Packet Management of AoI in the Finite Block-Length Regime

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***Abstract*—Mission-critical applications, such as real-time monitoring and tracking, are of significant importance to six generation (6G)'s massive and ubiquitous Internet of things (IoT). To this end, finite blocklength (FBL)-based wireless communication is a promising solution. In addition to that, to assess the freshness of information, age of information (AoI) has been widely adopted. In AoI optimization, packet management is an effective way. However, the impact of packet errors is inevitable in the FBL regime, which is mostly omitted in prior studies. Motivated by exploring the joint impact of the above factors, we consider a system equipped with a single buffer, and propose two schemes of packet management in this article. We subsequently derive the closed-form expressions for the average AoI and the average peak AoI for the two schemes. Simulation results validate the theoretical analysis and demonstrate the advantage of the proposed scheme.**

***Index Terms*—Age of information, packet management, finite blocklength, Internet of things.**

I. Introduction

The Internet of things (IoT) applications in the era of six generation (6G) is calling for massive ubiquitous communications, in which massive control and command type data interactions are vastly existing [1], [2]. The driven force of these applications attributes to the finite blocklength (FBL)-based short packet communications [3]. In these applications, the freshness of information is a pivotal metric. For instance, in autonomous driving system, sensors continuously monitor and transfer the vehicle's real-time status, e.g. speed and direction, to the controller to ensure safe driving [4]. Moreover, it is found that the freshness of information affects various metrics, e.g. security and accuracy, in different applications [5].

To measure the freshness of information, age of information (AoI) has been introduced in the FBL regime. AoI is defined as the time elapsed since the generation of the last successfully received packet, specifically denoting the freshness of received information. Assuming that the generation instant of the latest received packet is $g(t)$, the instantaneous AoI is represented as $A(t) \triangleq t - g(t)$ [6]. Distinctly, a smaller value of AoI corresponds to receiving fresher information at the destination. In prior studies, [6] initially investigated the average AoI employing the first-come-first-serve (FCFS) scheme under three different queuing models: M/M/1, M/D/1, and D/M/1 (where the Kendall symbols respectively specifies the inter-arrival time distribution, the service time distribution and the number of servers and can be extended with an extra entry to denote the number of waiting rooms for customers). Subsequently, the last-come-first-serve (LCFS) scheme was investigated in [7], and it was demonstrated that the AoI performance can be enhanced by prioritizing the transmission of the latest update.

Nevertheless, in the FBL regime, the code length is typically short, inevitably results in unreliable communications [8]. Since AoI will increase until a packet is successfully received, packet error becomes a critical issue. In this regard, [9] studied the performance of AoI under the traditional protocol where the sender discards the error status packets directly, and it is found that automatic repeat-request (ARQ) can increase the reliability of transmission. In addition, the relationship between latency and AoI in the FBL regime with non-preemption and re-transmission schemes is explored in [10], [11], where the authors also introduce an algorithm to optimize the tradeoff between AoI and latency. However, a high status update rate is rarely considered in these studies, which makes it unfeasible to be applied in massive and ubiquitous IoT communications in 6G.

From the analysis above, we know that in 6G IoT-related high update rate scenarios, it is necessary to transmit the latest packet promptly to avoid congestion in the queue. To this end, AoI is analyzed in the FBL regime based on the M/G/1/1 queuing model under three packet management schemes: *non-preemption* (NP), *preemptive* (PR), and *retransmission* (RT) [12]. But it is found that in M/M/1/1 and M/G/1/1 queuing systems, whenever the server is busy, the arriving packet will either be discarded directly under the NP scheme or preempt the ongoing transmission under the PR scheme. If the update rate is high, frequent preemption will lead to unsuccessful transmission in the PR scheme. Meanwhile, in the NP scheme, fresher packets are simply discarded, both of which have negative effects on the performance of AoI. However, these effects can be alleviated in the systems with a waiting room for buffering one packet [13]. Therefore, we investigate the impact of packet management on the AoI in this article in the system equipped with a buffer. The main contributions of this paper are summarized as follows: (1) The impact of packet management on the AoI is investigated in the FBL regime. (2) The closed-form expressions of the average AoI and the average peak AoI are derived dedicated to different schemes, considering the block error rate in the system. (3) Simulation results validate the theoretical analysis and show that the proposed scheme with replacement is suitable to higher update rate scenario and achieves lower value of AoI.

