Minimizing Age of Information on NOMA Communication Schemes for Vehicular Communication Applications

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***Abstract*—Real-time communication schemes supporting fresh information are of major importance for vehicular networks. In this direction, the Age of Information (AoI) concept is a power-full tool to operate with. Current publications bring equal importance to the AoI of packets in spite of the common case of unequal channel capacity and source entropy between them, this results in reduced user perception of fairness. This report analyses the use of power-domain NOMA to balance the assigned power between nodes to reduce the overall AoI. We verify an improved user perception of fairness in regard to the freshness of information at the destination.**

***Index Terms*—Age of Information (AoI), NOMA, wireless sensor networks (WSN).**

I. Introduction

AGE of Information (AoI) becomes an important metric to asses the proper performance on real-time communication systems [1]. Communication system design based on information freshness criteria allows planning resource assignments to optimal reduce the aged updates at the destination point. This criterion is of paramount importance in a wide range of applications such as vehicular, mobile and wireless sensor networks [2]. In this regard, the concept of AoI brings a metric to optimize system performance in terms of maintaining fresher information at the destination about a remote system.

Specifically, low AoI system behavior is critical for transportation safety applications [3]. For instance, intelligent transportation systems demand to have fresh information avoiding collisions and congestion on the road [4], [5]. Additionally, a variety of solutions are reported to balance freshness and service latency in vehicular networks [6], power minimization [7] or the average system age [8] on vehicular networks.

However, the reported use of AoI, on these applications, is not linked to the restriction imposed by the physical layer. For instance, on the vehicular networks, the information is transmitted through a wireless medium, which in turn introduce restrictions on the rate of transmission and the produced errors. At the destination, packets will be corrupted and discarded, the freshness of information criteria will be compromised by the impact of the channel.

The concept of AoI have been studied under the effects of errors to consider imperfect packet transmission schemes [9]–[13]. Freshness of information is deteriorated whenever arriving packets are discarded due to corrupted received samples. These papers analyze several transmission and reception policies over unreliable channels (binary symmetric erasure channels) where received messages could be corrupted.

The work in [9] derives closed-form formulas for the AoI based on two policies: the last-come-first-served (LCFS) scheduling and to keep transmitting the most recent packet upon reception by re-transmissions. The study in [10] uses coded updates and a comparative analysis is provided for two policies: transmitting k symbols until k symbols are received (IIR, infinite incremental redundancy), and in case of transmitting k symbols as a packet with n symbols (FR, finite redundancy). Additionally, in [11] a system with randomly generated updates is studied for IIR and FR cases but including ARQ (automatic request) procedure. The paper in [12] employs differential encoding technique to exploit the correlation in the resource messages, then to improve the timeliness performance. Finally, authors in [13] analyses the balance between data protection and timely delivery of collected data through the use of random linear coding.

The reported use of AoI is based on assigning equal importance to each transmitted packet from two different sources. However, when the different sources differ on the information entropy, then freshness at the destination point will be different when resources are equally allocated for both, for instance. In this case, the source with the higher entropy will be more aged and the user perception of fairness will be deteriorated.

These reported results can be extended to have a more realistic approach to describe the freshness of information through not only unreliable channels but also with the use of specific modulation schemes and information theory metrics (source entropy and allowable bit rate) as well. To take into account these additional metrics will convey not only a more realistic approach but also a more fair criterion to balance the

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performance of multiple sources.

In this report, we use the Peak Age of Information (PAoI) concept as a tool to state a problem formulation in a communicating scenario context through the use of power-domain non-orthogonal multiple access (NOMA). PAoI is a more tractable alternative to the study of complicated models [1]. NOMA is a promising radio access technique actively investigated in recent years to support a higher number of users through non-orthogonal resource allocation [14].

NOMA has been analyzed in comparison to orthogonal multiple access (OMA) in regard to the obtained AoI [15]. The publication derives a closed-form expression of the total average age of the network relying on a stochastic hybrid system framework. The resulting analyses indicate that the use of NOMA does not guarantee a lower AoI in the network in comparison to OMA. However, NOMA can be used to increase (at least to the double) the total number of distributed users in orthogonal resources. The dimension of power may be employed to allow more than one user to transmit on a given resource to deal with the increasing density of connected nodes in networks (e.g. vehicular networks [16]) .

