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Foundations and Trends® in Networking

Published, sold and distributed by:
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
United States
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Outside North America:
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2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is

H. H. Yang *et al.*. *Age of Information: A Wireless Networking Perspective®*. Foundations and Trends® in Networking, vol. 16, no. 3-4, pp. 171–242, 2025.

ISBN: 978-1-63828-669-1

Foundations and Trends® in Networking
Volume 16, Issue 3-4, 2025

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Foundations and Trends® in Networking, 2025, Volume 16, 4 issues. ISSN paper version 1554-057X. ISSN online version 1554-0588. Also available as a combined paper and online subscription.

Contents

Age of Information: A Wireless Networking Perspective®

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ABSTRACT

Age of information (AoI) is a metric that quantifies the timeliness of information delivered in a system, which is an emerging requirement for a variety of services like autonomous driving, industrial internet of things, as well as the likes of mobile applications. This monograph presents an overview of AoI from the perspective of wireless networking. It gives a comprehensive introduction to the analytical techniques used in deriving this metric as well as networking strategies that improve the AoI. Extensions to other age-related metrics, applications, and future research directions are also discussed.

Howard H. Yang, Zhengchuan Chen, Nikolaos Pappas and Tony Q. S. Quek (2025), "Age of Information: A Wireless Networking Perspective®", Foundations and Trends® in Networking: Vol. 16, No. 3-4, pp 171–242. DOI: 10.1561/1300000064.

1

Introduction

1.1 Importance of Timeliness in Modern Network Applications

In the rapidly evolving landscape of network communications, the timeliness of information has emerged as a critical factor influencing the effectiveness of various applications. As systems increasingly integrate advanced technologies such as the Internet of Things (IoT), autonomous vehicles, and smart infrastructure, the demand for real-time control and a short-time sensing-decision-making-execution loop has intensified, which requires timely data exchange, including both fresh status updating and command-and-control by instructions. This shift towards real-time communication highlights the growing importance of ensuring that information is not only transmitted efficiently but also remains relevant and up-to-date upon arrival. In environments where instantaneous decision-making is required, outdated or delayed information can lead to suboptimal outcomes, affecting everything from traffic management in smart cities to the performance of industrial automation systems. Consequently, the need to optimize the timeliness of information has become a focal point for improving system performance and user experience across diverse domains.

1.2 Definition of Age of Information

To qualify the timeliness of information, the age of information (AoI) is proposed as a pertinent metric. For a specific status update, the AoI at time t is $t - u$, where u denotes the epoch in which the status update packet is generated. That is, the AoI of a packet stands for the difference between the current time and the generation time, which is just the literature meaning of 'age'. Hence, it evolves in a linear way.

While the effectiveness of the AoI for an individual packet is constrained by the intuition behind its definition, the AoI is more meaningful when viewed from a pragmatic perspective. As data exchange keeps occurring, the AoI of a system is often considered from the destination end, which is usually the decision-maker, where the semantic of information is abstracted for applications.

At this time, the AoI of the system, which is often called the AoI in the literature, characterizes the time elapsed since the newest generated status update among all of those that have already arrived at the destination end. Formally, at time t, denote the index set of all the received packets at the destination by $\mathcal{S}(t)$. Denote the generation time and received time of status update $i \in \mathcal{S}(t)$ by t_i and t'_i, respectively. Then, the AoI of the system at time t, denoted by $\Delta(t)$, admits that

$$\Delta(t) = t - u(t), \tag{1.1}$$

where

$$u(t) = t_j, \;\; j = \arg\max_{i \in \mathcal{S}(t)} \{t'_i \leq t\}, \tag{1.2}$$

That is, at time t, the AoI of the system is just the age of the youngest one among all the packets received until time t. Noting that decisions in applications are made based on all available observations, the AoI of the system reflects the timeliness of information from a user's perspective. As long as the status updating continues, the AoI would evolve in a sawtooth shape as the youngest packet would be refreshed. Figure 1.1 shows a typical example of the evolution of the AoI. One can see that at time t'_j, the AoI is dropped as $t - t_j$, i.e., the age of packet-j, since the successful receiving of packet-j leads to it becoming the latest packet.

