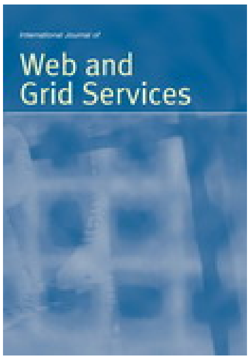

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A survey on the optimisation of age of information in wireless networks

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Abstract: This article comprehensively surveys the area of age of information (AoI) in the wireless networks and focuses on categorising and reviewing the current progress on AoI from an optimisation perspective. We first present the multiple definitions of AoI and its variants. Then, we give an overview of AoI-optimal sampling policies and packet management strategies from data source. We also summarise the work of minimising AoI in the case of resource-constraint source nodes, such as energy harvesting and UAV-assited sampling. We provide a summary of many kinds of scheduling policies for efficiently managing the use of resources in different network settings, which consist of various data sources and servers. In addition, we discuss some other applications focusing on the optimisation of AoI. Finally, we explore the performance of those policies in practical implementation and some potential future directions on AoI research.

Keywords: time-sensitive application; age of information; AoI; queue network; optimal policy; scheduling.

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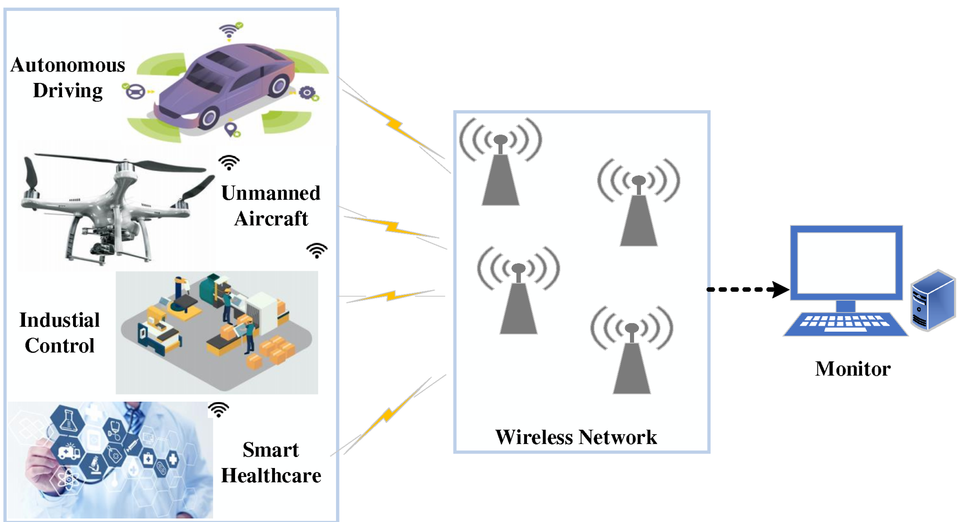
1 Introduction

Current communication technology provides an abundance of wireless connectivity methods and lays the foundation of our hyperlink of digital equipment and the development of automation technology. For example, future applications (such as autonomous driving, industrial control and smart medical, etc.) as shown in Figure 1, will increasingly depend on sharing time-sensitive information for remote monitoring and control. It is of paramount importance to maintain information freshness in such application domains, as outdated information will lose its real-time value and more likely to cause system failure or security risks. However, due to the unreliable and restricted of the wireless channels, it is impractical for the monitor continuously receives fresh information about every physical phenomena. In such case, the system has to make efficient use of the available channel resources to ensure the freshness of the information received by the destination.

The most relevant metrics of information freshness, such as delay and inter-delivery, are not suitable for characterising the freshness. Packet delay tracks the time elapsed from when a transmission starts to when that transmission is finished. It is an end-to-end metric that only ensures the timeliness of the information on an individual data packet and cannot characterise the information freshness from the destination. In addition, the optimisation strategy for delay commonly hopes to reduce the latency as small as possible. However, a more significant reduction of network delay also cannot guarantee information freshness from the perspective of applications, while inter-delivery time measures the time between two successive deliveries and only tracks the frequency of packet deliveries. The lower inter-delivery time means a higher arrival rate rather than fresher information. The higher arrival rate may cause transmission congestion, which will make an update very likely to experience long network delays and indirectly cause the information packet to become old. Both of two parameters compared above influence the freshness of updates received by the destination. Thus, a metric that implies two influential parameters (packet delay and inter-delivery time) was proposed to measure the information freshness in networks, called age of information (AoI). It is defined as the amount of time elapsed since the generation of the recently received packet.

From the observation above, we know that AoI is not only related to the transmission process of the data, but also related to the frequency of data generated by the source, thus there is a big gap between the optimisation of AoI and the minimisation of delay. Recently, researchers from both academia and industry have a strong interest in the optimisation of AoI. It includes optimisation operations performed on the data source (e.g., AoI-optimal sampling and packet management), optimisation during transmission (e.g., designing AoI-optimal scheduling policies), optimising AoI in some typical applications (e.g., caching and MEC), and optimising AoI in the system implementation (e.g., design an age-optimal communication protocol).

Figure 1 An overview of real-time application in wireless network (see online version for colours)



Subsequently, two survey articles have been published to provide overviews in the field of AoI. The first overview of AoI is presented by Abd-Elmagid et al. (2019a), which summarises the existing queuing systems in the AoI-aware IoT networks. It presents a review on the scheduling and optimising AoI-aware IoT networks. Thus, it is more suitable for research on the demand for information freshness in the IoT. A fairly comprehensive overview of AoI has been presented by Yates et al. (2021), which focuses on numerous contributions to AoI analysis, the process of AoI, some associated age metric, and basic methods for the study of AoI. Simultaneously, it gives the comprehensive and detailed summary of AoI in elementary queues and queuing networks, and further figures out how AoI is influenced by the resource-constrained source, different network settings, and sampling methods. At last, it concludes the efforts of employing AoI in various application areas and gives some future directions. Although there has some similarities in content with the above articles, The literature review in current paper gives the classification, analysis, and discussion of the literature from a completely new perspective of optimising AoI, it shall be a valuable addition to the existing survey literature of AoI and will benefit readers from the research community and business world by building up a systematic understanding of AoI.

This paper differs from existing surveys on AoI in the following aspects:

1 The current survey provides a deep summary of the most relevant metrics of AoI, those variants of AoI will enable researchers to have a more comprehensive understanding of AoI without digging through the details presented in many studies.

2 We provide an overview of some of key strategies that optimise AoI from source and provide a summary of related research work. Moreover, we explore the relation between the AoI and other emerging technologies including energy harvesting and UAV-assisted sampling.

3 We present a literature review on wireless channel resource allocation for the optimisation of AoI, AoI-optimal applications, and system implementations, which are the additional themes of the current paper.

4 We identify and discuss several research directions in the future, which can provide some ideas for follow-up researchers.

The rest of the paper is organised as follows. In Section 2, we present two different definitions and some variant metrics of AoI. Section 3 summarises various AoI-optimal strategies that focus on the data sources, and shows that how AoI is effected by the packet generation process and resource-constrained data sources. Then, we continue to make a review of channel resource allocation, with a focus on scheduling updates for different channel conditions (such as optimisation with assuming general channel conditions and special channel conditions); the AoI-optimal scheduling strategies and those corresponding literature are summarised and discussed in Section 4. Subsequently, the optimisation of AoI in four applications is discussed in Section 5. Section 6 summarises the several implementations of AoI and discusses the strengths and weaknesses of different platforms. In addition, a set of future direction areas of AoI are presented in Section 7. Finally, Section 8 concludes this survey.

2 AoI and its variants

2.1 Definition of AoI

AoI is a recently proposed metric, which accurately measures the time from the generation of the packet until the present. Generally, a system is considered to have two types of nodes, including the source node and destination node, as described in Figure 1. Each collected packet needs to be transmitted over a communication link to the destination. Let $\tau(t)$ be the time-stamp of the newest packet received by the destination at the time t, then, the instaneous value of AoI can be said as $\Delta(t) := t - \tau(t)$ at a time $t > \tau(t)$. From the instaneous age, we found that when the t is more closer to $\tau(t)$, the packet received by the destination is more fresher. In order to introduce the idea of AoI more vividly, we use Figure 2 to depict a realisation of AoI. Without loss of generality, we assume that the observation begins at $t = 0$ with an empty queue at the destination. The data source generates status updates at $S_1, S_2, ..., S_n$, and they are received at $D_1, D_2, ..., D_n$, respectively. In the absence of any updates, the AoI increases linearly in time and decreases just after an update is received.