Our goal is to optimally reduce PAoI by considering the errors produced by the channel noise, the source entropy and the allowable bit rate on the channel. We are interested in describing the effects of the source entropy on the minimum PAoI and the user perception of fairness. We conduct our study by considering a queue transmission model between source nodes and a destination taking into account transmission (source entropy, rate, and power) and channel (noise, allowable bit rate, bandwidth) parameters, as well as the symbol error rate performance at the destination.

The contribution of this study is the development of a model to account for the fresher of information in a more realistic scenario. By considering the transmitter and channel parameters we formulate an optimization problem with the aim of optimally reducing the age at the destination node. The resulting solution exhibits improved user perception of fairness in regard to the freshness of information at the destination.

The rest of the paper is organized as follows. Section II introduces the system model to account for the inclusion of transmitter and channel parameters, as well as the symbol error rate performance. The problem formulation and the solution to find the best source rate and transmission power are discussed in Section III under power constraints. Section IV exhibit the results in regard to the obtained minimum PAoI and presents PAoI behavior versus the source entropy value. The resulting overall and user perception of fairness is also discussed and presented. Finally, Section V concludes the paper.

II. System Model

A. System Model

Fig. 1 depicts the system model, where the two sensor nodes are denoted by x_1 and x_2, both randomly transmitting their packets at rates λ_1, λ_2, respectively. Sources are also described by entropy values H_1 and H_2. We consider a two users case only provided the degradation introduced in the bit error rate [17]. Sensor bits are queued following a first-come-first-served (FCFS) discipline. Then, on the transmitter block sensor's updates are packaged with non-orthogonal multiple access (NOMA) communication systems. Each packet on the queue is the superposition of the updated information from source nodes. The transmitter serves packets to the channel randomly with average rate μ, these packets arrive at destination node D through a band-limited additive white Gaussian noise (AWGN) channel.

We also assume an M/M/1 system to model arrivals according to a Poisson process and exponential service time. Band-limited channel of bandwidth W will, in turn, establish a lower limit on the allowable service time by $\frac{1}{W}$. To consider this restriction, we assume a right-shifted exponential distribution for the service time centered at $\frac{1}{W}$.

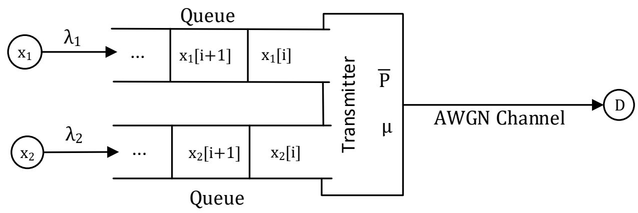

Fig. 1. Packets delivery process in a queuing system with AWGN Channel model.

Noisy channel in Fig. 1 will produce errors on the received symbols. Accordingly, the average peak of information will be given by [9]:

$$\Delta_{Peak_j} = \frac{1}{(1-\text{SER})\lambda_j} + \frac{1}{\mu - \lambda_j}. \quad (1)$$

for each specific node $j \in \{1, 2\}$ when $\lambda_j < \mu$, where SER denotates the symbol error rate at the receiver. Additionally, both sources will experience non-similar channel capacity based on their respective transmitted power P_j. Through the use of NOMA, each node may transmit a given total number of information bits per channel use by the following relation [18]:

$$b_j < R_j = \log_2(1 + \text{SNR}_{j,\Gamma}), \quad (2)$$

where:

$$\text{SNR}_{1,\Gamma} = \frac{P_1/\Gamma}{N}, \quad (3)$$

and:

$$\text{SNR}_{2,\Gamma} = \frac{P_2/\Gamma}{P_1 + N}, \quad (4)$$

when the receiver implements a successive interference cancellation (SIC) and the strong user (here assumed to be node x_2) is decoded first. Here we assume to operate over the minimum SNR threshold required to establish a reliable link [16]. The terms N and Γ_i in (3) and (4) accounts for the noise power and SNR gap approximation [19], respectively. We consider the use of M-QAM, on which case the analytic expression for Γ_i is given by [20]:

$$\Gamma = \frac{1}{3}\left[Q^{-1}\left(\frac{\text{SER}}{4}\right)\right], \tag{5}$$

for a given symbol error rate SER.