II. System Model

A. System Description

The considered system is illustrated in Fig.1. The source generates N bits information according to a Poisson process with update rate λ, and the data will be encoded into a packet with m symbols. We assume a finite buffer that can accommodate only one packet in one time slot. In addition, the duration time of each symbol is T_s, then the transmission time of each packet is $M = mT_s$. As shown in Fig.1, the block error rate (BLER) during the transmission is ε. Additionally, according to prior study in [8], ε can be given as

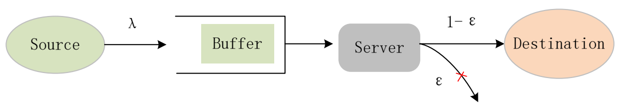


Fig. 1. System model of the packet delivery process, includes a source, a buffer, a server and a destination.

$$\varepsilon \approx \mathbb{Q}\left(\frac{\frac{1}{2}\log_2(1+\gamma)-\frac{N}{m}}{\log_2(e)\sqrt{1-\frac{1}{(1+\gamma)^2}}}\right), \tag{1}$$

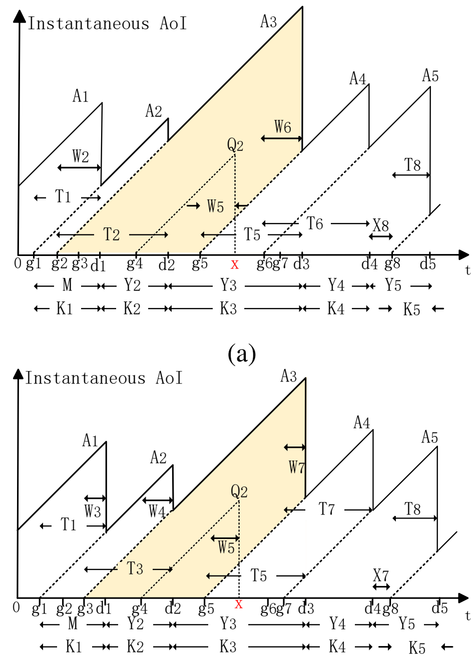
where γ is the received signal-to-noise ratio (SNR), and the formula of the Q-function is $\mathbb{Q}(x) = \int_x^{\infty}\frac{1}{\sqrt{2\pi}}e^{-\frac{u^2}{2}}du$.

B. The Evolution of AoI

Taking the packet management into consideration, two management schemes are introduced in this article, which are summarized as follows:

- *No Replace* (NR): Whenever the server is idle, the arriving packet is transmitted directly. On the contrary, if the server is busy, an arriving packet will be stored in the buffer if it is empty, or discarded if it is full.
- *Replace in Buffer* (RiB): If the server is idle, the arriving packet is transmitted directly. If the server is busy, an arriving packet will be stored in the buffer, regardless of empty or not.

The evolution of AoI is depicted in Fig.2, where on the horizontal axis, g_i denotes the generation time of the i-th update, and d_i denotes the successfully received time of the i-th update. The red 'x' denotes the failure of packet transmission. In addition to that, W_i denotes the waiting time in the buffer of the i-th successfully transmitted packet, T_i is the time staying in the system of the i-th successfully transmitted packet, Y_i denotes the interval between two consecutively successful transmission d_i and d_{i-1}, K_i is the interval form the start of the service immediately after a successful transmission to the next successful transmission, and X_i is the generation interval between g_i and g_{i+1}. Since the status updates are generated according to a Poisson process, X_i thus follows an exponential distribution with a probability density function (PDF) given by $f_{X_i}(x) = \lambda e^{-\lambda x}$.