2.1.1 Time-average AoI

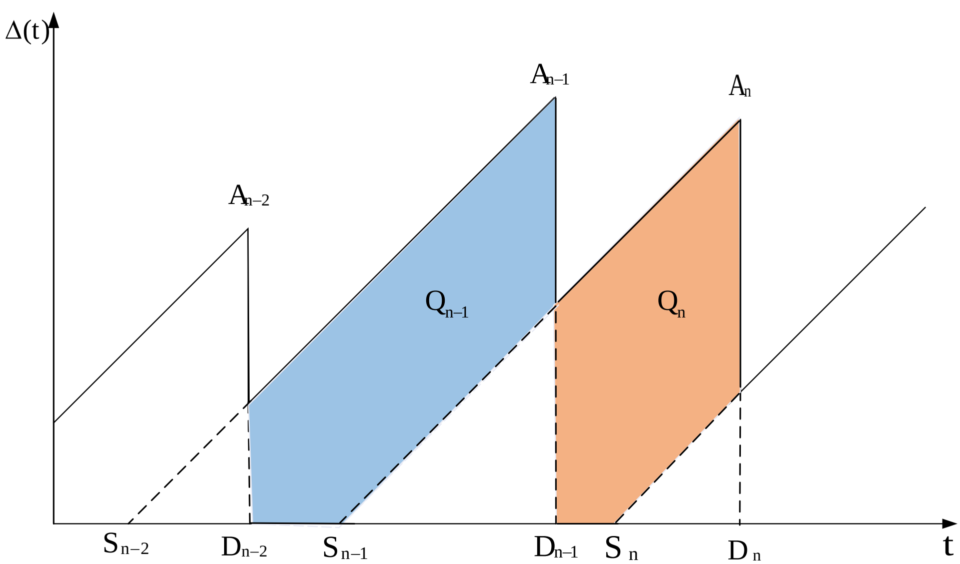
The area under the age graph normalised by time T gives the time average of AoI.

$$\bar{\Delta} = \frac{1}{T}\int_0^T \Delta(t)dt = \frac{Q_1 + \sum_{j=2}^{N(T)} Q_j + Y_n^2/2}{T} \tag{1}$$

$$\lim_{T\to\infty} \bar{\Delta} = \frac{1}{T}\sum_{j=2}^{K} Q_j \tag{2}$$

where $Q_j = \frac{1}{2}\left(2D_i - S_i - S_{i-1}\right)\left(S_j - S_{j-1}\right)$, and $K = \max\{n \mid r_n \leq T\}$, note that, we assume $X_j = (S_j - S_{j-1})$, which is the inter-arrival time between two successive delivery updates.

Figure 2 An example of age evolution (see online version for colours)



2.1.2 Peak AoI

The peak AoI as an alternative metric to the average AoI is obtained by observing the peak value in the sawtooth curve. It is the worst case of time average AoI, and can be easily calculated in most cases. The average peak AoI can be expressed as follows:

$$f_{\text{peak-age}}(\{\Delta(t), t \in [0,\infty)\}) = \frac{1}{K}\sum_{k=1}^{K} A_k, \tag{3}$$

where A_k means the j^{th} peak value of $\Delta(t)$ since time $t = 0$, as illustrated in Figure 2.

2.2 Variants of AoI

From the definition of AoI above, we may find that AoI increases linearly between any two consecutive update receptions. However, the performance degradation caused by information aging may not be a linear function of time. Thus, there are some other extended forms of AoI, for choosing an appropriate form to apply in a personalised model can make a different effect. Now, we take into account the following four variants of AoI:

2.2.1 Cost of update delay

Considering the time-varying pattern of the source signal and the dependence of two sampling points, a metric called the cost of update delay (CoUD) has been introduced by Kosta et al. (2020) for exploring the potential usage of AoI. The function of CoUD tracks the degree of the packet delay. Apart from defining the metric of CoUD, it also gives the definition of value of information of update (VoIU), which captures the degree of importance of the information received at the destination. CoUD is also the foundation of VoIU. Thus, we can use different CoUD functions to explore a wide array of potential uses of the notion of cost since other cost functions can represent different utilities. As a smaller CoUD corresponds to a more freshness of information, hereafter, it is desirable to minimise the average CoUD. While VoIU is the impact of a reception event on the monitor, a bigger value of VoIU represents the importance of an update. Thus, when the function of CoUD is the linear case, spare no effort to increase the value of VoIU and decrease the value of CoUD are more beneficial to the system because two of them are independent. However, for the exponential and logarithmic function of CoUD, the option for obtaining a better AoI performance is to make a trade-off between CoUD and VoIU.

2.2.2 Age of incorrect information

As can we see from the introduction above, a monitor is interested in obtaining accurate information about a remote process (e.g., a drone's position and velocity). To achieve this goal, most of the researches on the performance metric of AoI focus on calculating and minimising the long-term average AoI. It raises a question of whether the metric of AoI can be perfect enough for real-time remote process estimation. The answer to this question can stem from the fact that the AoI, by definition, does not capture the information content. Similarly, the AoI was shown by Jiang et al. (2019b) to be sub-optimal for minimising the status error in remotely estimating Markov sources. All those shortcomings of the standard AoI metric in real-time monitoring applications incentives to produce a new performance metric. Thus, a metric called the age of incorrect information (AoII) in the status updates system has been introduced by Kosta et al. (2017), which elegantly extends the definition of freshness updating to that of freshness 'informative' updating.

In this context, the term 'informative' refers to updates that bring new and correct information to the monitor. Specifically, AoII evolves when the estimated state $\hat{X}(t)$ in the monitor side is different from the actual state of the interest of source $X(t)$. Otherwise, the AoII does not evolve with $X(t) = \hat{X}(t)$. To obtain more accurate and fresh updating packets, Maatouk et al. (2020b) aim at finding the optimal transmission policy for minimising the average AoII on a transmitter-receiver pair communication network with an unreliable channel. They develop the optimal approach that proved to be a form of threshold-based policy. To illustrate the impact of sampling strategy on AoII, Kam et al. (2020) study the AoII metric in a time-delay system with feedback, and use different sampling strategies to monitor the situation with the symmetrical binary data source. After that, they derive the optimal sampling strategy for three performance metrics, including real-time error, AoI, and AoII. Different from above studies, Kriouile et al. (2021) deal with a more typical case in which a scheduler captures the states of multiple remote sources and each time selects a subset of them for updating, and minimises the mean AoII without knowing the instantaneous state of the remote sources.

2.2.3 Effective age of information

Similar to AoII, another metric called effective age of information (EAoI) is used to capture estimation errors, for which a smaller value of EAoI will produce a lower estimation error. To capture this result from the information structure of the signal and sampling patterns, Kam et al. (2018a) take several options of sampling mechanisms and signal models into account and investigate the influence of sampling policy on the AoI and estimation errors. Those also are the steps for the definition of EAoI. Based on the analysis of AoI and estimation error, Kam et al. (2018b) further present two effective age metrics, namely cumulative marginal error and sampling age, and observe that both of them display a monotonic relationship when concerning estimation error is for the Markov source system. Since the AoI is not equivalent to the accurateness of action or decision, Sang et al. (2017) propose a requesting replication scheme for a user to improve the EAoI of a single query. In contrast, Yin et al. (2019) use the term EAoI to characterise the AoI that is associated with decision-making. For providing users with the fresh decision information, two tractable scheduling policies for solving EAoI minimisation problem in the static and dynamic request environment have been put forward, respectively. Similarly, Chang et al. (2021) use the metric of EAoI to characterise the timeliness of information update in the control system. By analysing the throughput of wireless control systems and their relationship with average EAoI, they show the advantage of using EAoI and provide a guideline for URLLC network design.