Due to the different channel capacity values for both sources in (2) and the source entropy, information from each node should experience different age at destination node even with similar transmission and service packet-rates. To illustrate, consider the two systems shown in Fig. 2, each system comprised by sources of entropy values H_1 and H_2, similar transmission and server -rates λ and μ, but different allowable bit rates R_1 and R_2 determined by relation in (2). Provided that information produced by each source has an average word length given by H_j and the maximum allowable bits per channel use is R_j, then in average the transmission of information needs $\frac{H_j}{R_j}$ channel accesses per updated information unit.

Here we remark that information from the source is updated at the receiver side after receiving the H_j bits instead of considering the updating of bits or generic packets. Taking into consideration this information unit (given by H_j), it will reflect a fair metric to compare the aged information between sources at the destination node.

For instance, in case that $\frac{H_1}{R_1} = \frac{H_2}{R_2}$, then both sources in Fig. 2 will be equally aged provided they both needs same total number of packets to update information unit at destination node. However, in case that $\frac{H_1}{R_2} < \frac{H_2}{R_2}$ then source 1 will be less aged than source 2 at destination node provided that total number of packets to update information unit from node 1 will be less than source 2, and vice-versa. Here we assume that processing delays on the communication chain is independent on the packet length.

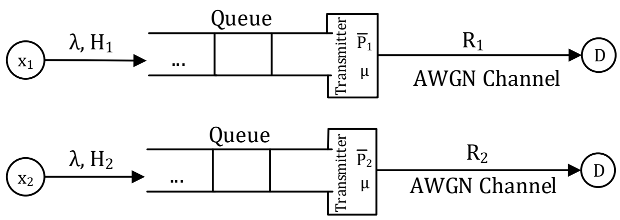

Fig. 2. Packets delivery process of two queuing systems with AWGN Channel model.

To consider these dissimilarities on source entropy and channel capacity to each node, we suggest to weight the average peak of information in (1) by the factor $\frac{H_j}{R_j}$ as follows:

$$\Delta^R_{Peak_j} = \frac{H_j}{R_j}\left(\frac{1}{(1-\text{SER})\lambda_j} + \frac{1}{\mu - \lambda_j}\right). \tag{6}$$

Based on this definition, the age of each information unit at the destination node will be increased by the total number of packets needed to update new information from the source. This will account for a reduced capability of node j to update packets due to limitations on the allowable bit rate with respect to the entropy source. This definition in (6) will provide different importance to each source packet in order to reduce PAoI, and thereby will improve the user perception of fairness. Additionally, this definition reflects some a connection between the concept of Age of Information and Information Theory [1] by means of terms R_j and H_j, which in turn will establish a more realistic approach to the communication scenario.

III. Problem Formulation and Solution

In this study, our goal is to reduce as much as possible the overall age of information at the destination node to both user nodes. Based on the proposed definition for average peak of information in (6), we expect to find the minimum average cost [21] (in regard to PAoI) of both nodes subject to an available total power $\bar{P}$:

$$\min_{\lambda_1,\lambda_2,P_1,P_2} \sum_{j=1}^{2}\left[\frac{H_j}{R_j}\left(\frac{1}{(1-\text{SER})\lambda_j} + \frac{1}{\mu-\lambda_j}\right)\right] \tag{7}$$

$$\text{s.t.:}\quad \bar{P} = \sum_{j=1}^{2} P_j, \tag{7a}$$

by computing optimal values of rate and average power of transmitted symbols given by λ_j and P_j, respectively. Proper analytic expressions for maximum allowable bit rate (R_i) are given by relations in (2). Quantities H_j, μ, SER and $\bar{P}$ are given constant values.