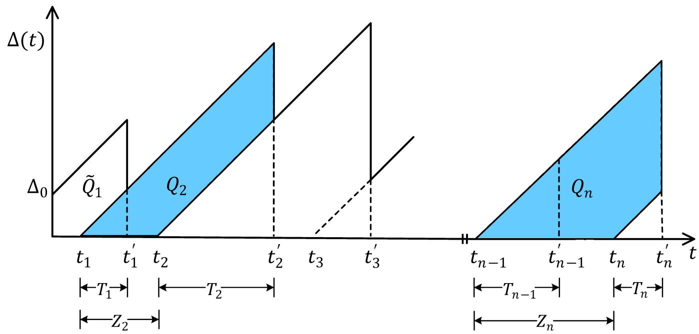

Figure 1.1: A typical evolution example of the AoI of the system.

This is because the generation times of all the other received packets are less than t_j, the generation time of packet-j.

Note that, as a destination-centric timeliness metric, the AoI differs from traditional communication-system performance metrics such as throughput and delay. Delay measures the time taken for data to travel from the sender to the receiver, encompassing various factors such as propagation delay, queueing delay, and processing delay. Intuitively, a small delay would yield only a short time difference between the generation time and the time of arrival at the destination. However, this does not imply the youngest packet is up-to-date and a small AoI of the system can be achieved. In fact, long update intervals (i.e., low update frequency) would lead to less frequent refreshing of the youngest packet at the destination, thereby increasing the AoI. This indicates that the AoI emphasizes the timeliness of data updates over transmission speed, underscoring the relevance of the received information in real-time applications. In contrast, throughput measures the rate at which data is successfully transmitted across the network, typically expressed in bits per second (bps). A high throughput can usually guarantee frequent status updates; however, potential delays, including queueing and waiting, can also increase the time difference between the generation time and the receipt time of the status update. In essence, throughput focuses on the volume of data transferred, whereas AoI ensures that the transmitted data is timely and relevant for real-time decision-making and processing. The uniqueness of the AoI ensures it can characterize the information freshness and timing semantics of information accurately. Meanwhile, the destination-centric property implies different behavior of the AoI in terms of the generation process and transmission organization of status updates. Hence, the design of the communication system, including sensing, packet management, transmission scheduling, and processing in the event of transmission failures, should be carefully reconsidered.

1.3 Applications of AoI

In this section, we introduce the application of AoI across a range of services, including unmanned aerial vehicle (UAV)-assisted applications, vehicle-to-everything (V2X) communications, social networks, digital twin (DT) networks, and industrial Internet of Things (IIoT).

1.3.1 UAV-assisted applications

Information timeliness has become increasingly critical in modern communication frameworks, including UAV operations. In various UAV applications, information timeliness ensures that the data collected and transmitted remains relevant and current to meet specific operational needs. More precisely, information timeliness measures the interval between the generation of the most recent data update and its successful reception by the intended recipient. Ensuring timely information is essential in these domains, as delays can lead to adverse outcomes or missed opportunities for intervention [2].

Equipped with advanced transceivers, UAVs play a pivotal role in collecting real-time data essential for assessing environmental conditions, coordinating complex rescue operations, and managing resources efficiently [21, 37, 71]. Optimizing information timeliness becomes crucial, as it directly influences decision-making processes that rely on timely and accurate data. For instance, in monitoring systems where environmental changes occur rapidly, outdated data can result in ineffective responses or inappropriate resource allocation, exacerbating existing issues and complicating response efforts. A promising strategy to enhance information timeliness involves transmitting only the most pertinent and updated data, which improves data freshness while conserving UAV battery power, thereby extending operational capabilities and lifespan [46].

However, many existing studies neglect a critical aspect: energy replenishment. These works often assume that UAVs possess sufficient energy reserves to complete their tasks without issue, significantly limiting their applicability in complex or long-duration missions that demand continuous operation and sustainable energy management [35]. Various strategies have been proposed to address this limitation, such as scheduling UAVs for energy replenishment via battery swapping or deploying charging stations [17, 50]. By jointly optimizing UAV trajectories and charging station schedules, persistent data services can be maintained while minimizing information timeliness delays [49, 75].