2.2.4 Age upon decisions

From the AoI-related work, it is not difficult to find that AoI evaluate the freshness of updates at every epoch after they are received. However, in many updated decision systems, the freshness of updated information is only vital for some decision epochs. With the observation of these findings, Dong and Fan (2018) present the notion of age upon decisions (AuD) to quantifies the freshness of received updates at the epochs of interest, and show that the average AuD of an update decision system is independent of the decision rate when the arrival process, service process, and inter-decision process are all exponentially distributed. Thus, increasing the decision rate not bring the timeliness of decisions. For further investigating the AuD in a general update decision system, Dong et al. (2018) propose an efficient algorithm to search optimal distribution parameters for any given type of inter-arrival time distribution, but only provide the optimal distribution parameters for G/M/1 update decision systems. In addition, to investigate the impact of the type of arrival process and the decision process on the average AuD, Dong et al. (2020) present the performance of average AuD under different arrival processes and decision processes, including deterministic arrival process, periodic arrival process, Poisson decisions, and arbitrary decisions. It shows that if we make reasonable control on decision-making and periodical updates, the value of AuD will be declined and the average AuDs presented by Dong and Fan (2018) and Dong et al. (2020, 2018) are the same, they evaluate the freshness of received information at the decision epochs. The average AuD can be given by:

$$\bar{\Delta}_{\mathrm{d}} = \lim_{T\to\infty} \frac{1}{N_{\mathrm{T}}} \sum_{j=1}^{N_{\mathrm{T}}} \Delta_{\mathrm{d}}\left(\tau_j\right) \tag{4}$$

where N_T means the total decisions made during a period of T, $\Delta_{\mathrm{d}}\left(\tau_j\right) = \tau_j - U\left(\tau_j\right)$, τ_j is the decision time that j^{th} decisions is made.

Since lots of IoT systems not only as the platforms for information collecting and exchanging, but also the unattended decision-making ecosystem, therefore, the metric of AuD is very suitable for most IoT systems as it specially focuses on the decision epochs. Based on this, Bao et al. (2021) investigate the timeliness and utilisation of the received updates in an IoT-based update decision system, where a Poisson arrival process and a general service process are used. Especially, it focuses on the influences of both kinds of decision processes and service processes on the performance of AuD.

3 Optimisation from the perspective of data sources

3.1 Optimisation for general case

According to the definition of AoI, a factor that affects AoI is the time interval between the generation of successive status updates. This interval is controlled by the sampling frequency on the data source. Thus, a promising direction for minimising AoI is how to shorten the time interval between two successive status updates while ensuring a low transmission delay. There have two major research lines of the generation process for minimising AoI. One research line is to explore how to sample the underlying physical information for minimising the AoI intelligently. The other research line is managing the massive packets at the source, also called packet management.

3.1.1 Sampling

One critical problem of optimising AoI on the source or transmitter side is how to regularly take the samples, so that the freshness of the causally received packets at the monitor is maximised. In this section, we present various sampling strategies to manage time-sensitive information from the source. As summarised in Table 1, most works employ sampling controllable policies for the generation of samples, such as, zero-wait policy, ϵ-wait policy, randomised threshold policy and rate control policy. This is because the sampling controllable policies can effectively prevent samples from becoming stale when waiting for transmission.

Table 1 Sampling

Reference	*Sampling methods*	*Object*	*Remarks*
Bacinoglu et al. (2015) and Sun and Cyr (2018)	Arbitrary-sampling policy	Average AoI	Facilitate the analysis of AoI in the queue but uncontrollable
Sun and Cyr (2019), Yates (2015), Kaul et al. (2012b) and Costa et al. (2014b)	Zero-wait/ just-in-time	Average AoI and peak AoI	Achieve the maximum throughput and the minimum delay, but not always obtain optimal AoI
Sun et al. (2016)	ϵ-wait	Average AoI	A suitable waiting time for generating the next packet will contribute to obtaining the minimum AoI
Jiang et al. (2019b)	Randomised threshold	Average AoI	Propose a unified sampling and scheduling approach and derive a mean-field approach
Zhou et al. (2018), Ceran et al. (2018) and Fountoulakis et al. (2020)	Sampling rate control	Average AoI and resource allocation	Develop a dynamic algorithm to decide when to generate a new packet using optimisation theory

Table 2 Packet management

Reference	*Policies*	*Object*	*Remarks*
Costa et al. (2014a)	LCFS with preemptive and non-preemptive	Average AoI and peak AoI	General distribution of the service time
Zou et al. (2020)	Waiting or discarding	Average AoI and peak AoI	Heavy-tailed distribution
Yates and Kaul (2019)	LCFS-prioritised	Average AoI	Stochastic hybrid system technique
Moltafet et al. (2020b)	LCFS-S and LCFS-W	Average AoI	Can only preempt the packet from same source
Xu and Gautam (2021)	LCFS-prioritised	Peak AoI	Investigate the influence of ordering of priorities and service disciplines on the various scenarios
Wang et al. (2019)	FCFS with preemptive, FCFS with non-preemptive and FCFS with retransmission	Average AoI	Three policies is suitable under finite blocklength regime, and outperform the ones without packet management
Moltafet et al. (2021)	LCFS-S/LCFS-W/ LCFS-C	Average AoI	Use SHS technique to derive average AoI under three packet manage policies
Kaul et al. (2012a), Javani et al. (2020a), Najm and Nasser (2016), Bao et al. (2021) and Inoue et al. (2019)	Packet preemption and strategy/LCFS	Average AoI and peak AoI	Under a finite buffer

3.1.2 Packet management

With the massive IoT devices and numerous applications deployed in the wireless networks, a massive amount of data will be produced on those mediums or applications in an instant. How to manage those countless information packets or what policy should be taken to avoid outdated packet in the transmission process is a very challenging issue. Therefore, packet management techniques have been proposed to manage the traffic entering a network. The works are summarised in Table 2.

3.2 Optimisation with particular techniques

As the IoT promoted by the next-generation 5G network, considerable IoT applications show explosive growth and increasingly rely on sharing time-sensitive information for monitoring and control, such as autonomous driving, smart healthcare, smart factory, etc. The applications mentioned above are consist of massive sensing devices, which are usually wireless and equipped with limited energy. Thus, it is of great challenge to minimise AoI with energy constraint sensors. In order to address this problem, a number of research works (Yates, 2015; Farazi et al., 2018; Zheng et al., 2019; Bacinoglu et al., 2015; Bacinoglu and Uysal-Biyikoglu, 2017; Wu et al., 2018a; Moltafet et al., 2020a; Arafa et al., 2020b; Bacinoglu et al., 2015; Yang et al., 2016; Hatami et al., 2020; Bacinoglu et al., 2018; Farazi et al., 2018; Arafa et al., 2020a; Baknina and Ulukus, 2018; Feng and Yang, 2018b; Leng and Yener, 2019a; Arafa et al., 2018, 2019b; Feng and Yang, 2018c; Zeng et al., 2016; Galkin et al., 2019; Park et al., 2017; Ferdowsi et al., 2020; Liu et al., 2018; Tong et al., 2019; Abd-Elmagid and Dhillon, 2019; Jia et al., 2019; Tripathi et al., 2019; Li et al., 2019; Abedin et al., 2020; Abd-Elmagid et al., 2019b; Wu et al., 2018b; Ahani et al., 2020; Zhang et al., 2020b; Yi et al., 2020) focusing on the optimisation of AoI with particular techniques have been emerged, which can be divided into two categories, one is sending timely status updates by using energy harvesting technique, and the other is UAV-assisted data collection for saving sending energy of sensing devices.

3.2.1 Energy harvesting

For keeping track of the status, sensor nodes (SNs) should remain operational over long periods. However, resource constraints are ubiquitous in wireless networks, particularly in updating systems. When running on batteries, SNs have limited energy in their initial power storage, energy in this form maybe quickly run out. The limited lifetime of the SNs is one of the main challenges for transmitting packets as timely as possible. Thus, the notion of harvesting energy from the surroundings to recharge the batteries or power the SNs directly has been put forward. Recently, there are a significant number of works concerning AoI optimisation in energy harvesting communication systems under various considerations, including service time (time for the update to take effect), battery capacity, and channel assumption. Now, we list the following three primary considerations for optimisation of AoI:

- *Service time:* With different types of service time, the method and policy for optimisation of AoI will change within a certain range, thus, many researchers (Yates, 2015; Farazi et al., 2018; Zheng et al., 2019; Bacinoglu et al., 2015;

Bacinoglu and Uysal-Biyikoglu, 2017; Wu et al., 2018a; Arafa and Ulukus, 2017) focus on energy harvesting with different service times, such as random, zero, non-zero, and controlled. Random service time has been considered by Yates (2015), Farazi et al. (2018) and Zheng et al. (2019). Yates (2015) analyse the long-term average AoI with random service times and show that the lazy update policy outperforms the greedy policy. However, the optimal update policy remains open in such a setting. Farazi et al. (2018) derive the closed-form expressions for average age with the random service times and reveal the influence of system parameters (such as status update rate, energy arrival rate, service rate, and server battery capacity) on the AoI. Both zero service time and random service time are considered by Zheng et al. (2019) for calculating the average penalty function of AoI and average peak AoI, perspectively. Zero service time is also considered by Bacinoglu et al. (2015), Bacinoglu and Uysal-Biyikoglu (2017) and Wu et al. (2018a), Bacinoglu et al. (2015) consider a problem with finite energy storage capability but an infinite time window horizon. An optimal online status update policy for an energy harvesting source with various battery sizes is also investigated by Bacinoglu and Uysal-Biyikoglu (2017). In addition, Wu et al. (2018a) considers offline and online policy with zero service times. Arafa and Ulukus (2017) present an offline policy to minimise AoI in a two-hop relay channel.

