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Contents

Age of Information: A New Concept, Metric, and Tool

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ABSTRACT

Age of information (AoI) was introduced in the early 2010s as a notion to characterize the freshness of the knowledge a system has about a process observed remotely. AoI was shown to be a fundamentally novel metric of timeliness, significantly different, to existing ones such as delay and latency. The importance of such a tool is paramount, especially in contexts other than transport of information, since communication takes place also to control, or to compute, or to infer, and not just to reproduce messages of a source. This volume comes to present and discuss the first body of works on AoI and discuss future directions that could yield more challenging and interesting research.

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Introduction

The concept of *Age of Information* (AoI) was introduced in 2011 in [31] to quantify the freshness of the knowledge we have about the status of a remote system. More specifically, AoI is the time elapsed since the generation of the last successfully received message containing update information about its source system. Utilizing a simple communication system model, in a series of papers ([32], [33], [30], and [58]), the first group of characterizations of the Age of Information metric had appeared by 2012. Since then, AoI has attracted a vivid interest, with over 50 publications, in the last six years [1].

The attention AoI has been receiving is due to two factors. The first is the sheer novelty brought by AoI in characterizing the freshness of information versus for example that of the metrics of delay or latency. Second, the need and importance of characterizing the freshness of such information is paramount in a wide range of information, communication, and control systems. By now, age has been studied with considerable diversity of systems, being as a concept, a performance metric, and a tool.

[1] In this volume we take into consideration works that have been published no later than June 2017.

The purpose of this volume is to present a critical summary of this first body of works performed on AoI and discuss future research directions. Already at this early point we need to put down our first disclaimer: we have chosen to treat the early works with significantly more detail, going deeper in the derivations and presenting more results and insights from them than we do with more recent works. The reason for this is to achieve a tutorial nature in the volume, which can provide a solid ground of the AoI as a concept. Moreover, the first works, which we chose to present in more detail than the rest, aim to provide fundamentally new knowledge in the premise of maintaining information fresh in a system. This basic goal opens up a wide range of communication contexts that span from estimation and prediction, to applications such as vehicular networks and information caching, to name a few.

With this in mind, we begin this volume presenting the AoI **concept** as it was originally introduced. For this, we discuss the original models of Kaul, Gruteser and Yates of [33], considering a system where a source is transmitting packets containing status updates to a destination. The analysis presented is based on a simple queueing model. Already in that work the minimization of AoI was shown to be non-trivial for the source sampling methods studied. However, it had already become clear that timely updating a destination about a remote system is neither the same as maximizing the utilization of the communication system, nor of ensuring that generated status updates are received with minimum delay. This is because utilization can be maximized by making the source send updates as fast as possible which would lead to the destination receiving delayed statuses because messages are backlogged in the communication system studied. In this case, delay suffered by the stream of status updates can be reduced by decreasing the rate of updates. Alternatively, decreasing the update rate can also lead to the destination having unnecessarily outdated status information because of lack of updates.

AoI has spawned relevant performance metrics that are more tractable such as the Peak Age of Information or the Cost of Update Delay, opening even more research opportunities. Under the timely update context, the relevant timeliness **performance metrics** should be kept at values that ensure high freshness of information. Already the first AoI lower bound had appeared in [33] and we discuss it in Section 2. We then continue the discussion on the early works of AoI as a performance metric in Section 3, where we present the case of AoI for multiple sources, its use in scheduling, and demonstrate packet management techniques that have been employed. Section 4 treats AoI as a metric for rate control, addresses the case of packets with deadlines, and presents an optimal policy for optimizing age, throughput, and delay.

Keeping the AoI metrics low is of high interest when AoI is being treated as a **tool** to facilitate the timely update of information that will eventually improve performance metrics in different contexts. Consider for example remote estimation; if the process under observation consists of highly correlated data, then the frequency of generation and transmission of updates can be significantly reduced without affecting the timeliness of the information at a remote receiver. In Section 5, we discuss three domains in which AoI has been treated as a tool: Channel State Information (CSI) estimation, energy harvesting, and scheduling.

Recent works that have appeared in the time of writing of this volume have been categorized and treated in Section 6. Finally, in Section 7, we provide a brief discussion of indicative future topics on which the AoI can contribute. The topics we cover there are not a complete list, as there is an immense wealth of possible problems associated with the notion of timeliness as captured by age, in the form of either a tool, a performance metric, or even a concept.