Provided we assume a given SNR value on the channel and the power restriction $\bar{P}$ in (7a), then the average noise power will be also fixed to $N = \bar{P} \cdot 10^{-\frac{\text{SNR}}{10}}$. Additionally, we also assume a given SER value, which in turn will determine the value of Γ in (5). Therefore, based on these three quantities ($\bar{P}$, N and Γ) and the restricted power value in (7a), the allowable bit rate will be also upper bounded by the corresponding $\text{SNR}_{\Gamma,j}$ ratio in (3) and (4). In this respect, we do not need to require for further restrictions related to channel capacity in problem formulation in (7). By means of this problem formulation, we may study the behavior of the minimum peak of information as well as the dependence of source rate (λ_j) and power (P_j) with the source entropy (H_j).

Solution to posed problem in (7) yields the proper values of power (P_1, P_2), and rate (λ_1, λ_2) for each node to minimize the average age of information. Considering the available channel capacity, and the source entropy, we aim to find the right balance on power and source rate for each node. To that end, we follow an exhaustive search plan to analyze the optimal ratios $\frac{P_2}{P_1}$ and $\frac{\lambda_2}{\lambda_1}$ that account for the less average PAoI. Next Section is devoted to present and discuss the simulation results.

IV. Simulation results and Discussion

We evaluate the minimum average peak of information in (7) for a varying ratio between the rate of the stronger user (λ_2) and the server rate (μ) given by $\rho = \frac{\lambda_2}{\mu}$ (server utilization). We assume that the server rate is $\mu = 1$, the symbol error rate is SER $= 10^{-5}$, the total power is $P = 1$ and the signal to noise ratio is SNR $= 5$ dB. We solve the posed problem in (7) by an exhaustive search plan evaluating 100 consecutive steps of the ratio $\rho = \frac{\lambda_2}{\mu}$ ranged on the interval $(0\ 1)$.

Fig. 3 shows the obtained average peak of information and the node parameters (P_j, λ_j) with varying server utilization ρ. To illustrate, we assume that both sources have equal entropy values given by $H_1 = H_2 = 1$. The obtained minimum peak of information and the node parameters is found by solving the problem in (7) for each specific value of λ_2. Based on obtained results in Fig. 3 a), the minimum age is 44.4748 units, node rates and energy values for both nodes must be equal when the server utilization is $\rho = 0.5$. Resulting peak age of information is higher for small and large server utilization provided the influence of the increased rate and waiting time on the packet delay [22].

Additionally, based on Fig. 3 b) and c) both rates must be equal ($\lambda_1 = \lambda_2$) overall ρ and the average power will be increased for the stronger user (node x_2) in case of larger server utilization. The minimum peak of information is attained for equal node rates (λ_j) overall ρ, provided that power-domain NOMA implements a communication scheme where the available bandwidth is used indistinguishably by both sources, an identical solution for the node rate is derived for both. On the other hand, by means of power, it is possible to increase the amount of transmitted information. The results in Fig. 3 c) indicates that the stronger user (node x_2) will reduce their age of information by increasing their respective allowable bit rate (R_2) in comparison to the weak user.

Fig. 4 illustrates the effects of the entropy source values on the average peak of information and the node parameters (P_j, λ_j). The larger the entropy of the stronger user in comparison with the weak user, the less the average peak of information as depicted in Fig. 4 a). In average, the updated information will be less aged when the stronger user transmits the information unit with the larger entropy. Additionally, both source ratios (λ_1 and λ_2) remain equal over all ρ. Similar to the case in Fig. 3, identical solution is verified for the source rate in both cases. Meanwhile the power ratio (P_2/P_1) will be an increasing value of ρ. That is, the stronger user will be favored in correspondence with their increasing source entropy.