- *Battery capacity:* Since the idea of acquiring energy from nature to power the wireless transmitters has appeared, it intrigued some researchers on designing the transmission scheduling for the optimisation of AoI under both settings of infinite battery and finite battery. Specifically, the infinite battery capacity case is studied by Wu et al. (2018a), Arafa et al. (2020b), Bacinoglu et al. (2015) and Yang et al. (2016), whereas Wu et al. (2018a), Hatami et al. (2020), Bacinoglu et al. (2018), Farazi et al. (2018) and Arafa et al. (2020a) consider the case of finite battery capacity. For the infinite battery case, Wu et al. (2018a) investigates the influence of sensing costs on AoI and finds that the best-effort uniform updating policy is optimal when the channel condition is perfect. Arafa et al. (2020b) focus on both offline and online policies with infinite battery, and they aim at obtaining the minimisation of the time average AoI. By obtaining the knowledge of the current age and current energy level of the sender side, the optimal threshold policy is developed by Bacinoglu et al. (2015). Furthermore, Yang et al. (2016) investigate the trade-off between the number of updates and service time under the infinite battery. To fully explore the impact of battery capacity on the freshness of status update packets, Wu et al. (2018a) study the optimal online policies for an energy harvesting sensor under considering three scenarios (infinite, finite, and one unit only). When the battery size is finite, the optimal policies are shown to have certain threshold structures. Arafa et al. (2020b) investigate the performance of online threshold policies for the finite battery case with zero service times, and they give the proof that the threshold policies considered in this article are optimal in continuous time, but with no proof of optimality. An interesting method is followed by Bacinoglu et al. (2018) who consider that source need to send extract encoded information to the receiver with one unit size battery, and the trade-off between the achievable message rate and the achievable average AoI is also studied. Furthermore, Farazi et al. (2018) consider a sensor with a finite battery and employ tools from stochastic hybrid systems to analyse the long-term average AoI. Arafa et al. (2020a) consider two energy arrival models, including random battery recharge model and incremental battery recharge model, which is under the assumption of finite battery capacity.

- *Channel assumption:* Optimising AoI in energy harvesting networks with the assumption of perfect or noisy channel is discussed in some references (Baknina and Ulukus, 2018; Feng and Yang, 2018b; Leng and Yener, 2019a; Bacinoglu and Uysal-Biyikoglu, 2017; Feng and Yang, 2018a; Arafa et al., 2018). Generally, noise is normal for the channel. Thus, many authors (Baknina and Ulukus, 2018; Feng and Yang, 2018b; Leng and Yener, 2019a; Bacinoglu and Uysal-Biyikoglu, 2017; Feng and Yang, 2018a) devote themselves to study the energy efficiency in such a system with noise channel. Timely coding over erasure channels is studied by Baknina and Ulukus (2018), where two types of channel coding have been considered to encode the status update symbols for coping with the effects of the erasures in the channel and the uncertainty in the energy arrivals. Feng and Yang (2018b) consider a scenario where the channel condition is not always perfect, Leng and Yener (2019a) focus on the impact of imperfect spectrum sensing on AoI minimisation and formulates it as an infinite horizon partially observable Markov decision process (MDP). Bacinoglu and Uysal-Biyikoglu (2017) design an optimal online status updating policy for minimising the long-term average AoI at destination with no channel feedback, and show that the online updating policy to be optimal in the case of perfect channels and update failures arise. This model is then extended by Arafa et al. (2019b) and Feng and Yang (2018c), which consider the knowledge of erasure feedback information. Wu et al. (2018a) investigate the optimal online status update policies with updating erasures under both cases, in which perfect feedback or no updating feedback is available to the source. Under an ideal channel model, Wu et al. (2018a) and Arafa et al. (2020a) show the optimal policy when the channel between sensor and recipient is perfect.

3.2.2 UAV-assisted data collection

Although the 5G communication method greatly improves the transmission efficiency, the data samples generated by all devices cannot be transmitted to the BS simultaneously. The reasons can be summarised as follows: the potentially large number of SNs, constraint coverage in specific places, the limited energy capacity of sources, as well as the limited transmission capacity between SNs and the destination (BS, edge and cloud). IoT network's intrinsic nature faces scalability challenges for the countless IoT devices that will generate enormous sensing data for the IoT applications. Zeng et al. (2016) use the unmanned aerial vehicle (UAV) as a mobile data collector or a relay attracts many researchers from academic and business. By utilising its high mobility, Galkin et al. (2019) use UAV to collect data from the SNs energy-efficiently as it can fly close enough to SNs for data collection. Thus, the link between SNs and the UAV is reduced significantly, the transmission energy of each SN can be saved by Park et al. (2017). It is easy to see that UAV-assisted data collection reduces the SN's transmission energy and has a significant influence on the AoI of each SN. Because of this, a considerable number of works investigated the age-optimal trajectory planning problem in UAV-assisted data collection sensor networks. Generally, UAV is used as a mobile relay between a source-destination pair to minimise the maximum AoI by Tong et al. (2019). According to whether the UAV visits all SNs, works related to the UAV-assisted optimising AoI can be divided into two following groups:

- *Nodes treated fairly:* Liu et al. (2018), Tong et al. (2019), Abd-Elmagid and Dhillon (2019), Jia et al. (2019), Tripathi et al. (2019) and Li et al. (2019) assume that all SNs are equally important and need to be visited all by the UAV before flying back to the BS. Liu et al. (2018) design two age-optimal trajectories (ave-AoI-optimal and max-AoI-optimal) for minimising two different ages. By assuming Euclidian distances between the SNs, both dynamic programming and genetic algorithms are employed to obtain the two age-optimal flight paths, respectively. Dynamic programming-based methods are proposed by Tong et al. (2019). UAV used as a relay is studied by Abd-Elmagid and Dhillon (2019), where an iterative algorithm is proposed for coping with the problem of jointly optimising the flight path as well as energy and service time allocations for packet transmissions. Jia et al. (2019) minimise the average AoI of SNs under energy constraint. Furthermore, Tripathi et al. (2019) consider that a UAV flies to along the randomised trajectory, and study an AoI-optimal data collection and dissemination problem on graphs. Since the channel link between the sensor and UAV not always perfect, encouraged by this factor, Li et al. (2019) study the AoI that influenced by the UAV trajectory.
- *Nodes treated unfairly:* Although every node treated fairly for data collection can simplify the problem-solving, but it is not always suitable when the time-sensitivity of packet information collected by SNs is different. Thus, nodes with higher timeliness demand need treat prioritised. Ferdowsi et al. (2020), Abd-Elmagid et al. (2019b) and Yi et al. (2020) consider the SNs differ in weights. Ferdowsi et al. (2020) and Abd-Elmagid et al. (2019b) consider UAV data collection from a set of energy-constrained SNs, and aim at minimising the weighted sum of AoI. The problem is modelled as a finite-horizon MDP with finite state and action spaces by Abd-Elmagid et al. (2019b), the reinforcement learning (RL) algorithm is proposed for solving the curse of dimension. This work is then extended by Yi et al. (2020), which consider the energy consumption of the UAV and focus on designing the AoI-optimal flight path. Jia et al. (2019) optimise AoI under energy constraint of SNs. They aim at finding a new data acquisition method by jointly considering the node visiting order and data acquisition mode. In addition, learning-based algorithms are also utilised by Abedin et al. (2020) and Ahani et al. (2020) for age-optimal UAV routing. Data collection via multiple UAVs is studied by Abedin et al. (2020) to maximise energy efficiency and data freshness. When considering the fair performance among users, Wu et al. (2018b) use multiple UAV-mounted base stations for serving users on the ground, and the iterative algorithm is proposed for solving the problem of joint trajectory and adaptive communication scheduling. Different from these studies that account for a battery capacity of one trip, Ahani et al. (2020) investigate the route scheduling of UAVs with battery recharging, which can enable the UAV to perform multiple trips. Besides, there is a trade-off in the time cost between UAV sensing and UAV transmission for a given length of time. Zhang et al. (2020b) propose a policy that combination of ground SN and flight

path to make a balance between the upload time of the SNs and flight time of the UAVs using dynamic programming in different scenarios.