References

[1] Arafa, A. and S. Ulukus. 2017. "Age-Minimal Transmission in Energy Harvesting Two-hop Networks". *CoRR*. abs/1704.08679. URL: http://arxiv.org/abs/1704.08679.

[2] Bacinoglu, B. T., E. T. Ceran, and E. Uysal-Biyikoglu. 2015. "Age of information under energy replenishment constraints". In: *Information Theory and Applications Workshop (ITA)*. 25–31.

[3] Bacinoglu, B. T. and E. Uysal-Biyikoglu. 2017. "Scheduling status updates to minimize age of information with an energy harvesting sensor". In: *IEEE International Symposium on Information Theory (ISIT)*. 1122–1126.

[4] Bedewy, A. M., Y. Sun, and N. B. Shroff. 2016. "Optimizing data freshness, throughput, and delay in multi-server information-update systems". In: *IEEE International Symposium on Information Theory (ISIT)*. 2569–2573.

[5] Bedewy, A. M., Y. Sun, and N. B. Shroff. 2017. "Age-optimal information updates in multihop networks". In: *IEEE International Symposium on Information Theory (ISIT)*. 576–580.

[6] Bertsekas, D. and R. Gallager. 1992. *Data Networks (2Nd Ed.)* Upper Saddle River, NJ, USA: Prentice-Hall, Inc.

[7] Bhambay, S., S. Poojary, and P. Parag. 2017. "Differential Encoding for Real-Time Status Updates". In: *IEEE Wireless Communications and Networking Conference (WCNC)*. 1–6.

[8] Chen, K. and L. Huang. 2016. "Age-of-information in the presence of error". In: *IEEE International Symposium on Information Theory (ISIT)*. 2579–2583.

[9] Chen, Y., Y. C. Eldar, and A. J. Goldsmith. 2013. "Shannon Meets Nyquist: Capacity of Sampled Gaussian Channels". *IEEE Transactions on Information Theory*. 59(8): 4889–4914.

[10] Cooper, R. B. 1981. *Introduction to queueing theory*. Includes index. New York: North Holland.

[11] Costa, M., M. Codreanu, and A. Ephremides. 2014. "Age of information with packet management". In: *IEEE International Symposium on Information Theory (ISIT)*. 1583–1587.

[12] Costa, M., M. Codreanu, and A. Ephremides. 2016. "On the Age of Information in Status Update Systems With Packet Management". *IEEE Transactions on Information Theory*. 62(4): 1897–1910.

[13] Costa, M., S. Valentin, and A. Ephremides. 2015a. "On the age of channel information for a Finite-State Markov model". In: *IEEE International Conference on Communications (ICC)*. 4101–4106.

[14] Costa, M., S. Valentin, and A. Ephremides. 2015b. "On the age of Channel State Information for non-reciprocal wireless links". In: *IEEE International Symposium on Information Theory (ISIT)*. 2356–2360.

[15] Eldar, Y. C. 2015. *Sampling Theory: Beyond Bandlimited Systems*. Cambridge University Press.

[16] Grolinger, K., M. Hayes, W. A. Higashino, A. L'Heureux, D. S. Allison, and M. A. M. Capretz. 2014. "Challenges for MapReduce in Big Data". In: *IEEE World Congress on Services*. 182–189.

[17] He, Q., D. Yuan, and A. Ephremides. 2016a. "On optimal link scheduling with min-max peak age of information in wireless systems". In: *IEEE International Conference on Communications (ICC)*. 1–7.

[18] He, Q., D. Yuan, and A. Ephremides. 2016b. "Optimizing freshness of information: On minimum age link scheduling in wireless systems". In: *14th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*. 1–8.

[19] He, Q., D. Yuan, and A. Ephremides. 2017. "On optimal link scheduling with deadlines for emptying a wireless network". In: *IEEE International Symposium on Information Theory (ISIT)*. 461–465.

[20] Hespanha, J. P. 2006. "Modelling and analysis of stochastic hybrid systems". *IEE Proceedings - Control Theory and Applications*. 153(5): 520–535.

[21] Hsu, Y. P., E. Modiano, and L. Duan. 2017. "Age of information: Design and analysis of optimal scheduling algorithms". In: *IEEE International Symposium on Information Theory (ISIT)*. 561–565.

