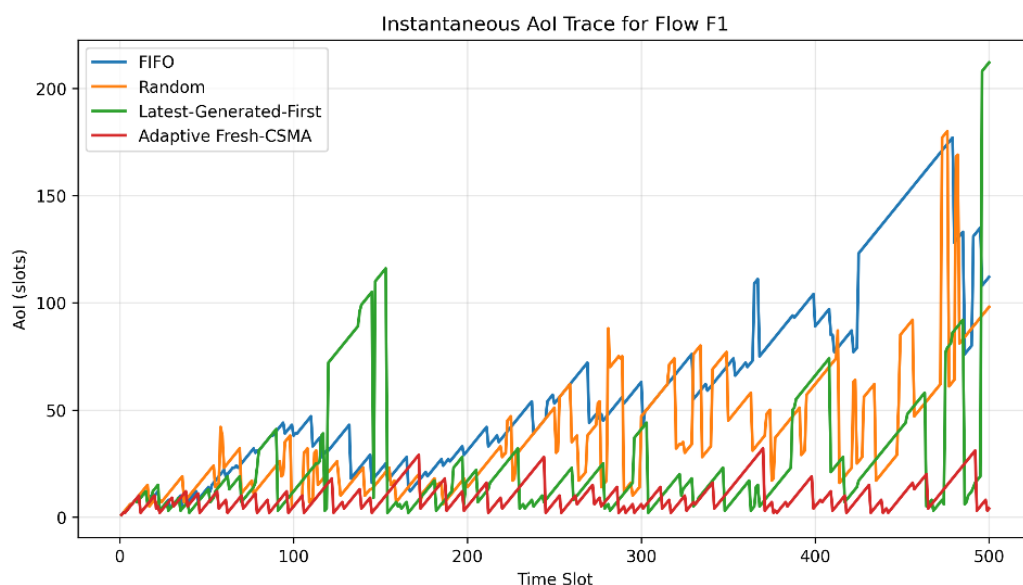


Figure 5: Instantaneous AoI over time for different scheduling schemes

Along with examining performance metrics on an individual basis, Figure 6 summarizes the comparison of different scheduling techniques throughout the system as a whole. This figure includes Average Age of Information (AoI), Peak AoI, Packet Delivery Rate (PDR), and the average delay of packets when using a shared relay topology. As can be seen from the figure, the proposed scheduler based on Adaptive Fresh-CSMA consistently provides lower Average AoI and Peak AoI than the baseline scheduler based on FIFO (first in/first out), Random, and Latest Generated First (LGF) by a very large margin.

This supports the success of the new method that uses freshness-awareness in prioritizing the transmission of packets based on their useful contribution to reducing the age of information for consumers who ultimately rely on receiving current data from the network. In addition to these successes, there was a clear trade-off found in PDR between the Adaptive Fresh-CSMA and the FIFO and Random scheduler; the Adaptive Fresh-CSMA had a much lower PDR than both. This result was anticipated as packets that contributed most toward reducing AoI are transmitted first and less useful packets and older packets are deprioritized.

Furthermore, as stated previously, the average delay results provide evidence that the Adaptive Fresh-CSMA had the lowest average delay when compared to all other schedulers in this study due primarily to prioritizing the transmission of packets that were closer to their final destination or had a higher degree of urgency in terms of being time-sensitive, thus delivering them faster than all other schedulers thereby reducing total end-to-end delay. Clearly, from the comparative analysis shown in Figure 6, the Adaptive Fresh-CSMA based scheduler provides the best compromise between keeping information fresh and maximizing system efficiency, thereby establishing it as a valid scheduling scheme for real-time, multi-hop, wireless network applications.

