Measuring Age of Information on Real-Life Connections

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***Abstract*—Age of Information (AoI) is a relatively new metric to measure freshness of networked application such as real-time monitoring of status updates or control. The AoI metric is discussed in the literature mainly in a theoretical way. In this work, we want to point out the issues related to the measuring AoI-related values, such as synchronization and calculation of the values. We discussed the effect of synchronization error in the measurement and a solution for calculating an estimate of average AoI without any synchronization.**

Keywords*—*Age of Information (AoI), AoI on UDP, AoI over Internet, Experimental AoI, Average AoI Estimation

I. Introduction

Ubiquitous connectivity of monitoring/control/automation systems such as Internet of Things (IoT) have created new applications where they generate time-stamped status updates and forward them through a network to an intended machine. These status could be as simple as the temperature of a room or as complicated as a vehicle's position or velocity [1][2].

The ever-increasing number of Machine-Type Communication devices is leading to the peremptory challenge to provide fresh data in the real-time information updating systems. Generally, the value of a status update is inversely related to its freshness, therefore updates should be as timely as possible.

To measure the freshness of data, the Age of Information (AoI), a new metric for communication systems, was introduced in [3]. Authors formulated the average age for the case of First-Come-First-Served (FCFS) disciplines for the cases of M/M/1, M/D/1 and D/M/1. Results shown that to minimize the average age, an optimal packets generation rate can be suggested.

Authors in [4] considered a single server, where at a time at most one update packet can be serviced. The investigated system can control the order in which the packets get serviced and the service time distribution, with a given service rate. The proof of tradeoff between the AoI and packet delay is their contribution for AoI society. To illustrate the benefits of applying parallel servers for reducing AoI, [5], [6] investigated M/M/2 and M/M/∞ systems.

Age in Last-Come-First-Served (LCFS) disciplines for parallel queues with preemptive service (LCFSp) was studied in [7]. Furthermore [8], [9] analysed average AoI for a series of LCFSp queues in tandem networks. For realistic applications with multi-hop scenarios when the transmission times of packets in the network are exponentially distributed across all nodes, it was shown that to minimizes the average age, the Last-Come First-Served (LCFS) preemptive policy must be applied at the relaying nodes [10]. For single server with multiple flows, [11], [12] suggested preemptive and non-preemptive Maximum Age Difference (MAD) scheduling algorithms which have superior performance on minimizing the average AoI over all flows. Authors in [6] introduced average peak age and also demonstrated the packet managing in the source is one of the methods to reduce the average age.

Energy is one of the main factors for communication in the IoT based networks which has direct effect on average age. Equipping IoT nodes with energy harvester [13][14] and calculating the energy consumption with simulator [15] is crucial for prolonging and estimating the lifetime of the node. There are several studies (e.g., [16],[17]) that clarified the impact of energy harvesting on the age of information.

Q-learning is a field of machine learning which allows an agent to learn the environment behaviors by interacting with environment.In IoT based smart home applications [18] Q-learning was used to satisfy the user comfort and energy efficiency. Recently deep Q-learning was used as a tool in [19] to minimize the AoI with no prior knowledge of network topology.

According to literature review from publication,[20], most of AoI studies are theoretical. However, for the first time a real-life implementation which measuring the variation of AoI over TCP/IP links served by WiFi, LTE, 3G, 2G and Ethernet was demonstrated in [21]. A realistic system model as a tandem queue which collected raw data and pre-processed before forwarding to the destination was consider in [22] to express peak age of information. Authors in [23] introduced the Age Control Protocol (ACP). Duty of this protocol is to keep the age at the monitor small. For calculating the total average age of the network in a CSMA environment where N links contend for the channel, SHS tools was applied in [24]. They formulated an optimization problem to minimize the total average age and implemented the proposed solution in an IEEE 802.11 network.

The rest of this paper is organized as follows: Section II introduces AoI. The synchronization issue is discussed in III and methods for AoI measurement are given in IV. The real-world testbed and the experiment results are introduced in section V. Finally, the conclusion is in Section VI.

II. Age of Information: definition

According to age metric, after a packet generation, as time goes on, it gets older. Similarly, the freshness of the receiver can be defined in a similar way. In the period the receiver gets no packet, the process going on at the receiver become stale. When the receiver gets a fresh data, the age of the connection is updated with the age of recently arrived packet.