4 Optimisation from the perspective of channels

The channel between source and destination also can be named link, server, and network, which is a key part of the source-destination pair in the status update system. Similar to the optimisation of AoI at the source, There are some strategies and methods for minimising AoI under different channel conditions. Roughly, we summarise works that optimise AoI under two types of channel conditions: one is that the channel has a fixed probability for data transmission, which is called general channel conditions here; the other can be called special channel conditions where the channel state have special property.

4.1 Optimisation with assuming general channel condition

This section will overview the works that focus on optimising AoI in queuing networks with assuming general channel conditions. AoI optimising in such channel conditions can be further evolved into scheduling problems with different network settings, such as multiple sources and multiple servers. Now, we discuss how to schedule update for minimising AoI in the two types, multi-sources with a sharing server queue and multi-sources with multi-server queues, respectively.

4.1.1 Multi-sources with a sharing server queue

A large number of researchers (Yates and Kaul, 2012; Moltafet et al., 2019; Huang and Modiano, 2015; Najm and Telatar, 2018; Chen et al., 2019; Kosta et al., 2018; Pappas and Kountouris, 2019; Fountoulakis et al., 2021; Sun et al., 2021) make significant efforts on the optimisation of AoI in multiple sources with a sharing server queue system. According to whether the source node is homogeneous or heterogeneous, the works can be divided into two categories: optimisation with homogeneous sources and optimisations with heterogeneous sources.

- *Homogeneous sources:* Depending on the single-source setups, Yates and Kaul (2012) firstly study the performance of AoI in a multi-sources with a sharing server queue network. They derive the average AoI for a multi-source M/M/1 FCFS queuing model. The closed-form expression of average AoI for such model is derived by Moltafet et al. (2019) and is minimised by Huang and Modiano (2015) by optimising the rate of each source. The expression of average peak AoI in a multi-source M/G/1/1 preemptive queuing model is derived by Najm and Telatar (2018). Those works have a common feature, as shown in Figure 3, each source generates updates as an independent stochastic process with rate λ_i and service time S of an update has expected value $1/\mu$. Therefore, source has provided load $\rho_i = \lambda_i/\mu$ and the total provided load is $\rho = \sum_{i=1}^{N} \rho_i$.
- *Heterogeneous sources:* There is a line of works (Chen et al., 2019; Kosta et al., 2018; Pappas and Kountouris, 2019; Fountoulakis et al., 2021; Sun et al., 2021)

that consider the sources are heterogeneous, and there has a interplay of AoI with another metric, such as throughput or latency, shown in Figure 4. For example, Chen et al. (2019) investigate the performance of AoI in a multiple access channel with heterogeneous traffic nodes, including bursty traffic node and energy harvesting node, and then derive two expressions of delay and AoI, respectively. Kosta et al. (2018) investigate a scenario where one high-priority AoI-oriented source competes with N throughput-oriented sources, and analyse the AoI performance of ALOHA protocol. Then, Pappas and Kountouris (2019) propose an age-aware policy for improving the information freshness while satisfying timely throughput constraints. In Fountoulakis et al. (2021), there are only two users, one is AoI-oriented, and the other is delay oriented. Average AoI in a two-user wireless multiple-access channel with multi-packet-reception (MPR) capability is studied in this article. For further improving information freshness, this model is extended by Sun et al. (2021), who consider a packet with deadlines. They also reveal a trade-off between the average AoI of one source and the drop rate of another source.

Figure 3 Independent sources send status updates through a shared queue to a destination (see online version for colours)

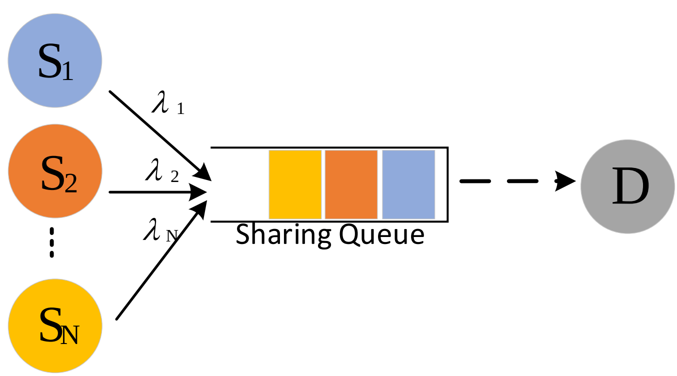
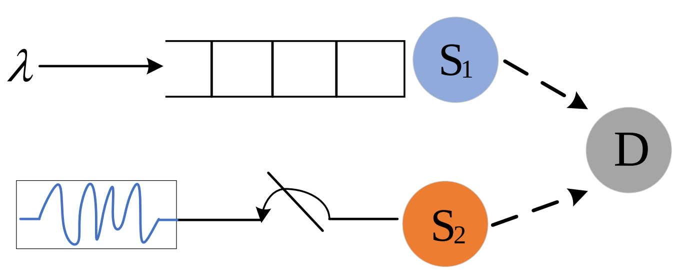


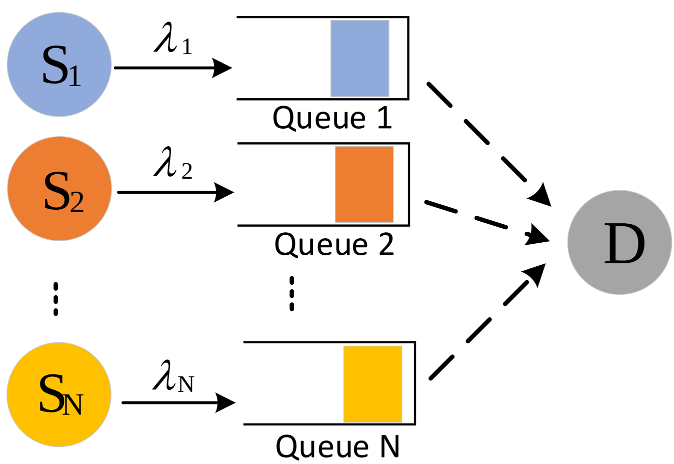
Figure 4 Heterogeneous model: for example: source 1 has external traffic with stringent delay requirement, while source 2 samples a status update each slot (see online version for colours)



4.1.2 Multi-sources with multi-server queues

One of the most fundamental problems in wireless networks is the shared medium, such as sharing channel. Many works focus on designing and analysing delay-or throughput-oriented multiple scheduling policies. However, the strategies may no longer be optimal when the AoI is concerned. Thus, a lot of effort has been put into optimising AoI in multi-source multi-server queues. In this subsection, we summarise various policies that schedule the communication resources between the sources and destination for minimising AoI, as showed in Tables 3 and 4. Depending on where the decision is made, the scheduling policies can be divided into two types. One type of policy that most works considered are centralised policies or pull-based policies (Table 3), which aim at avoiding network collision by scheduling senders one by one. The opposite of centralised scheduling policy is called distributed or push-based model (Table 4), where the sources decide when they want to send updates in a distributed fashion. As illustrated in Figures 3 and 5, there are two queuing forms for two above types of scheduling strategies, multiple sources at a sharing queue and multiple sources at many individual queues, respectively. For the first form, it considers that the updates have random service time, minimising AoI in such scenes proven to be challenging. For the second form, the difference of queuing discipline at source and packet arrival rate significantly impacts the AoI.

Figure 5 System model: multi-source multi-server (see online version for colours)



4.2 *Optimisation with special erasure channel*

Recently, coding for minimising AoI has received increasing attention in wireless networks. In this section, we summarise the optimisation of AoI under the erasure channel condition (Feng and Yang, 2019a; Bhambay et al., 2017; Bobbili et al., 2020; Javani et al., 2020b; Arafa et al., 2018; Baknina and Ulukus, 2018; Yates et al., 2018; Feng and Yang, 2019b, 2018a), the main research content of those researchers can be roughly divided into two classes. One type is that the monitor employs an error-free feedback channel to notify the source of symbol erasures. For example, Feng and Yang (2019a) employ an adaptive coding method to improve the information freshness of users with two different AoI demand levels. Subsequently, the differential encoding method is utilised by Bhambay et al. (2017) to improve information freshness with variable codeword length. In addition, Bobbili et al. (2020) investigate the relationship between information freshness and decision making, and show that the average AoI decrease with the increase of the feedback rate in a hybrid ARQ scheme for a range of codeword lengths. Furthermore, it is extended by Javani et al. (2020b) for finding the optimal tolerance when the erasure probability is close to zero.