(a)

(b)

Fig. 2. The evolution of AoI: (a) sample path of the NR scheme; (b) sample path of the RiB scheme

As depicted in Fig.2 (a), two packets successively arrive at the network while the first packet is being served. In accordance with the NR scheme, the third packet is discarded. Conversely, according to the RiB scheme, the third packet replaces the second packet and is ultimately transmitted in Figure.2 (b). In other words, in the NR scheme, packet within the buffer will not be discarded, whereas in the RiB scheme buffered packet can be transferred or replaced. This is the distinction between the two schemes.

III. The Proposed Schemes and AoI Analysis

In line with Fig.2, the average peak AoI can be given as $A_i = T_{i-1} + Y_i$. Let $N_t = \max\{\mathrm{i}|d_i < t\}$ be the number of successfully received packets during the interval $[0, t]$, the average AoI can be described as the sum of geometric areas under the instantaneous AoI curve, which is

$$\Delta = \lim_{t\to\infty}\frac{N_t}{t}\frac{1}{N_t}\sum_{i=1}^{N_t}Q_i = \lim_{t\to\infty}\frac{N_t}{t}\mathbb{E}\{Q_i\}, \tag{2}$$

where $\mathbb{E}$ represents the expectation operator. According to Fig.2, the area of Q_i can be expressed by $Q_i = \frac{(Y_i+T_{i-1})^2}{2} - \frac{{T_i}^2}{2}$. Since Y_i and T_i are mutually independent, we can obtain

$$\mathbb{E}\{Q\} = \frac{\mathbb{E}\{Y^2\}}{2} + \mathbb{E}\{Y\}\mathbb{E}\{T\}. \tag{3}$$

In addition, we have $\lim_{t\to\infty}\frac{N_t}{t} = \frac{1}{\mathbb{E}\{Y\}}$, then the average AoI can be simplified as

$$\Delta = \frac{\mathbb{E}\{Y^2\}}{2\mathbb{E}\{Y\}} + \mathbb{E}\{T\}, \tag{4}$$

and the average peak AoI can be rephrased as

$$\Delta^P = \mathbb{E}\{Y\} + \mathbb{E}\{T\}. \tag{5}$$

In the following section, we evaluate the average AoI and the average peak AoI of the proposed schemes by $\mathbb{E}\{Y\}$, $\mathbb{E}\{T\}$ and $\mathbb{E}\{Y^2\}$, which are the expectations of Y_i, T_i and Y_i^2.

A. AoI Analysis for the NR Scheme

In the NR system, the packet may undergo the following processes after arrival: 1) transmitted immediately, 2) stored in the buffer, 3) directly discarded. The specific process will depend on whether the server is busy and whether the buffer is occupied or not. For the sake of simplicity, we assume that the buffer can only accommodate one packet, in this case, one can calculate the probability that the server is idle as the probability of no new arrival between the serving period of the last packet, which is $p_i = \mathrm{e}^{-\lambda M}$. Otherwise, the probability that the sever will be busy after the last transmission is $p_b = 1 - p_i = 1 - e^{-\lambda M}$. Thus, $\mathbb{E}\{Y\}$ can be expressed by

$$\mathbb{E}\{Y\} = p_i(\mathbb{E}\{X\} + \mathbb{E}\{K\}) + p_b\mathbb{E}\{K\}, \tag{6}$$

where the first item with probability p_i signifies that the system need to wait for an update after a successful transmission. The second item denotes that there has been a packet in the buffer after the last transmission with probability p_b. Concretely, if the transmission of the i-th packet is successful, we have $K_i = M$, otherwise $K_i = M + p_i X_{i+1} + K_i^{'}$. This is because there is a probability of packet errors in the FBL regime, then the server needs to wait for an new update with probability p_i if there is no packet in the buffer. On account of the memory-less nature of the Poisson process, the waiting time and the interval between the generation of state updates obey a same distribution, which can be represented by X_{i+1}. Then $\mathbb{E}\{K\}$ is

$$\mathbb{E}\{K\} = (1-\varepsilon)M + \varepsilon\mathbb{E}(M + p_i X + \hat{K}), \tag{7}$$

where $\mathbb{E}\{X\} = \frac{1}{\lambda}$ and $\hat{K}$ is the remaining process of transmitting a new packet when the previous transmission is unsuccessful, and $\hat{K}$ has the same distribution as K, which gives

$$\mathbb{E}\{K\} = \frac{M}{1-\varepsilon} + \frac{\varepsilon e^{-\lambda M}}{\lambda(1-\varepsilon)}. \tag{8}$$