The status age $\Delta(t)$ is defined as the time that has elapsed since the newest data available at the destination at time t was generated at the source. More precisely, $\Delta(t) = t - U(t)$, where $U(t)$ is the generation time (i.e. time stamp) of the

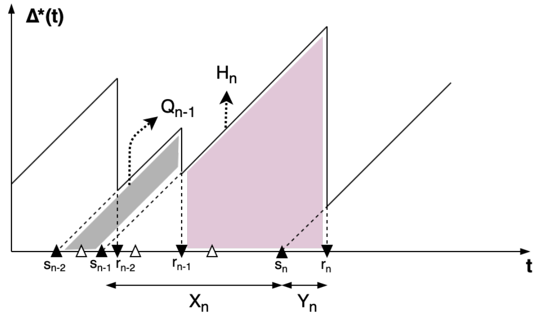

Fig. 1. Sample path of the age process $\Delta(t)$

newest data the destination has received by time t. This definition leads to age following a saw-tooth pattern as in the sample path given in Fig. 1. The example in Fig. 1 assumes a case where the observation begins at $t = 0$ with an empty queue at the destination and $\Delta(0) = \Delta_0 > 0$. The source generates status updates at $s_1, s_2, \cdots, s_n$, which are received at $r_1, r_2, \cdots, r_n$, respectively. In the absence of any updates, the status age of source at the destination increases linearly in time and decreases just after an update is received. The area under the age graph normalized by time T in Fig. 1 gives the time average of AoI which is defined by:

$$\overline{\Delta} = \frac{1}{T}\int_0^T \Delta(t)dt \tag{1}$$

As shown in Fig. 1, the area under the sample path of the age process can be presented as sum of the areas of trapezoid either Q_i's or H_i's.

For n transmitted packets, the area is composed of the area of polygon Q_1, isosceles trapezoids Q_i's for $2 \le i \le n$ and the triangle of length Y_n positioned at the bottom of Q_n.

$$\overline{\Delta} = \frac{Q_1 + \sum_{i=2}^{n} Q_i + Y_n^2/2}{T} \tag{2}$$

Since Q_1 and Y_n is constant, as $T \to \infty$, they disappear in the equation. Therefore, in steady state, the area of the isosceles trapezoids become important and can be calculated using the arrival and departure instances of packets.

$$Q_i = \frac{(2r_i - s_i - s_{i-1})(s_i - s_{i-1})}{2} \tag{3}$$

Note that, $(s_i - s_{i-1})$ is X_i which is the inter-arrival time between successfully transmitted packets.

Since the formulation using Q_i's makes the mathematical analysis easier, it is used in most of the AoI studies. However, the formulation using H_i's is useful for the practical measurement of AoI. Next, we will discuss the definition of time average of AoI in terms of H_i's.

$$\overline{\Delta} = \frac{1}{T}\sum_{i=1}^{n} H_i \tag{4}$$

$$H_i = (r_i - r_{i-1})(r_{i-1} - s_{i-1}) + \frac{(r_i - r_{i-1})^2}{2} \tag{5}$$

where $(r_i - r_{i-1})$ is the inter-departure time between $i-1^{th}$ and i^{th} packets and $(r_{i-1} - s_{i-1})$ equals to Y_{i-1} which is the system time of $i-1^{th}$ packet.

In the AoI dependent controlling applications require the calculation on receiver or transmitter depending on the capabilities of the devices or because of the essence of the controlling problem. For example, if we want to measure average AoI of a connection between a dummy sensor and a server, we have to calculate the AoI on receiver. On the other hand, if the transmitter device is adaptively changing the sampling rate to achieve the minimum average AoI possible, then the transmitter needs to know the AoI values with minimum latency, so in this application the AoI is measured on transmitter. Therefore, different methods are needed to measure AoI-dependent values on receiver or transmitter.

Each of these two ways of computing average AoI are useful depending on where the computation is done, at the receiver or at the transmitter.

Note that, as seen in (3) and (5), the timestamps r_i's and s_i's should be with the same reference of time. However, since the receiver and transmitter are separate machines, the synchronization problem appears between them.

Another metric investigated in the AoI literature is the time average of peak age of information.

$$\overline{\Delta_{peak}} = \frac{1}{n}\sum_{i=1}^{n} \Delta(r_i^-) \tag{6}$$

The time average can be calculated iteratively using arrival and departure instances of packets

$$\overline{\Delta_{peak}} = \frac{1}{n}\sum_{i=1}^{n} (r_i - s_{i-1}) \tag{7}$$

In the next section we will cover these issues for the transmitter and the receiver case separately.