Table 3 Centralised scheduling

Reference	*Policies*	*Remarks*
Skinner et al. (2016)	Replication scheme, max-age matching and iterative max-age policies	Trade-off between the freshness at the sensor and response time mechanism
Tripathi and Moharir (2017)	RR-ONE and Lyapunov optimisation-based and max-AoI-weigh policy	Explore the energy-efficient variants in terms of two policies
Sombabu and Moharir (2018)	SQRT-weight policy	Minimise the cost function of weighing AoI
Jhunjhunwala et al. (2020)	Optimal average cost schedule (OACS) and optimal maximum cost schedule (OMCS)	Map the scheduling problem to the problem of finding the minimum cycle in directed graphs, but this strategy is computationaly expensive
Kadota et al. (2018)	Randomised policy max-weight policy, Whittle's index policy and drift-plus-penalty policy	Propose four low-complexity policies to minimise AoI with minimum throughput constraint, but it is not applicable in the packet random arrivals
Saurav and Vaze (2021)	Stationary randomised policy and threshold policy	Consider a joint scheduling problem of AoI and energy consumption
Hsu (2021)	Whittle's index policy	Allow stochastic packet arrivals and design a scheduling strategy for zero-buffer cases
Sun et al. (2020)	Index-prioritised random access (IPRA)	Permit arbitrary buffer management schemes

The other type is considered that the source has no feedback knowledge about reception status. Whether to transmit a status updating mainly depends on the current channel status and the instantaneous AoI. Specifically, Arafa et al. (2018) investigate the problem of how to minimise the long-term average AoI of an energy harvesting sensor that sends status updating through an erasure channel, and propose a threshold-greedy policy for solving it. Then, Baknina and Ulukus (2018) utilise maximum distance separable (MDS) codes and rateless erasure codes to encode the status update symbols in the energy harvesting erasure channel, and show that rateless coding with save-and-transmit outperforms MDS based on schemes. In order to better adapt to timely updates in erasure channels with feedback information or without feedback information, Yates et al. (2018) study the long-term average AoI under MDS and rateless coding strategies and characterises AoI in single and multiple monitor systems. Different from depicting the long-term average AoI under the given coding scheme, Feng and Yang (2019b) focus on the optimisation of AoI for an erasure channel with rateless codes, and design the optimal scheduling strategy based on the instantaneous feedback. Feng and Yang (2018a) aim at designing an optimal online packet updating strategy to minimise the average AoI of a sensor that subjects to the energy constraint, and then propose two policies under two different cases. It is shown that the best-effort uniform updating (BU) is optimal without available feedback and the best-effort uniform updating with retransmission (BUR) strategy is similar optimal with available feedback. Bhambay et al. (2017) investigate the periodic data transmission policy by exploiting the temporal correlation under no feedback information and show that the fixed-length differential encoding strategy can improve the information freshness with available feedback information.

Table 4 Distributed scheduling

Reference	*Access protocol*	*Policies*	*Remarks*
Jiang et al. (2018)	CSMA	Index-prioritised random access policy	Optimise the CSMA access mechanism
Jiang et al. (2019a)	CSMA	RR-ONE and Lyapunov optimisation-based and max-AoI-weigh policy	Prove that the RR-ONE is asymptotically optimal
Kaul et al. (2011)	CSMA	Rate adaptation algorithm	Propose an optimal average back-off time point, but not give the closed-form results
Maatouk et al. (2020a)	CSMA	Sequential convex approximation (SCA) approach	Use a convex formulation to find the optimal back-off time of each link
Talak et al. (2018)	ALOHA	Optimal distributed policy	Obtain the relation between the attempt probability and the optimal AoI, and find the optimal probability
Chen et al. (2020b)	Slotted-ALOHA	Stationary age-based thinning	Slotted ALOHA-type algorithms are age-optimal when the arrival rate is below $\frac{1}{eM}$, the age-based policy is used when the arrival rate is larger
Chen et al. (2021)	Slotted-ALOHA	Age-based threshold policies error-based threshold policy	Two classes of policies are investigated under two case
Gopal and Kaul (2018)	ALOHA	Scheduling with feedback	Consider an unreliable channel and show that ALOHA-like access leads to AoI is worse when the different nodes with the same AoI
Kadota and Modiano (2021)	Slotted-ALOHA and CAMA	Theoretical analysis, simulation, implement the system	Investigate the effect of arrival rate, network size and access probability on the AoI

5 Optimisation from multiple applications

5.1 AoI-aware caching

In this section, we review the works that apply the metric of AoI in caching networks. Works are related to AoI-aware caching can be divided into two categories.

One type considers the information freshness that a user or a recipient can obtain some needed packet from the cache rather from the source (Zhang et al., 2020a; Pappas et al., 2020; Gao et al., 2012; Yang et al., 2019; Kam et al., 2017), e.g., a local cache or an intermediate cache. An interesting scheme that maintains cache freshness has been proposed by Zhang et al. (2020a), which basic idea of the scheme is to let each caching node responsible for a specific set of caching nodes, and maintain cache freshness in a distributed and hierarchical manner. Gao et al. (2012) consider that the update duration is changing with file and file's AoI, and an updated policy relied on the file popularity has been designed to minimise the average AoI of all files. Since the capacity-constrained link limits the ability of cache to hold the latest version of each item at all times, thus, Yang et al. (2019) design an updated policy for minimising the AoI of items at the local cache, and the policy mainly focuses on the content changes. Although the various strategies proposed above can greatly improve the freshness of files at the cache, service delay is still a problem that cannot be ignored. A freshness-aware refreshing scheme has been proposed by Kam et al. (2017), which balance the service delay and content freshness. Specifically, if the AoI exceeds a certain threshold, the cached content items will be refreshed to the up-to-date version, and the approximate forms reveal a trade-off relationship of AoI and delay with respect to the refreshing window, the only downside is that the capacity of the base station is assumed to be unlimited and can cache all contents.

Another type considers the AoI at the user that connected to the source via a single cache or multiple caches (Tang et al., 2020; Zhang et al., 2019; Yates et al., 2017; Yang et al., 2019). This is different from the studies that consider files freshness from the perspective of cache. For example, Tang et al. (2020) focus on the relationship between the popularity and the freshness of content, and propose a dynamic cache management policy for selecting suitable cache content with a higher hit rate. This policy focuses on the changes in popularity, which is much different from the policy that is mainly focusing on the content changes (Yang et al., 2019). A trade-off between storing the information at the cache and directly obtaining the packet from the source is investigated by Yates et al. (2017), which aim at finding the analytical expressions for the average freshness of the files at the user. In order to better meet the user requirements for different applications, such as time-critical or high throughput, Zhang et al. (2019) propose a service-oriented hierarchical soft slicing framework for cache-enabled vehicular networks by considering two typical on-road content services, including driving-related context information service (CIS) and bandwidth-consuming infotainment service (IS). The analysis of throughput of the IS slice, the content freshness, and delay performances of the CIS slice shows that the soft slicing method can enhance the IS throughput while guaranteeing the same level of CIS content freshness and service delay.

5.2 AoI optimisation with learning

The scheduling problem of the age minimisation is NP-hard in general. One reason is that prior knowledge about the network conditions or packet transmission process is almost unavailable in actual situation. The other reason is the complexity of time-varying networks. Thus, as a multi-domain interdisciplinary subject, machine learning is widely used in many typical networks.