The ability of UAVs to operate close to sensor nodes further enhances their efficiency, enabling strong line-of-sight communication links and improving energy efficiency and data collection performance. Nevertheless, designing UAV trajectories requires careful consideration of limited energy resources and periodic charging or battery swapping to ensure uninterrupted operations. Optimizing the trade-off between information timeliness and energy management presents a multifaceted challenge requiring innovative strategies. Effective solutions must seamlessly integrate real-time data collection with energy replenishment strategies, enabling UAVs to meet diverse data traffic requirements while maintaining operational continuity within broader IoT networks. These considerations highlight the importance of incorporating information timeliness and energy management into UAV-assisted systems, paving the way for substantial advancements across various application domains.

1.3.2 Vehicle-to-everything

Information timeliness is a critical metric in V2X communication, significantly impacting the effectiveness of intelligent transportation systems. In this context, information timeliness is essential for ensuring prompt data updates crucial for real-time applications, such as communication between self-driving vehicles and traffic signals. Access to the most current information is vital for optimizing routes, reducing waiting times, and enhancing overall traffic efficiency [1]. For instance, in emergency scenarios requiring rapid response, maintaining low information timeliness facilitates the swift transmission of critical warnings between vehicles, significantly improving collision avoidance and enhancing road safety [10]. The importance of information timeliness in V2X applications is amplified by the high mobility of vehicles and the dynamic nature of their communication environments. As vehicles navigate ever-changing road conditions, the ability to rapidly update and relay information regarding traffic signals, road hazards, and the behavior of surrounding vehicles is paramount for maintaining safe and efficient traffic flow.

Integrating information timeliness into resource allocation strategies can significantly enhance communication efficiency while ensuring reliable and prompt dissemination of critical information. Recent research has explored various strategies to minimize information timeliness while maintaining reliability in vehicle-to-vehicle communication. For example, a study introduced a multi-agent deep deterministic policy gradient resource allocation algorithm aimed at reducing information timeliness while ensuring secure and reliable data transmission [41]. Another investigation proposed an information timeliness model for both vehicle-to-infrastructure and vehicle-to-vehicle communication, coupled with a joint spectrum and power allocation scheme to reduce average information timeliness and overall power consumption in the network [42].

1.3.3 Social Networks

To better reflect the freshness of information in social networks, the age-based metric is proposed, offering a detailed perspective on the temporal dynamics of information propagation. In particular, version age has been proposed as an alternative to classical AoI in contexts where updates are treated as discrete versions rather than continuous flows. In [6, 57], version age reflects the number of updates missed by a receiver, effectively measuring information staleness in gossip-style protocols. These works primarily analyze version age in structured, single-source environments across various network topologies, such as rings, fully connected graphs, and clustered community models. However, real-world social networks exhibit dynamic, multi-source, and recurrent sharing behaviors, where users repeatedly disseminate information over time. Field experiments such as [39] illustrated that heuristic-driven propagation can be effective for promoting content in realistic settings. Moreover, [26] highlights the role of persistent contact patterns in shaping optimal diffusion strategies over complete graphs, emphasizing the importance of leveraging ongoing interactions for sustained dissemination. To address the limitations of static seeding models, the authors in [33] proposed a multi-stage seeding framework that explicitly incorporates AoI into the information diffusion process. Their formulation targets the minimization of both peak and average AoI under budget constraints, capturing the need for freshness-aware dissemination. The authors develop polynomial-time approximation algorithms with theoretical performance bounds, and validate their approach through comprehensive simulations across varied network topologies and behavioral models. Results show significant improvement in reducing staleness compared to baseline strategies. These advancements underscore the growing relevance of AoI-based metrics in modeling information spread in social systems, particularly in applications such as viral marketing, emergency alerting, and online rumor containment. Future research directions may explore integrating context-aware relevance models, temporal decay functions, and learning-based adaptive seeding strategies to further optimize freshness in complex, evolving social environments.