III. Synchronization

As mentioned in the previous sections, to calculate AoI-related values, such as average peak AoI or average AoI, we need to get time-stamps from both receiver and transmitter. However, since the receiver and transmitter are distant from each other, they have their own system clocks. If we assume that the time shift of each clock is negligible for a certain period, we can say that the difference between two clocks is only a constant bias.

Let's sample the clocks at the transmitter and receiver side at the same instance, and the values sampled are t_r and t_t, respectively. With the assumption mentioned above, B is a constant real number.

$$t_r = t_t + B \tag{8}$$

Because of this constant time difference between two machines a bias term appears in the calculation of average AoI.

If the average AoI is calculated using Eq. 2 at the transmitter side, the constant bias is add on the timestamps sampled at the receiver. After this point, we will show the timestamps sampled at the distant clock with an apostrophe.

$$r_i' = r_i + B \tag{9}$$

When Eq. 9 is substituted in Eq. 3 and 5, an additional linear bias term appears.

$$Q_i' = Q_i + B(s_i - s_{i-1})$$

$$H_i' = H_i + B(r_i - r_{i-1}) \tag{10}$$

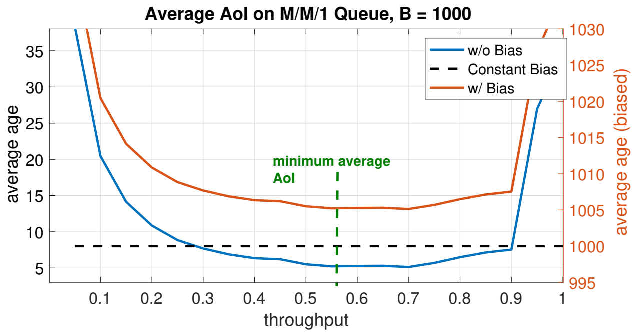

Fig. 2. Average AoI measured using Monte Carlo simulation, artificial synchronization error is add on the departure timestamps, B = 1000

As seen in Eq. 10, since B is a constant, area of trapezoids suffer from a linear bias, increases with the inter-arrival time between packets. When this result is applied to Eq. 4;

$$\overline{\Delta}' = \frac{1}{T}\sum_{i=1}^{n}(H_i + B(r_i - r_{i-1})) \tag{11}$$

If T with $\sum_{i=1}^{n}(r_i - r_{i-1})$ substituted in Eq. 11:

$$\overline{\Delta}' = \overline{\Delta} + B \tag{12}$$

Eq. 12 shows the synchronization error between receiver and transmitter appears as a constant bias on average AoI calculation. Similarly, considering Eq. 7 the time synchronization error causes a constant bias in addition to average peak AoI.

$$\overline{\Delta_{peak}}' = \overline{\Delta_{peak}} + B \tag{13}$$

Considering average AoI and average peak AoI, the constant bias may not be that much harmful, since it doesn't move the operating point for minimum age in terms of throughput. But if it is required to measure exact AoI values, the constant bias appears in the measurements can be problematic. Monte Carlo simulation results for Average AoI measurements where artificial synchronization error is add on the departure timestamps is shown in Fig.2

To overcome the synchronization issue, there are a few solution, depending on the application. for instance, GPS module is used for synchronization of distant machines, pre-synchronization method with common reference which is equipped with RTC component is applied in time based devices and Network Time Protocol (NTP) is designed to synchronize devices over network.

IV. Methods for Measuring AoI

Depending on the application, the AoI-related values are needed to be calculated at receiver or transmitter. In this section we will discuss the practical issues regarding the AoI measurement.

A. *Measuring AoI at Receiver*

To measure the AoI-related values at the receiver, the transmitter and receiver should be synchronized using one of the synchronization methods which mentioned in the section III. Assuming that the synchronization is done good enough, to measure the AoI we need to send the generation timestamps of packets. UDP and TCP headers carries the timestamp information of the packet. If the header of the packet is available, there is no need to put the timestamp in the payload. Otherwise, the timestamp should be put into the payload.

For the calculation average AoI, (4) is preferable, because this method is more accurate while averaging in a short window.

B. *Measuring AoI at Transmitter*

To measure AoI at the transmitter, the received times of packets are needed. This information can be carried using an ACK for each packet. The received times of the transmitted packets can be put into the payload of the ACKs. This methods requires the transmitter and receiver to be synchronized. The drawbacks of this method are to calculate AoI-related values, it is necessary to wait until the ACK is received, which induces additional delay for calculation, and the ACKs may be lost while transmission. Additionally, this method uses the channel in both ways and occupies it more.