Particularly, RL has been widely used in such scheduling problems. The first employment of RL to the AoI-optimal scheduling problem is considered by Ceran et al. (2018), which utilised a SARSA algorithm for scheduling packet transmission on a link using hybrid ARQ, and more recently extends to a multi-user network (Ceran et al., 2021). Elgabli et al. (2019) consider optimising AoI in an ultra reliable low latency communication, and use the RL to make trade-off between minimising the expected AoI of each node and maintaining the probability that the AoI of each node exceeding a predefined threshold. An optimal online sampling policy by jointly optimising the wireless energy transfer and AoI-optimal policy is proposed by Abd-Elmagid et al. (2020), which uses a deep RL algorithm for high-efficient computing. For the multiuser networks, Ceran et al. (2021) address the problem of how to schedule the status updates in a multiuser network under both standard ARQ and HARQ protocols, a RL approach is introduced to address the scheduling decision problem without any prior channel status information. For multiple flows network, Beytur and Uysal (2019) formulate the problem of designing AoI-optimal scheduling with a single server, by applying the RL method to achieve scheduling decision. For considering energy-constrained ground nodes, researchers (Yi et al., 2020; Abd-Elmagid et al., 2019b) employ deep RL framework for optimising the UAV's flight trajectory while scheduling status update packets with the optimisation of AoI. The employment of DQN to AoI minimisation for sample generation problem is considered Abd-Elmagid et al. (2019b) on an experimental end-to-end IoT setup with a single source-destination pair running a TCP/IP connection. The scheduling decisions with multiple receivers over a perfect channel is studied by Hsu et al. (2017), where the goal is to learn packet arrival statistics, then then Q-learning is used for a generate-at-will model. Policy gradients and DQN methods are also employed for the optimisation of AoI in a wireless adhoc networks by Leng and Yener (2019b), in which each node continuously broadcasts its status information and receives updates from other places. Since methods like DQN and policy gradients can only handle discrete and continuous actions, respectively. Akbari et al. (2021) apply compound action actor critic (CA2C) DRL method to supports both discrete and continuous actions, thus for optimising the average AoI as well as transmission and VNF placement cost.

Different from the using of RL in AoI optimisation, there also has some other learning methods. Yang et al. (2020) propose a scheduling policy which jointly considering the staleness of the received parameters and instantaneous channel states to improve the running efficiency of federated learning. Ceran et al. (2021) apply the optimisation of AoI in multi-access networks to solve the issue that how to deal with general diversified QoS requirements, and derive a distributed policy learning based state-driven multiple access scheme. A D2D link scheduling problem is considered by Liu et al. (2021), which utilises the deep learning method to deal with such non-convex scheduling problem.

5.3 AoI optimisation with gaming

Transmission interference caused by multiple nodes sharing same channel is a common thing in the wireless networks, one way to reduce the occurrence of such conflicts is to introduce a scheduler to avoid inter-node conflicts. However, this approach will bring huge communication costs when nodes are increased on a large scale. Game theory, as a theoretical framework that produce optimal decision-making of independent and competing actors in several settings, can be applied in the real-time status update system that exist of resource contention of two or more players.

A real-time status updates system in a adversarial setting is considered by many researchers (Xiao and Sun, 2021; Garnaev et al., 2019; Wang et al., 2021; Nguyen et al., 2017a, 2017b; Saurav and Vaze, 2020), AoI by jamming the channel. For example, Xiao and Sun (2021) model the interaction between the attacker and the system as a dynamic game in a general networks and prove there exists a stationary equilibrium in the game. The proof of stackelberg utility function exceeds the Nash function by Nguyen et al. (2017a). The effect of Rayleigh fading on the power cost of two players is investigated by Nguyen et al. (2017b). In order to decrease the cost caused by the centralised scheduler, Saurav and Vaze (2020) focus on a distributed paradigm, where each sensing nodes autonomously make decisions depending on its own current time-averaged age, average transmission cost and past process of packet transmission. Garnaev et al. (2019) model the UAVs hostile interference as a game between a UAV transmitter and an adversarial interferer, and prove that in contrast with the Nash equilibrium it exists multiple Stackelberg equilibrium. Furthermore, a mean field game method to optimise the positions of UAVs for minimising the AoI in ultra-dense UAV networks is proposed by Wang et al. (2021).

Some researchers (Badia et al., 2022; Badia, 2021) investigate the game method for optimising AoI in access protocols of slotted ALOHA. Badia et al. (2022) consider the inefficiency of slotted ALOHA when the number of nodes is large and focus on the transmission probability of a specific terminal node, and then choose to optimise the individual objective. Badia (2021) capture the strategic choices of the nodes by using the game theory, and aim at minimising the sum of a transmission cost and the average AoI, and show a better coordination among the nodes.

In addition, the coexistence of two different access mechanisms networks considered by Gopal and Kaul (2018) and Gopal et al. (2019). Gopal and Kaul (2018) model a coexistence of DSRC and Wi-Fi networks as a game where DSRC network want a small AoI while the Wi-Fi want a large throughput. The Nash and Stackelberg equilibrium strategies between two players has been investigated. The coexistence of AoI and throughput optimising networks is investigated in another hybrid access mechanism (Gopal et al., 2019), where model the coexistence network of CSMA/CA and Wi-Fi as a repeated game framework. They then investigate the evolution of the equilibrium strategies over time, and show that throughput optimising networks share spectrum with an age optimising networks will beneficial for the throughput optimising networks. Further, they also show that the age optimising network nodes occasionaly constraint by the equilibrium strategy of the age optimising networks for ensuring freshness of updates.

In ordet to tackle the obstacle of insufficient spectrum resource and communication overhand, Ning et al. (2020) use MEC to enable 5G health monitoring, and formulate a cooperation game and non-cooperative game for intra-wireless body area networks (WBANs) and beyond-WBANs, respectively. The Nash equilibrium has been admitted to solve the non-cooperative game by a decentralised approach, they finally derive the upper bound of the time complexity and demonstrate the effectiveness of their algorithm.

5.4 AoI optimisation in MEC

MEC techniques (Al-Fuqaha et al., 2015; Xu et al., 2014) have been applied to optimising the AoI in different applications (Xia et al., 2020; Gong et al., 2020; Xu et al., 2020; Zou et al., 2021a, 2019, 2021b; Alabbasi and Aggarwal, 2020; Xu et al., 2021; Wu et al., 2021; Chen et al., 2020a; Arafa and Ulukus, 2017; Zhu et al., 2021; Arafa et al., 2019a). The use of MEC technology to optimise AoI can be divided into two categories, one is focuses on reducing the transmission time by the pre-processing method, and the other is to extract the status update information from raw data.

5.4.1 Pre-processing

With the emergence of MEC, data processing can not only be processed at the data source, but also transmitted to the edge for further processing. For example, Zou et al. (2019, 2021b) address various computation-communication queues with a single transmit serve. Gong et al. (2020) consider AoI minimisation with MEC under a given deadline and model the procedure of computing and transmission as a tandem queue. The simulation results show that the no-wait computing policy can obtain optimal performance. Xu et al. (2020) also consider the tandem queue of computing and communication, but with an aggregator that not only forwards the packets but also regenerates the packets with different sizes, such as for preprocessing the packet, which would alter the service time of the second queue. The computation time has a general distribution (Zou et al., 2021a). Alabbasi and Aggarwal (2020) investigate a similar tradeoff under different system models, and show that the processing and transmission phase impact both the AoI and the completion time. Thus, offline and online strategies for optimising both network and computing scheduling is developed for it. Xu et al. (2021) characterise the setting that the packets generated by IoT sensor either can be directly transmitted to the data centre for processing or be preprocessed by the MEC server through determining the probability of preprocessing and the ratio of sharing transmission resources on two different paths appropriately, the average AoI and average PAoI can be minimised. Xia et al. (2020) jointly consider the query evaluation cost, computing resource, and the AoD of queries, aim at minimising the expected overall AoD of all evaluated queries. MEC-assisted AoI-aware optimisation has also been expanded to other research directions such as big data, federated learning, industrial internet of things (IIoT), and energy harvesting networks. Arafa and Ulukus (2017) investigate the optimal offline scheduling strategy in energy harvesting two-hop relay networks where the two hops can not transmit simultaneously, thus, the operation of transmission and computation can be scheduled simultaneously. Different from the simultaneous option of computing and transmitting in the scheduling process, Wu et al. (2021) study the resource scheduling problem with low-power wireless devices in IIoT, and design a set of age-aware virtual queues to tackle the challenge of time-coupling uplink/downlink decisions while guaranteeing the freshness of offloaded information.