Finally, Fig. 5 provides a comparison between the proposed solution and the reported in [9] based on the overall fairness as well as the user perception for each node. The paper in [9] is implemented by the relation in (1) without considering the effects of the allowable bit rate (R_j) as well as the source entropy (H_j). To illustrate, here we consider the case in which both users present the same entropy ($H_1 = H_2 = 1$) but the stronger user will have an increased allowable bit rate ($R_2 > R_1$) provided the higher power to transmit information

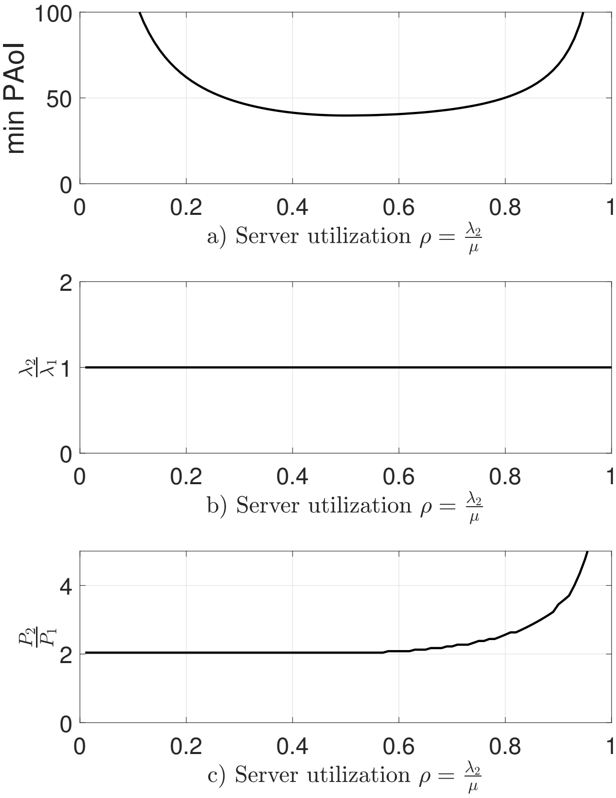

Fig. 3. Illustration of average peak of information and node parameters versus server utilization. a) Minimum peak of information. b) Ratio of node transmission rates. c) Ratio of derived energy values for each node.

($P_2 > P_1$). In this scenario, packets from the stronger user will be less aged than the weaker user provided that the stronger one has more chance to use the channel than the weaker one.

Overall and user fairness are computed by [23]:

$$f = \frac{\left[\frac{1}{2}\sum_{j=1}^{2}\Delta_j\right]^2}{\frac{1}{2}\sum_{j=1}^{2}\Delta_j^2} \tag{8}$$

and,

$$f_j = \Delta_j \frac{\sum_{j=1}^{2}\Delta_j^2}{\sum_{j=1}^{2}\Delta} \tag{9}$$

respectively. Where $\Delta_j = \Delta_{Peak_j}^{C}$ (eq. (6)) for the proposed solution and $\Delta_j = \Delta_{Peak_j}$ (eq. (1)) for the reported solution in [9].

Reported average peak of information in [9] does not consider the restriction on the allowable bit rate of the channel and the required amount of information to transmit by the nodes. In this case, the overall fairness and the user perception will be worst than the proposed solution, to balance the source entropy in correspondence with the allowable bit rate provides a metric to improve the user perception of fairness.