Meanwhile there is another way to calculate AoI-related values, mentioned in [23], using the ACK arrival instances instead of packet received times. Note that, this method doesn't require the transmitter and receiver to be synchronized. We will explain this method in details.

C. *Overestimate of AoI using RTT*

In this method, receiver sends an ACK for each packet, and the transmitter uses RTT of that packet instead system time to calculate AoI-related values. Since the ACK doesn't carry timestamp information, it is shorter. Consequently, the error probability of ACKs is lower. However, this method provides an overestimate of average AoI, since synchronization is no more required, this method is very promising.

V. Test on Real Network

A. *Testbed*

In this study a real-world network services for AoI measurement which involves a sampler-transceiver node and an echo server was created (Fig. 3). The sampler-transceiver node in METU campus (Ankara, Turkey) samples data which contains the timestamp (sample generation time), packet number and a payload. Then it transmits the packet to an echo server in Istanbul, Turkey on UDP connections through Internet. Echo server echoes complete line to the sampler-transceiver node again outright. When the packet is completely received and decoded, received time of the packet is recorded and compared with generation timestamp to calculate the instantaneous age. Since the packet generation node and destination node are the same, there is not any synchronization issue for age calculation. A multi-threaded or multi-process solution was used in sampler-transceiver node. It means that it has ability to sample, transmit and receive packets simultaneously. In this setup, while measuring average AoI, the estimation method discussed in Section IV-C was used.

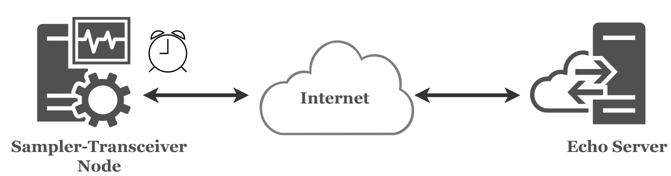

Fig. 3. A simplified model of physical testbed.

Additionally, if we assume that the Echo Server is one of routers in the network, the two way connection between Sampler-Transceiver Node and Echo Server can be thought as a way one connection from transmitter node to receiver node through Echo Server. This just makes the way the packet travels longer. Due to the estimation method mentioned in

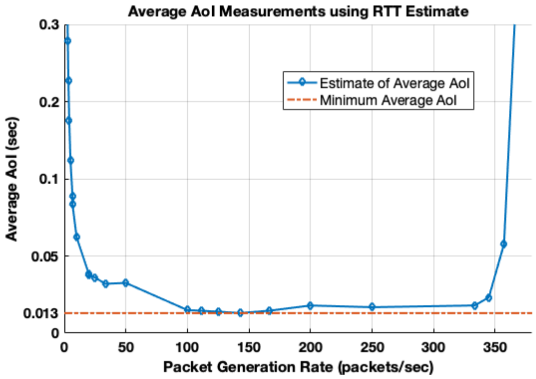

Fig. 4. Results on a testbed using measurement method mentioned in (IV-C). For transmission UDP protocol is used.

(IV-C), without any synchronization issue, we are able to measure the average AoI without any bias. In our setup, the packet is travelling through 18-20 hops (including coming back from echo server), with an average RTT of 12.5 ms.

B. Results

In the test, UDP packets consist of 1058 byte (including header) are sent at constant rate, periodically. The average AoI is calculated then the rate is increased, and the process is repeated. As seen in the Fig. 4, average AoI vs. Rate plot is U-shaped. Since the Internet infrastructure is using FCFS queues in routers and switches, getting results similar to ones in [3] is quite expected. An interesting result is that unlikely the results for D/M/1 queues, the average AoI distribution has larger flat region, where the AoI values don't change. For example, although the packet generation rate is increased up to 340 Hz, we don't get significant improvement in average AoI after 100 Hz. This phenomena because of the service distribution observed in the real Internet infrastructure. Additionally, according to experiments, the increase of the average AoI at the high rates occurs not because of the longer waiting time in the queue but because of the packet losses.

VI. Conclusions

In this paper, we have discussed the issues related with the AoI measurement in the real network, such as synchronization and iterative way of calculating average AoI and peak AoI. We have mentioned a method which is able to estimate average AoI without any synchronization requirement. At the end, we gave the results of this method.

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