1.3.4 Digital Twins Networks

In the evolving landscape of Digital Twins, information timeliness has emerged as a cornerstone for advancing real-time data management and decision-making processes. This metric, which quantifies the interval between the generation and delivery of data, plays a critical role in ensuring that the virtual representation of a physical asset remains synchronized with its real-world counterpart. Effective management of information timeliness is particularly vital in high-latency environments, such as lunar missions or remote industrial sites, where communication delays can significantly impede responsive actions [70].

By minimizing delays in data synchronization, operators can ensure that decisions are based on the most up-to-date information, enabling faster and more informed responses [5]. In mobile edge computing networks, strategically placing DTs close to physical assets significantly enhances information timeliness by reducing data propagation delays. This optimization improves the speed and accuracy of query results, proving indispensable in critical domains. For example, in healthcare, clinicians rely on real-time patient data to make life-saving decisions, while in manufacturing, instantaneous monitoring can prevent costly system downtimes [30, 31, 36, 51]. The interplay between information timeliness and the adaptability of DTs facilitates dynamic deployment strategies tailored to the mobility of physical objects and user interactions. Service providers can proactively adjust DT placements by leveraging predictive algorithms, anticipating user needs, and optimizing network resources to deliver relevant and timely information [47]. This adaptability is essential in environments with variable connectivity and mobility constraints, where precise alignment of virtual models with physical states is critical. As industries increasingly adopt IoT and advanced analytics, the strategic management of information timeliness becomes central to the operational efficiency of DTs. By embedding this metric into the deployment and synchronization frameworks of DT systems, organizations can enhance the accuracy and reliability of their virtual models, driving innovation across diverse applications. These range from autonomous vehicles navigating complex environments to smart cities optimizing resource management [32]. Such a holistic approach to managing data freshness will underpin the next generation of intelligent systems, enabling superior performance in constrained environments while delivering exceptional user experiences [7, 9].

1.3.5 Industrial Internet of Things

In the Industrial IoT context, information timeliness has become an essential metric for ensuring timely updates of status information, which is vital for the functioning of intelligent and automated manufacturing systems [44]. With rapid advancements in sensor technology, a growing number of intelligent robots and automated systems are interconnected, enabling them to perform complex and repetitive tasks autonomously. This interconnectedness facilitates a level of coordination and efficiency previously unattainable [11, 34, 53]. In IIoT environments, a central control center is typically necessary to monitor the status of various workbenches and direct the actions of robots in real time. Given the dynamic nature of workbench statuses and operational demands, the control center must receive timely updates from the robots to issue accurate control commands effectively. This continuous flow of fresh status information is fundamental to maintaining operational efficiency and ensuring smooth production processes [62]. Subsequent studies have explored specific wireless systems extensively, investigating how various communication parameters influence information timeliness. For instance, research has addressed the average information timeliness within low-Earth orbit satellite-terrestrial-integrated networks, analyzing how satellite communication dynamics impact information freshness [20]. Additionally, studies have examined optimal energy capacitor sizes in wireless-powered networks, delving into how energy constraints affect the timeliness of data updates [29]. Another significant area of inquiry has focused on maintaining information timeliness in UAV networks, further underscoring the importance of information timeliness in modern communication frameworks [38]. While early studies predominantly concentrated on long packet communications utilizing the Shannon formula, it is important to recognize that the IIoT environment has evolved to encompass diverse communication methods, necessitating a shift toward understanding how these changes influence information timeliness. With the proliferation of ultra-reliable low-latency communication standards and enhanced wireless technologies, the IIoT landscape requires efficient data transmission that prioritizes reliability and minimizes latency, ensuring the information remains current and actionable. In IIoT applications, the challenge lies in balancing data transmission frequency with the energy constraints of IoT devices. Devices often operate on limited power, making it imperative to optimize communication schedules that maintain low information timeliness without depleting battery resources too quickly. Various strategies have emerged, including adaptive transmission scheduling and event-driven updates, where devices transmit data only upon detecting significant status changes.