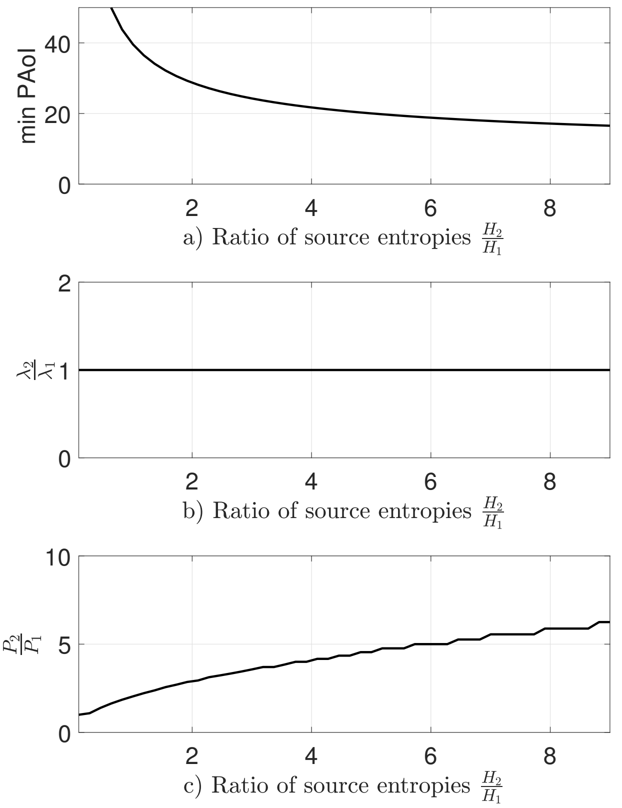

Fig. 4. Illustration of average peak of information and node parameters versus the ratio of sources entropies. a) Minimum peak of information. b) Ratio of node transmission rates. c) Ratio of derived energy values for each node.

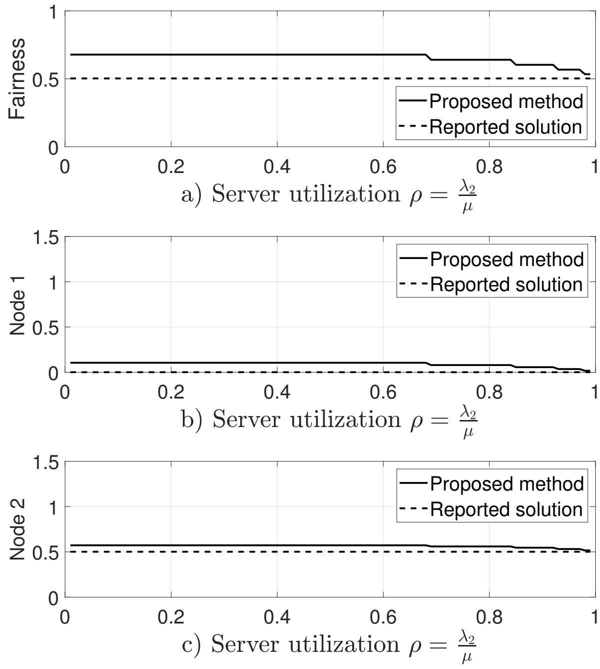

Fig. 5. Overall and user perception of fairness. a) Overall fairness. b) Node 1 perception of Fairness. c) Node 2 perception of Fairness.

V. Conclusion

Current paper addressed the optimal reduction of the overall peak average of information (PAoI) at a destination node about a remote pair of nodes. The formulation considers not only imperfect packet transmission but also the channel capacity limits. Based on the source entropy to the channel capacity ratio a more fair criteria is developed to enhance the user perception of the overall fairness. The importance of the received packets is considered based on the needs to transmit information (source entropy) and the limits on the rate of information transmission (channel capacity). Future work will be conducted to study the derive closed-form expressions to describe the minimum PAoI versus the ratio of source entropies $(\frac{H_2}{H_1})$ for the further study of limiting cases. Additionally, to formulate an optimal problem based on fairness criteria to balance the PAoI between users will be conducted.

References

[1] A. Kosta, N. Pappas, and V. Angelakis, *Age of Information: A New Concept, Metric, and Tool*. now, 2017. [Online]. Available: https://ieeexplore.ieee.org/document/8187436

[2] Y. Sun, E. Uysal-Biyikoglu, R. D. Yates, C. E. Koksal, and N. B. Shroff, "Update or Wait: How to Keep Your Data Fresh," *IEEE Transactions on Information Theory*, vol. 63, no. 11, pp. 7492–7508, Nov. 2017.

[3] P. Papadimitratos, A. D. L. Fortelle, K. Evenssen, R. Brignolo, and S. Cosenza, "Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation," *IEEE Communications Magazine*, vol. 47, no. 11, pp. 84–95, Nov. 2009.

[4] R. D. Yates and S. K. Kaul, "The Age of Information: Real-Time Status Updating by Multiple Sources," *IEEE Transactions on Information Theory*, vol. 65, no. 3, pp. 1807–1827, Mar. 2019.