Substituting the results of $\mathbb{E}\{K\}$, $\mathbb{E}\{X\}$ into (6), we have

$$\mathbb{E}\{Y\} = \frac{M}{1-\varepsilon} + \frac{e^{-\lambda M}}{\lambda(1-\varepsilon)}. \tag{9}$$

According to Fig.2, the expending time of the successfully transmitted packet is $T_i = p_i K_i + p_b(W_i + K_i)$, where the waiting time is $W_i = T_{i-1} - X_i$. Then the expectation of T can be given by

$$\mathbb{E}\{T\} = p_i\mathbb{E}\{K\} + p_b(\mathbb{E}\{W\} + \mathbb{E}\{K\}), \tag{10}$$

and the waiting time in the buffer, say, $\mathbb{E}\{W\}$, will be

$$\mathbb{E}\{W\} = \mathbb{E}\{T\} - \mathbb{E}\{X|X < M\}. \tag{11}$$

The conditional expectation $\mathbb{E}\{X|X < M\}$ is the generation interval under the condition that the source generates an update before the current transmission is completed, which is

$$\mathbb{E}\{X|X < M\} = \frac{1}{\lambda} - \frac{Me^{-\lambda M}}{1-e^{-\lambda M}}. \tag{12}$$

Combining (8), (10) with (11) will give $\mathbb{E}\{T\}$ as

$$\mathbb{E}\{T\} = \frac{Me^{\lambda M}}{(1-\varepsilon)} + \frac{\varepsilon}{\lambda(1-\varepsilon)} + M - \frac{(1-e^{-\lambda M})}{\lambda e^{-\lambda M}}. \tag{13}$$

Substituting (9) and (13) into (5), which gives the expression of the average peak AoI as

$$\Delta_{NR}^P = \frac{M + Me^{\lambda M}}{1-\varepsilon} + \frac{e^{-\lambda M} + \varepsilon}{\lambda(1-\varepsilon)} + M - \frac{(1-e^{-\lambda M})}{\lambda e^{-\lambda M}}. \tag{14}$$

In order to obtain the closed-form expression of the average AoI, we need to derive the expectation of $\mathbb{E}\left\{Y^2\right\}$. Due to the independence between W_i and K_i, we have

$$\mathbb{E}\{Y^2\} = p_i(\mathbb{E}\{X^2\} + \mathbb{E}\{K^2\} + 2\mathbb{E}\{X\}\mathbb{E}\{K\}) + p_b\mathbb{E}\{K^2\}, \tag{15}$$

where $\mathbb{E}\{X^2\} = \frac{2}{\lambda^2}$. Then according to (8), the following equation holds

$$\begin{aligned}\mathbb{E}\{K^2\} &= (1-\varepsilon)M^2 + \varepsilon(M^2 + {p_i}^2\mathbb{E}\{X^2\} + \mathbb{E}\{K^2\} \\ &+ 2p_i M\mathbb{E}\{X\} + 2M\mathbb{E}\{K\} + 2p_i\mathbb{E}\{X\}\mathbb{E}\{K\}).\end{aligned} \tag{16}$$

Combining $\mathbb{E}\{K\}$, $\mathbb{E}\{X\}$, $\mathbb{E}\{X^2\}$ with $\mathbb{E}\{K^2\}$, $\mathbb{E}\{Y^2\}$ can be given by

$$\begin{aligned}\mathbb{E}\{Y^2\} &= \frac{2e^{-\lambda M}}{\lambda^2} + \frac{M^2}{1-\varepsilon} + \frac{2\varepsilon e^{-2\lambda M}}{\lambda^2(1-\varepsilon)} + \\ &\frac{2\varepsilon Me^{-\lambda M}}{\lambda(1-\varepsilon)} + \frac{2e^{-\lambda M} + 2\varepsilon\lambda M}{\lambda(1-\varepsilon)}\{\frac{M}{(1-\varepsilon)} + \frac{\varepsilon e^{-\lambda M}}{\lambda(1-\varepsilon)}\}.\end{aligned} \tag{17}$$