Such methods can effectively reduce unnecessary transmissions, thus conserving energy while providing timely information to the central control center [55]. Moreover, the design of communication protocols must consider the unique requirements of industrial applications, where the cost of delayed or outdated information can be substantial. In scenarios such as predictive maintenance, for instance, receiving timely updates on equipment status is critical for preventing failures and minimizing downtime. Research in this area has demonstrated the potential for using machine learning algorithms to predict when a device will likely need maintenance. This allows for proactive data collection and communication strategies that optimize information timeliness [69].

In addition to optimizing communication strategies, incorporating information timeliness considerations into the overall design of industrial systems can yield substantial benefits. For example, utilizing real-time monitoring and control systems that dynamically adjust their operational parameters based on information timeliness metrics can lead to more efficient resource allocation and enhanced system performance [45]. This adaptability is particularly valuable when operational demands change rapidly, necessitating real-time responses to varying conditions. Looking forward, the intersection of information timeliness, communication technologies, and industrial applications presents a rich field for exploration. Future research could benefit from further investigating the integration of advanced machine learning techniques to model information timeliness dynamics in complex industrial networks. Additionally, the development of hybrid communication strategies that leverage both traditional and emerging technologies could enhance the robustness of information timeliness management, ensuring that industrial systems remain efficient and responsive to evolving demands [4, 52, 60, 61, 76].

Information timeliness will only become more prominent as industries embrace digital transformation and IoT technologies. By prioritizing the minimization of information timeliness across various applications, organizations can ensure they make the most informed decisions, drive productivity, and maintain a competitive edge in an increasingly connected world. The ongoing exploration of strategies to manage information timeliness effectively will undoubtedly contribute to the success of future industrial systems, ensuring they are equipped to handle the complexities of modern operational environments while delivering timely and reliable information.

The multifaceted nature of information timeliness in UAVs, V2X communication, social networks, digital twins, and IIoT highlights its critical role in enhancing the efficiency and effectiveness of modern communication networks. As technology evolves, it is essential for researchers and practitioners to continuously explore innovative solutions that address the challenges posed by information timeliness, ensuring systems can maintain the freshness of data while optimizing resource usage. Insights from ongoing research will pave the way for more resilient, responsive, and intelligent communication frameworks across various applications, ultimately shaping the future of connected technologies.

1.4 Outline of the Monograph

While we have provided a general overview of the motivation for introducing the AoI metric, the remainder of this monograph is organized as follows.

Section 2 presents a general approach for quantitatively analyzing AoI under different queueing disciplines and transmission protocols, based on queueing theory. In particular, studies with a focus on the difference statistics of AoI of a single source with exogenous arrivals would be introduced, where classic queueing models, such as First-Come First-Serve (FCFS) and Last-Come First-Serve (LCFS) with and without preemption, are considered. Subsequently, the generate-at-will model and studies in which the generation of status updates can be controlled by the source are introduced. Then, a special analysis tool of AoI named stochastic hybrid systems is presented. AoI for discrete time systems is also introduced at the end of this section.

Section 3 constitutes one of the key components of this monograph, in which we elaborate on the analytical derivation of AoI in a wireless network. We particularly focus on the effects of interference on the age performance. To that end, we demonstrate how to leverage two widely used mathematical models, i.e., the protocol model and the physical model, to account for interference on the analysis of AoI in a general wireless network.

In Section 4, we go one step beyond the point-to-point transmission scenario to investigate a network where nodes can transmit in multi hops toward their destinations. We analyse the AoI performance under two typical situations: (a) the source nodes, as well as their destinations, are static and (b) all the nodes are moving rapidly in the network. The result of this section deepens the understanding of how AoI scales when a network grows in size.

In Section 5, we present results on AoI in single-source multi-server systems. We begin with infinite-capacity models under different queueing disciplines. Then, we present the results for finite-capacity models with random arrivals. After that, the results of zero-wait arrival models with random service times are introduced. Finally, we present some AoI results for models with deterministic service times.

In Section 6, we conclude this monograph.

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