[5] S. A. Ahmad, A. Hajisami, H. Krishnan, F. Ahmed-Zaid, and E. Moradi-Pari, "V2v System Congestion Control Validation and Performance," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 3, pp. 2102–2110, Mar. 2019. [Online]. Available: https://ieeexplore.ieee.org/document/8611373/

[6] S. Zhang, J. Li, H. Luo, J. Gao, L. Zhao, and X. S. Shen, "Towards Fresh and Low-Latency Content Delivery in Vehicular Networks: An Edge Caching Aspect," in *2018 10th International Conference on Wireless Communications and Signal Processing (WCSP)*. Hangzhou: IEEE, Oct. 2018, pp. 1–6. [Online]. Available: https://ieeexplore.ieee.org/document/8555643/

[7] M. K. Abdel-Aziz, C.-F. Liu, S. Samarakoon, M. Bennis, and W. Saad, "Ultra-Reliable Low-Latency Vehicular Networks: Taming the Age of Information Tail," in *2018 IEEE Global Communications Conference (GLOBECOM)*. Abu Dhabi, United Arab Emirates: IEEE, Dec. 2018, pp. 1–7. [Online]. Available: https://ieeexplore.ieee.org/document/8647466/

[8] M. Patra, A. Sengupta, and C. S. R. Murthy, "On minimizing the system information age in vehicular ad-hoc networks via efficient scheduling and piggybacking," *Wireless Networks*, vol. 22, no. 5, pp. 1625–1639, Jul. 2016. [Online]. Available: http://link.springer.com/10.1007/s11276-015-1056-3

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

[10] R. D. Yates, E. Najm, E. Soljanin, and J. Zhong, "Timely updates over an

erasure channel," in *2017 IEEE International Symposium on Information Theory (ISIT)*, Jun. 2017, pp. 316–320.

[11] E. Najm, R. Yates, and E. Soljanin, "Status updates through M/G/1/1 queues with HARQ," Jun. 2017, pp. 131–135.

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

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

[14] A. Yadav and O. A. Dobre, "All Technologies Work Together for Good: A Glance at Future Mobile Networks," *IEEE Wireless Communications*, vol. 25, no. 4, pp. 10–16, Aug. 2018.

[15] A. Maatouk, M. Assaad, and A. Ephremides, "Minimizing The Age of Information: NOMA or OMA?" in *IEEE INFOCOM 2019 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. Paris, France: IEEE, Apr. 2019, pp. 102–108. [Online]. Available: https://ieeexplore.ieee.org/document/8845254/

[16] L. Liang, H. Peng, G. Y. Li, and X. Shen, "Vehicular Communications: A Physical Layer Perspective," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 12, pp. 10 647–10 659, Dec. 2017. [Online]. Available: http://ieeexplore.ieee.org/document/8031287/

[17] H. Sari, A. Maatouk, E. Caliskan, M. Assaad, M. Koca, and G. Gui, "On the foundation of NOMA and its application to 5G cellular networks," in *2018 IEEE Wireless Communications and Networking Conference (WCNC)*, Apr. 2018, pp. 1–6, iSSN: 1558-2612.

[18] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*, edicin: 1 ed. Cambridge, UK ; New York: Cambridge University Press, Jul. 2005.

[19] Ana Garcia-Armada, "SNR gap approximation for M-PSK-Based bit loading," *IEEE Transactions on Wireless Communications*, vol. 5, no. 1, pp. 57–60, Jan. 2006.

[20] J. M. Cioffi, G. P. Dudevoir, M. V. Eyuboglu, and G. D. Forney, "MMSE decision-feedback equalizers and coding. II. Coding results," *IEEE Transactions on Communications*, vol. 43, no. 10, pp. 2595–2604, Oct. 1995.

[21] P. R. Jhunjhunwala and S. Moharir, "Age-of-Information Aware Scheduling," in *2018 International Conference on Signal Processing and Communications (SPCOM)*, Jul. 2018, pp. 222–226.

[22] S. Kaul, R. Yates, and M. Gruteser, "Real-time status: How often should one update?" in *2012 Proceedings IEEE INFOCOM*, 2012-03, pp. 2731–2735.

[23] R. Jain, *A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Computer System*. Eastern Research Laboratory, Digital Equipment Corporation, 1984.