Consequently, with the expressions of $\mathbb{E}\{Y\}$, $\mathbb{E}\{T\}$ and $\mathbb{E}\{Y^2\}$ in hand, the average AoI of the NR scheme will be

$$\begin{aligned}\Delta_{NR} &= \frac{Me^{\lambda M}}{(1-\varepsilon)} + \frac{\varepsilon}{\lambda(1-\varepsilon)} + M - \frac{(1-e^{-\lambda M})}{\lambda e^{-\lambda M}} \\ &+ \frac{1}{\lambda M + e^{-\lambda M}}\{\frac{(1-\varepsilon)e^{-\lambda M} + \varepsilon e^{-2\lambda M}}{\lambda} + \frac{\lambda M^2}{2} \\ &+ \varepsilon Me^{-\lambda M} + \frac{(e^{-\lambda M} + \varepsilon\lambda M)(\lambda M + \varepsilon e^{-\lambda M})}{\lambda(1-\varepsilon)}\}.\end{aligned} \tag{18}$$

B. AoI Analysis for the RiB Scheme

In the RiB scheme, the packet may undergo the following processes after arrival: 1) transmitted immediately, 2) transmitted after waiting a spell in the buffer, 3) replaced by a new arrival. Therefore, it is necessary to consider the probability of replacement. Note that replacement only impacts the duration that packets within the buffer and does not affect the interval between two consecutive successful transmissions. In this case, the partial results obtained in subsection A are still feasible, i.e., $\mathbb{E}\{K\}$, $\mathbb{E}\{Y\}$ and $\mathbb{E}\{Y^2\}$. We thus only need to analyze $\mathbb{E}\{T\}$ in this subsection. In order to obtain $\mathbb{E}\{T\}$, we need to consider the probability of replaced packets. Assuming that there are at most two updates, or rather once replacement within time M. Leveraging the characteristics of the Poisson distribution illustrated in, we can obtain the probabilities of generating one and two updates as follows,

$$\begin{aligned} p_1 &= e^{-\lambda M}\frac{(\lambda M)^1}{1!} = e^{-\lambda M}(\lambda M), \\ p_2 &= e^{-\lambda M}\frac{(\lambda M)^2}{2!} = \frac{e^{-\lambda M}(\lambda M)^2}{2}. \end{aligned} \tag{19}$$

We afterwards define the absence of replacement as event ϕ, and the opposite as event ψ. The waiting time of the successfully transmitted packet in the buffer under the RiB scheme can be given by

$$\mathbb{E}\{W\} = p_1(\mathbb{E}\{T\} - \mathbb{E}\{X|\phi\}) + p_2(\mathbb{E}\{T\} - \mathbb{E}\{\hat{X}|\psi\}). \tag{20}$$

where $\hat{X}$ represents the cumulative sum of two update intervals. Hence, we have

$$\begin{aligned} \mathbb{E}\{X|\phi\} &= \frac{\int_0^M x\lambda e^{-\lambda x}dx}{\lambda M e^{-\lambda M}} = \frac{1-e^{-\lambda M}}{\lambda^2 M e^{-\lambda M}} - \frac{1}{\lambda}, \\ \mathbb{E}\left\{\hat{X}|\psi\right\} &= \frac{\int_0^M \frac{\lambda}{2}xe^{-\frac{\lambda x}{2}}dx}{\frac{\lambda M}{2}e^{\frac{-\lambda M}{2}}} = \frac{4(e^{\frac{\lambda M}{2}}-1)}{\lambda^2 M} - \frac{2}{\lambda}. \end{aligned} \tag{21}$$