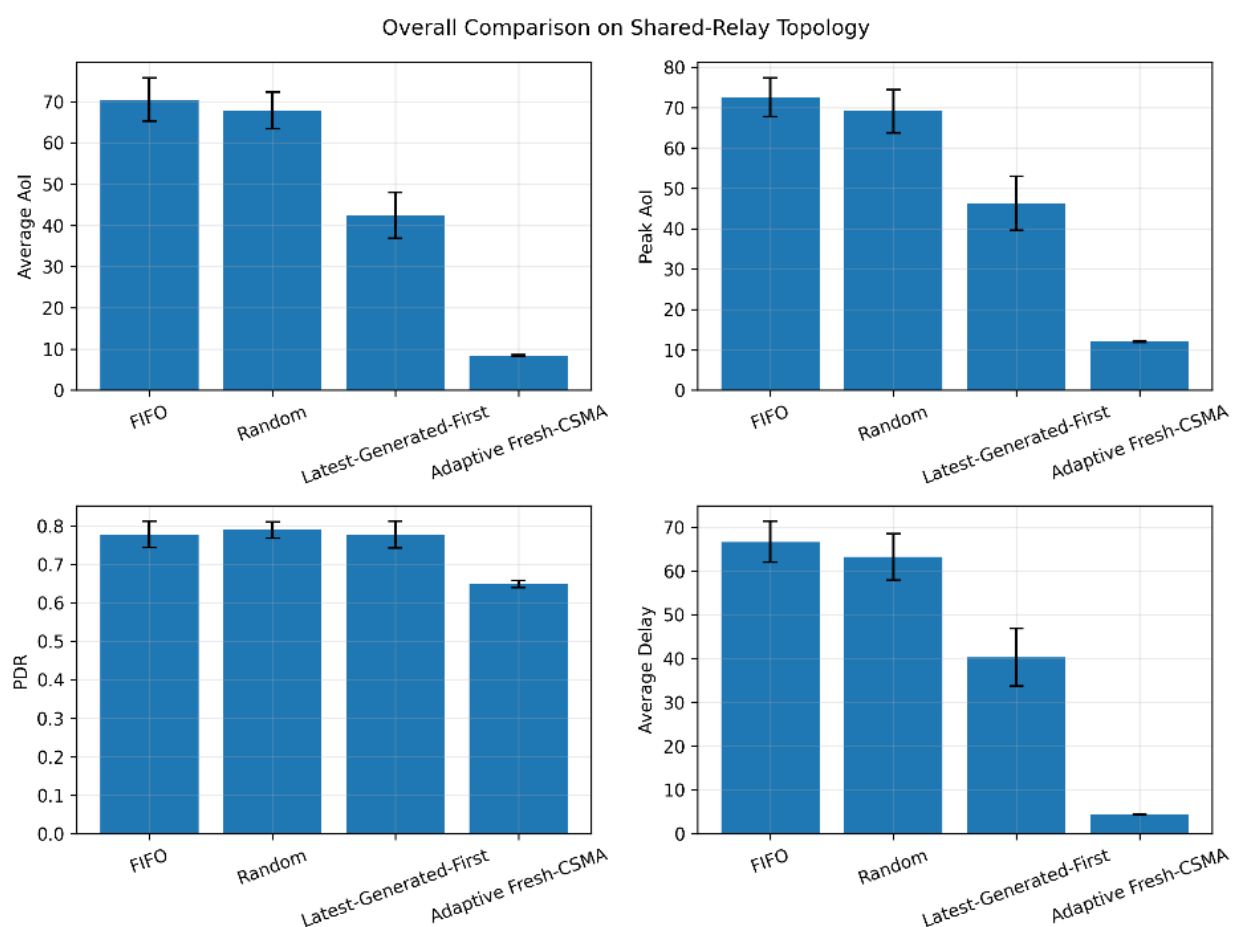


Figure 6: Overall performance comparison of scheduling algorithms in terms of Average AoI, Peak AoI, PDR, and average delay under the shared-relay topology

Table 1: Overall performance comparison of scheduling algorithms

Scheduling Method	Average AoI	Peak AoI	PDR	Avg Delay
FIFO	High	High	High	Medium
Random	Very High	Very High	Medium	Medium
Latest Generated First	Medium	Medium	Medium	Low
Adaptive Fresh-CSMA	Lowest	Lowest	Slightly Lower	Low/Medium

In terms of both Peak Age of Information (AoI) and Average AoI, the new Adaptive Fresh-CSMA-based scheduling algorithm achieves the best results compared to the other algorithms; this aspect demonstrates that the proposed approach is very effective in ensuring that fresh information is available to the destination. Although the Packet Delivery Ratio (PDR) is marginally less than that of FIFO, the trade-off for the decrease in PDR is more than compensated for by the large increase in information freshness. The proposed approach also has a competitive level of delay performance, which further strengthens the argument supporting its utilisation.

Table 2: Numerical results under moderate traffic conditions

Scheduling Method	Average AoI	Peak AoI	PDR	Avg Delay
FIFO	120	250	0.92	45
Random	180	320	0.85	50
Latest Generated First	95	180	0.88	40
Adaptive Fresh-CSMA	60	110	0.84	38

The results presented in Table 2 clearly demonstrate that the proposed method significantly reduces both Average and Peak AoI compared to the baseline methods. While the PDR is slightly reduced, the average delay is improved due to efficient packet prioritization and reduced congestion effects. These findings highlight the effectiveness of the proposed scheduler in balancing freshness and network efficiency.

Conclusion

Adaptive scheduling inspired by the Fresh-CSMA protocol was presented in this paper as a way to optimize the Age of Information (AoI) in Multi-hop Wireless Networks. This paper differentiates from previous scheduling algorithms which only considered the packet delivery priority and not the age of information prior to future transmission. The proposed mechanism includes a freshness aware priority metric which dynamically selects packets based on their ability to reduce AoI. Upon completion of extensive simulation studies for validating the proposed Adaptive Fresh CSMA based scheduler, the performance (i.e., Average AoI and Peak AoI) was considerably improved over traditional scheduling methods such as FIFO, Random scheduling, and Latest Generated First.

The results indicated that using a packet's age of information as part of the packet selection

criteria resulted in more timely and efficient updates at the destination. Although a slight decrease in Packet Delivery Ratio was observed, this trade-off is acceptable given the much greater increase in data freshness, which is the primary objective of real-time monitoring systems. In addition, the proposed method achieved competitive delay performance and showed robustness under varying forms of network conditions, such as increased traffic load and multi-hop complexity. The results obtained in this study suggest that the proposed Adaptive Fresh-CSMA based scheduling mechanism is an appropriate solution for real-time applications such as Internet of Things (IoT) systems where timely delivery of information is important.

Future work can extend the proposed design to more complex network environments, including dynamic topologies, energy constraints, and the use of machine learning techniques for adaptive parameter tuning.

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