[22] Huang, L. and E. Modiano. 2015. "Optimizing age-of-information in a multi-class queueing system". In: *IEEE International Symposium on Information Theory (ISIT)*. 1681–1685.

[23] Inoue, Y., H. Masuyama, T. Takine, and T. Tanaka. 2017. "The stationary distribution of the age of information in FCFS single-server queues". In: *IEEE International Symposium on Information Theory (ISIT)*. 571–575.

[24] Joo, C. and A. Eryilmaz. 2017. "Wireless scheduling for information freshness and synchrony: Drift-based design and heavy-traffic analysis". In: *15th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*. 1–8.

[25] Kadota, I., E. Uysal-Biyikoglu, R. Singh, and E. Modiano. 2016. "Minimizing the Age of Information in broadcast wireless networks". In: *54th Annual Allerton Conference on Communication, Control, and Computing (Allerton)*. 844–851.

[26] Kam, C., S. Kompella, and A. Ephremides. 2014. "Effect of message transmission diversity on status age". In: *IEEE International Symposium on Information Theory (ISIT)*. 2411–2415.

[27] Kam, C., S. Kompella, G. D. Nguyen, and A. Ephremides. 2016a. "Effect of Message Transmission Path Diversity on Status Age". *IEEE Transactions on Information Theory*. 62(3): 1360–1374.

[28] Kam, C., S. Kompella, G. D. Nguyen, J. E. Wieselthier, and A. Ephremides. 2016b. "Age of information with a packet deadline". In: *IEEE International Symposium on Information Theory (ISIT)*. 2564–2568.

[29] Kam, C., S. Kompella, G. D. Nguyen, J. E. Wieselthier, and A. Ephremides. 2017. "Information freshness and popularity in mobile caching". In: *IEEE International Symposium on Information Theory (ISIT)*. 136–140.

[30] Kaul, S. K., R. D. Yates, and M. Gruteser. 2012a. "Status updates through queues". In: *46th Annual Conference on Information Sciences and Systems (CISS)*. 1–6.

[31] Kaul, S., M. Gruteser, V. Rai, and J. Kenney. 2011a. "Minimizing age of information in vehicular networks". In: *8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*. 350–358.

[32] Kaul, S., R. Yates, and M. Gruteser. 2011b. "On Piggybacking in Vehicular Networks". In: *IEEE Global Telecommunications Conference (GLOBECOM)*. 1–5.

[33] Kaul, S., R. Yates, and M. Gruteser. 2012b. "Real-time status: How often should one update?" In: *IEEE International Conference on Computer Communications (INFOCOM)*. 2731–2735.

[34] Klein, A. G., S. Farazi, W. He, and D. R. Brown. 2017. "Staleness Bounds and Efficient Protocols for Dissemination of Global Channel State Information". *IEEE Transactions on Wireless Communications*. 16(9): 5732–5746. ISSN: 1536-1276.

[35] Kleinrock, L. 1975. *Queueing Systems*. Vol. I: Theory. Wiley Interscience.

[36] Kosta, A., N. Pappas, A. Ephremides, and V. Angelakis. 2017. "Age and value of information: Non-linear age case". In: *IEEE International Symposium on Information Theory (ISIT)*. 326–330.

[37] Labrinidis, A. and H. V. Jagadish. 2012. "Challenges and opportunities with big data". *Proceedings of the VLDB Endowment*. 5(12): 2032–2033.

[38] L'Heureux, A., K. Grolinger, H. F. Elyamany, and M. A. M. Capretz. 2017. "Machine Learning With Big Data: Challenges and Approaches". *IEEE Access*. 5: 7776–7797.

[39] Marz, N. 2014. *Apache Strom*. URL: http://storm.apache.org.

[40] Najm, E. and R. Nasser. 2016. "Age of information: The gamma awakening". In: *IEEE International Symposium on Information Theory (ISIT)*. 2574–2578.

[41] Najm, E., R. Yates, and E. Soljanin. 2017. "Status updates through M/G/1/1 queues with HARQ". In: *IEEE International Symposium on Information Theory (ISIT)*. 131–135.

[42] Nelson, R. 1995. *Probability, stochastic processes and queueing theory: the mathematics of computer performance modeling*. New York: Springer-Verlang.