Then substituting (8), (20) into (10), the time of packet within the buffer can be expressed by

$$\begin{aligned} \mathbb{E}\{T\} = &\frac{1}{(2-e^{-\lambda M})}\{\frac{Me^{\lambda M}}{1-\varepsilon} + \frac{\varepsilon}{\lambda(1-\varepsilon)} + \\ &(1-e^{-\lambda M})(M+\lambda M^2 - 2M(e^{\frac{\lambda M}{2}}-1) - \frac{e^{\lambda M}-1}{\lambda})\}. \end{aligned} \tag{22}$$

Substituting (9) and (22) into (5) will give the average peak AoI as

$$\begin{aligned} \Delta_{RiB}^P = &\frac{M}{1-\varepsilon} + \frac{e^{-\lambda M}}{\lambda(1-\varepsilon)} + \frac{1}{(2-e^{-\lambda M})}\{\frac{\lambda M e^{\lambda M}+\varepsilon}{\lambda(1-\varepsilon)} \\ &+ (1-e^{-\lambda M})(M+\lambda M^2 - 2M(e^{\frac{\lambda M}{2}}-1) - \frac{e^{\lambda M}-1}{\lambda})\}. \end{aligned} \tag{23}$$

In line with the analysis in subsection A, the average AoI of the RiB scheme can be given as

$$\begin{aligned} \Delta_{RiB} = &\frac{1}{(2-e^{-\lambda M})}\{\frac{\lambda M e^{\lambda M}+\varepsilon}{\lambda(1-\varepsilon)} + \\ &(1-e^{-\lambda M})(M+\lambda M^2 - 2M(e^{\frac{\lambda M}{2}}-1) - \frac{e^{\lambda M}-1}{\lambda})\} \\ &+ \frac{1}{\lambda M + e^{-\lambda M}}\{\frac{(1-\varepsilon)e^{-\lambda M}+\varepsilon e^{-2\lambda M}}{\lambda} + \frac{\lambda M^2}{2} + \\ &\varepsilon M e^{-\lambda M} + \frac{(e^{-\lambda M}+\varepsilon\lambda M)(\lambda M + \varepsilon e^{-\lambda M})}{\lambda(1-\varepsilon)}\}. \end{aligned} \tag{24}$$

IV. Simulation results

In the simulations, we set the information of each status update as N=160 bits and the duration time for each symbol as $T_s = 0.006$ ms, and the SNR as 3 dB. We respectively simulate the AoI versus the blocklenth m and update rate λ under different schemes and system settings. The AoI curve of the infinite queue system is incomplete here due to the congestion in the queue when $\lambda > \frac{1-\varepsilon}{M}$.

Fig.3 depicts the average peak AoI and the average AoI in relation to the blocklength m from 160 to 240 channel use (cu) with different update rates: 0.5 packets/ms, 1packets/ms and 2 packets/ms. We can see that the RiB scheme outperforms the others, especially when λ is 2 packets/ms, showcasing the superiority of replacing with newly arrived packets. Nevertheless, the infinite queue system achieves a lower AoI when the blocklength is small. This is because re-transmission can reduce the AoI while enhancing the communication reliability. Moreover, the AoI of the NR scheme is greatly large when λ is 1 and 2 packets/ms, because the packet in the buffer is relatively out of date in this scheme. Additionally, we find that the AoI exhibits a trend of decreasing initially and then increasing at around 180 cu in Fig.3. This is because the service time becomes longer with increasing blocklength, and the BLER becomes higher with a decreasing blocklength.

Fig.4 displays the average peak AoI and the average AoI to the update rate λ from 0.2 to 2 packets/ms with different blocklength: 160 cu, 180 cu, 220 cu. As displayed here, when m is 160 cu and λ is less than 1 packets/ms, the AoI of the infinite queue system is the lowest. That's because the infinite queue system adopts the LCFS packet management and prioritizes the transmission of the latest packets, which can reduce the AoI at the limited λ. In the RiB scheme, the value of AoI continuously decreases as λ increases and remains lower than that of the NR scheme and the no buffer scheme, because the replacement improves the freshness of the buffer packet and enables the system to achieve a low AoI at higher λ. The NR scheme exhibits similar performance of AoI to the RiB scheme when λ is low, which complies with the system settings, and the AoI increases significantly at moderately higher λ as the buffer is prone to retain the previous packets.