5.4.2 Extract status update information

Most existing works above consider that the real-time systems can be immediately updated when it is receiving a new packet data without being processed. However, for some real-time applications, the packets received by them need to be processed to expose the embedded status information. Due to the data collector have limited battery capacity and computation ability, it is not feasible for those devices to process computation-intensive packets while making sure that real-time applications can receive fresh status updates. To address this challenge, MEC has been used for solving the contradiction between computation-intensive packets and the limited resources of data collectors. Song et al. (2019) employ age of task to evaluate the temporal value of computation tasks and propose a lightweight age-based task scheduling and computation offloading algorithm. Kuang et al. (2020) focus on the analysis of AoI for computation-intensive messages with MEC and propose three computing strategies, including local computing, remote computing, and partial computing, which all follow the FCFS principle, finally, it gives the numerical guidance when the performance of remote computing better than the local computing. Considering the probability of packets becoming stale when waiting in the computing queue, a one-packet-buffer replacement policy is adopted in the computing stage for ensuring that packets received by edge servers are maintained fresh (Gong et al., 2019; Zhong et al., 2019). For the situation where task data arrives synchronously, Zhong et al. (2019) consider the real-time video applications that often need timely updates with MEC to ensure the service quality. Therefore, resource competition among different video streams can bring outdated information. In order to tackle this challenge, a greedy scheduling strategy has been developed for choosing the next user with maximum weighted age reduction. All studies presented above are focusing on one single MEC node. For the MEC system with multiple MEC nodes, Liu et al. (2020) focus on minimising the AoI by jointly optimising the generation of the packet and the resource allocation, and use the Lyapunov optimisation technique to address the time coupling of packet generation and computation offloading decisions.

6 Opitimisation in system implementation

Most of the works above is based on theoretical research on the optimisation of AoI, there are a few works (Kaul et al., 2011; Shreedhar et al., 2018, 2019b, 2019a, 2021; Han et al., 2020; Beytur et al., 2020, 2019; Barakat et al., 2019; Sönmez et al., 2018; Kadota et al., 2020, 2021) considering system implementation. As shown in the third part, the state update rate has a great impact on the freshness of information. Some system implementation works improve the packet freshness by applying the effective rate control methods.

The first work considering the impact of rates on AoI is presented by Kaul et al. (2011), who consider a vehicle network and use a system age to measure the end-to-end delay, and then develop an application layer rate adaptation algorithm to minimise the AoI, this algorithm is validated using an ORBIT testbed in Wi-Fi network of standard 802.11. Shreedhar et al. (2018, 2019b, 2019a, 2021) propose the age control protocol, which is a transport layer protocol that adjusts the rate to accommodate the data packets sent by the end-to-end application. Shreedhar et al. (2018, 2019b, 2019a) consider an IoT network and argue that ACP must maintain the right number of update packets in transmission at any given time, and then evaluate the performance of ACP by providing extensive simulations and real-world experiments. Later, based on the protocol of ACP, Shreedhar et al. (2021) propose the ACP+ algorithm and explain the difference between the two of them, and show that the big change in ACP+ over ACP is not making constraint on minimum updating rate, and the results from this change have great improvement in age achieved when numerous sources send updates over the shared access. Another decentralised channel access protocol, called AoI-oriented random access protocol, has been implemented on the software-defined radio (SDR) testbed (Han et al., 2020), which is built for testing and comparing the performance of the protocols. Different from using system age to measure the end-to-end delay, (Beytur et al., 2020, 2019) discuss the synchronisation issues between sampler and receiver in terms of AoI measurement and give a solution for calculating an estimate of average AoI without any synchronisation. An emulating M/M/1 queue has been carried out on a practical experiment (Barakat et al., 2019), and a method for obtaining the measurement of AoI and PAoI has been proposed. Furthermore, in order to explore the impact of different link service times on information freshness, Sönmez et al. (2018) measure the metric of AoI over the physical TCP/IP links (such as Wi-Fi, LTE, 3G, 2G, and Ethernet) under different status update generation rates. In addition to effectively alleviate the occurrence of network congestion through rate-adaptive control methods, another method for addressing the challenge of scalability and congestion in standard Wi-Fi network, a simplified version of WiFresh network architecture has been introduced by Kadota et al. (2020, 2021), in which two strategies for implementing WiFresh have been proposed from the MAC-layer and the application-layer respectively. WiFresh is a scheduling solution designed for Wi-Fi networks, and the experimental results show that WiFresh can significantly improve the expected network AoI when compared to the standard Wi-Fi network.

From the above discussion, it can be seen that although there are many ways to optimise AoI from the theoretical analysis, and to a certain extent, the value of AoI can be dropped significantly. However, when the scale of the wireless network of the actual system is large, it is not enough to only use scheduling strategies and sampling strategies for minimising AoI. For example, we can use sampling strategies (such as polling mechanisms) to avoid network congestion, but such sampling strategies always use centralised scheduling for controlling the sample generations, which will bring excessive overhead for large-scale networks. Even if we can utilise a decentralised scheduling method for decreasing the cost, the difficulty of designing such a strategy still exists, particularly in massive source access networks. Thus, it is vital to find the optimal transmission network that improves the information freshness from the actual system.

7 Current work thinking and future directions

7.1 Curret work thinking

Recently, although information freshness has received increasing attention and has been greatly improved by different methods, there are still some aspects that have been overlooked. For example, in most random updates systems with exponential service time, it is always assumed that the update packets are received by the destination in the same order as they were transmitted from the sensor. However, due to the randomness in the packet delivery time, there is a possibility that packets reaching the destination are out of order. Although there are some works studying the status update age for such systems, it only focuses on the minimisation of AoI by increasing system utilisation and service rate, while ignoring the increasing wasted resources that are spent on the absolute packets. Therefore, an open new research issue is what measures should be taken to reduce wastage of resources while meeting the demand for information freshness, or how to make a trade-off between minimising AoI and reducing resource cost. In addition, a fundamental challenge of the optimisation of AoI is how to sample at the data source, some optimal sampling policies are proposed for avoiding network congestion and information being obsolete, such as zero-wait policy, ϵ-wait policy, and sample-at-change policy. Though it is proved that those policies can minimise AoI to some extent, but the cost of computation and signaling overhead can not be ignored. Thus, a more intelligent sampler that can sense the network's status and its own data source characteristics will be an urgent need.

7.2 Future directions

Although there are many policies utilised in the optimisation of AoI from the perspective of packet sampling and link scheduling, most optimising strategies used are based on traditional optimisation theories, the computational complexity of these strategies will increase sharply as the number of devices increases. Thus, AI-based intelligent optimisation strategies are more suitable for future ultra-large-scale network systems, such as semantics-empowered sampling and scheduling, learning-based adaptive sampling and scheduling strategies.

Computing-aware networking (CAN) is a new network architecture proposed in response to the development trend of integrating computing and network, which interconnects dynamically distributed computing resources based on ubiquitous network connections. Real-time perception of the state of the entire network's computing power has become a very vital part, there is in need of developing a AoI-based technology for the evaluation of the computing-power availability. For example, the realisation of an arbitrary broadcast of dynamic services is based on the state of network and dynamic computing resource to route business requests to the equivalent service instance, if the calculation and network status information received by the access node is not fresh enough, the routing decision made according to the state of the computing power at this time may be inaccurate, and such a decision may bring about traffic conflicts. Thus, the evaluation of the availability of computing power can effectively prevent traffic conflicts. Simultaneously, it can also better meet users' demands for QoS of computing resources and improve the utilisation efficiency of computing resources.

Another promising area is orbital edge computing for time-critical earth-observing applications, such as smart agriculture, environmental monitoring, disease spreads and geopolitics. Due to the scarce and costly space resources (network and computing resources) of satellites, transmitting all the picture data collected on the satellite to the ground in real-time will not only increase the cost of infrastructure, but also make the observation information received on the ground not fresh enough, all of thoes will lead to the ground making wrong decisions due to the failure to get real-time fresh status update information. Thus, how to obtain real-time information cost-effectively upon emerging orbital edge computing is vital for time-critical applications.

8 Conclusions

AoI, as a metric for characterising information freshness from the perspective of application layer, has been widely utilised in wireless networks. In this survey paper, we have reviewed the recent researches on the AoI from the optimisation perspective. We firstly introduce the definition of AoI and its variants. Next, we have seen that the source can optimise the sampling rate or perform packet management for controlling the packet it updates. In particularly, we also have seen some AoI-optimal status updating with limited resources, such as energy harvesting sources and UAV-assisted sampling. Furthermore, we have given an overview of which scheduling policies the service facility can employ to maximise the freshness of delivered updates. We see that the AoI metrics can be optimised in various applications, such as cache, leraning, game and MEC. Therefore, designing of the AoI-optimal policy is the purpose of the above-mentioned works. In order to show the actual effect of those strategies in practical systems, we present an overview of optimising AoI in system implementation and show that finding an optimal transmission network is still a vital thing for improving information freshness in practical systems. Afterward, we analysed the research challenges and future directions associated with optimising AoI.

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