[43] Neumeyer, L., B. Robbins, A. Nair, and A. Kesari. 2010. "S4: Distributed Stream Computing Platform". In: *IEEE International Conference on Data Mining Workshops*. 170–177.

[44] Papoulis, A. 1991. *Probability, random variables, and stochastic processes. McGraw-Hill series in electrical engineering*. New York: McGraw-Hill.

[45] Pappas, N., J. Gunnarsson, L. Kratz, M. Kountouris, and V. Angelakis. 2015. "Age of information of multiple sources with queue management". In: *IEEE International Conference on Communications (ICC)*. 5935–5940.

[46] Parag, P., A. Taghavi, and J. F. Chamberland. 2017. "On Real-Time Status Updates over Symbol Erasure Channels". In: *IEEE Wireless Communications and Networking Conference (WCNC)*. 1–6.

[47] Rudin, W. 1987. *Real and Complex Analysis, 3rd Ed.* New York, NY, USA: McGraw-Hill, Inc. ISBN: 0070542341.

[48] Sang, Y., B. Li, and B. Ji. 2017. "The Power of Waiting for More than One Response in Minimizing the Age-of-Information". *CoRR*. abs/1704.04848. URL: http://arxiv.org/abs/1704.04848.

[49] Sesia, S., I. Toufik, and M. Baker. 2011. *LTE, The UMTS Long Term Evolution: From Theory to Practice*. Wiley Publishing.

[50] Shannon, C. 1948. “A mathematical theory of communication”. *Bell system technical journal*. 27.

[51] Sun, Y., Y. Polyanskiy, and E. Uysal-Biyikoglu. 2017. “Remote estimation of the Wiener process over a channel with random delay”. In: *IEEE International Symposium on Information Theory (ISIT)*. 321–325.

[52] Sun, Y., E. Uysal-Biyikoglu, R. Yates, C. E. Koksal, and N. B. Shroff. 2016. “Update or wait: How to keep your data fresh”. In: *35th Annual IEEE International Conference on Computer Communications (INFOCOM)*. 1–9.

[53] Tse, D. 2017. “2017 Shannon Lecture: The Spirit of Information Theory”. In: *IEEE Information Theory Society Newsletter*.

[54] Uhlenbeck, G. E. and L. S. Ornstein. 1930. “On the theory of Brownian Motion”. *Phys. Rev.* 36: 823–841.

[55] Wu, X., J. Yang, and J. Wu. 2017. “Optimal status updating to minimize age of information with an energy harvesting source”. In: *IEEE International Conference on Communications (ICC)*. 1–6.

[56] Yates, R. D. 2015. “Lazy is timely: Status updates by an energy harvesting source”. In: *IEEE International Symposium on Information Theory (ISIT)*. 3008–3012.

[57] Yates, R. D., P. Ciblat, A. Yener, and M. Wigger. 2017a. “Age-optimal constrained cache updating”. In: *IEEE International Symposium on Information Theory (ISIT)*. 141–145.

[58] Yates, R. D. and S. Kaul. 2012. “Real-time status updating: Multiple sources”. In: *IEEE International Symposium on Information Theory (ISIT)*. 2666–2670.

[59] Yates, R. D. and S. K. Kaul. 2017. “Status updates over unreliable multiaccess channels”. In: *IEEE International Symposium on Information Theory (ISIT)*. 331–335.

[60] Yates, R. D., E. Najm, E. Soljanin, and J. Zhong. 2017b. “Timely updates over an erasure channel”. In: *IEEE International Symposium on Information Theory (ISIT)*. 316–320.

[61] Yates, R. D. and S. K. Kaul. 2016. "The Age of Information: Real-Time Status Updating by Multiple Sources". *CoRR*. abs/1608.08622. URL: http://arxiv.org/abs/1608.08622.

[62] Yates, R. D., M. Tavan, Y. Hu, and D. Raychaudhuri. 2017c. "Timely Cloud Gaming". In: *IEEE International Conference on Computer Communications (INFOCOM)*. 2286–2294.

[63] Zhong, J. and R. D. Yates. 2016. "Timeliness in Lossless Block Coding". In: *2016 Data Compression Conference (DCC)*. 339–348.

[64] Zhong, J., R. D. Yates, and E. Soljanin. 2017. "Backlog-adaptive compression: Age of information". In: *IEEE International Symposium on Information Theory (ISIT)*. 566–570.