V. Conclusion

AoI analysis is addressed with two packet management schemes under the FBL regime in this article. The expressions of average AoI and the average peak AoI are derived. It is discovered that the RiB scheme exhibits a better AoI performance compared to the NR scheme, demonstrating the benefit of replacing the out of date packet with a newly arrived one in the buffer. In addition, the RiB scheme can be applied in higher update rate case compared to the other three schemes.

Acknowledgement

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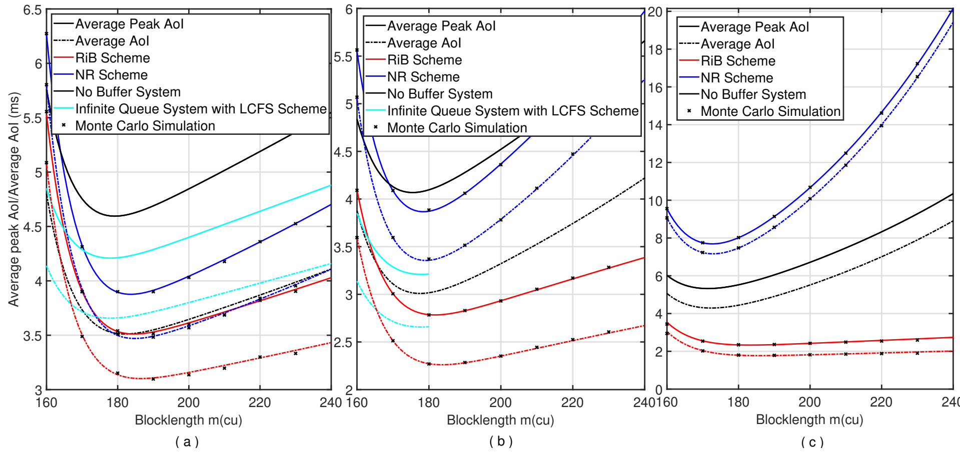

Fig. 3. The average peak AoI and the average AoI versus blocklength m: (a) λ=0.5 packets/ms; (b) λ=1 packets/ms; (c) λ=2 packets/ms.

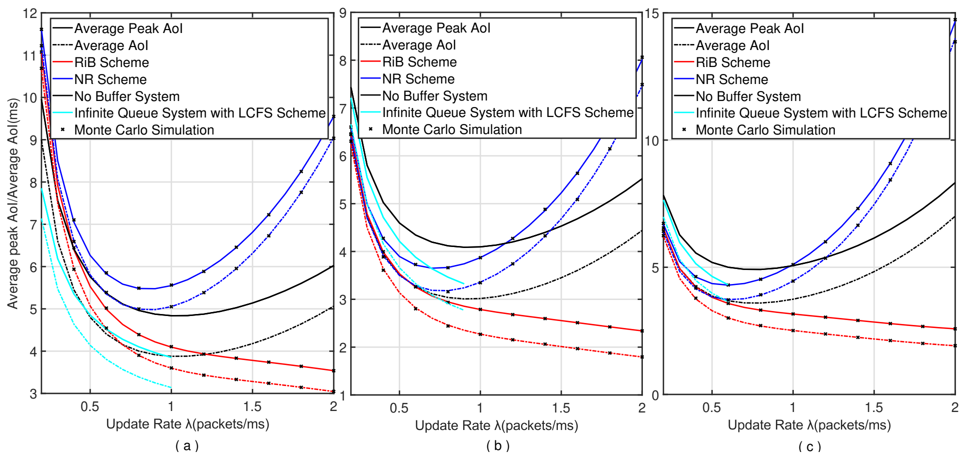

Fig. 4. The average peak AoI and the average AoI versus update rate λ: (a) m=160 cu; (b) m=180 cu; (c) m=220 cu.

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