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RPPR Final Report
as of 14-Dec-2022

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STEM Degrees: 5 **STEM Participants:** 3

Major Goals: Increasingly wireless data services extend beyond traditional best-effort communication to enhanced data applications such as interactive video, real-time multimedia streaming, high-throughput data access and Voice-over-IP. Additionally, the United States military greatly relies on wireless communications for its operations, including command, control, surveillance, reconnaissance, and targeting system. Invariably, meeting the quality-of-service (QoS) requirements of these applications translates into strict delay and throughput constraints. However, meeting such requirements over an unreliable wireless channel is a very challenging task, due to mobility, time-varying channel quality, energy and power limitations, and packet losses. Our goal is to develop transmission scheduling schemes for traffic with both latency and throughput requirements.
We propose to develop new approaches for supporting delay sensitive traffic over multi-hop wireless networks subject to interference constraints. In particular, we plan to develop routing and scheduling schemes for delay constrained traffic over multi-hop wireless networks using a combination of machine-learning, optimization, and stochastic control techniques. Our research include the following interdependent goals:

1) ? Develop transmission scheduling schemes for real-time traffic over wireless networks subject to interference constraints. We will consider both combinatorial interference models (as described by link activation sets) as well as SINR-based interference models.

2) Develop joint routing and scheduling schemes for multi-hop networks with delay constraints.

3) Develop delay sensitive routing schemes for hybrid networks, consisting of wired, wireless, and “black-box” components.

4) ?Develop a utility optimization framework for networks with delay constraints.

Accomplishments: Throughout this project we have addressed the problem of low-latency communication over multi-hop wireless networks. Some of our key contributions include:

In [1] we consider a wireless broadcast network with a base station sending time-sensitive information to a number of clients through unreliable channels. The Age of Information (AoI), namely the amount of time that elapsed since the most recently delivered packet was generated, captures the freshness of the information. We formulate a discrete-time decision problem to find a transmission scheduling policy that minimizes the expected weighted sum AoI of the clients in the network. We first show that in symmetric networks, a greedy policy, which transmits the packet for the client with the highest current age, is optimal. For general networks, we develop three low-complexity

scheduling policies: a randomized policy, a MaxWeight policy and a Whittle's Index policy, and derive performance guarantees as a function of the network configuration. To the best of our knowledge, this is the first work to derive performance guarantees for scheduling policies that attempt to minimize AoI in wireless networks with unreliable channels. Numerical results show that both the Max-Weight and Whittle's
Index policies outperform the other scheduling policies in every configuration simulated, and achieve near optimal performance.

In [2] we consider a discrete-time decision problem to find a transmission scheduling policy that minimizes the expected weighted sum AoI of the clients in the network. We first show that in symmetric networks, a greedy policy, which transmits the packet for the client with the highest current age, is optimal. For general networks, we develop three low-complexity scheduling policies: a randomized policy, a MaxWeight policy and a Whittle's Index policy, and derive performance guarantees as a function of the network configuration. To the best of our knowledge, this is the first work to derive performance guarantees for scheduling policies that attempt to minimize AoI in wireless networks with unreliable channels.
Numerical results show that both the Max-Weight and Whittle's Index policies outperform the other scheduling policies in every configuration simulated, and achieve near optimal performance.

In [3] we consider AoI minimization problem for a network with general interference constraints, and time varying channels. We propose two policies, namely, virtual-queue based policy and age-based policy when the channel state is available to the network scheduler at each time step. We prove that the virtual queue based policy is nearly optimal, up to a constant additive factor, and the age-based policy is at-most factor 4 away from optimality. Comparison with previous work, which derived age optimal policies when channel state information is not available to the scheduler, demonstrates a 4 fold improvement in age due to the availability of channel state information.

In [4] We consider the problem of minimizing average and peak AoI in a wireless networks, consisting of a set of source-destination links, under general interference constraints. When fresh information is always available for transmission, we show that a stationary scheduling policy is peak age optimal. We also prove that this policy achieves average age that is within a factor of two of the optimal average age. In the case where fresh information is not always available, and packet/information generation rate has to be controlled along with scheduling links for transmission, we prove an important separation principle: the optimal scheduling policy can be designed assuming fresh information, and independently, the packet generation rate control can be done by ignoring interference. Peak and average AoI for discrete time G/Ber/1 queue is analyzed for the first time, which may be of independent interest.

In [5] we consider the problem of timely exchange of updates between a central station and a set of ground terminals V, via a mobile agent that traverses across the ground terminals along a mobility graph G = (V, E). We design the trajectory of the mobile agent to minimize average-peak and average age of information (AoI), two recently proposed metrics for measuring timeliness of information. We consider randomized trajectories, in which the mobile agent travels from terminal i to terminal j with probability Pi,j . For the information gathering problem, we show that a randomized trajectory is average-peak age optimal and factor-8H average age optimal, where H is the mixing time of the randomized trajectory on the mobility graph G. We also show that the average age minimization problem is NP-hard. For the information dissemination problem, we prove that the same randomized trajectory is factor-O(H) average-peak and average age optimal. Moreover, we propose an age-based trajectory, which utilizes information about current age at terminals, and show that it is factor-2 average age optimal in a symmetric setting.

Finally, in [9] we we propose WiFresh: an unconventional architecture that achieves near optimal information freshness in wireless networks of any size, even when the network is overloaded. Our experimental results show that WiFresh can improve information freshness by two orders of magnitude when compared to an equivalent standard WiFi network. We propose and realize two strategies for implementing WiFresh: one at the MAC layer using hardware-level programming and another at the Application layer using Python. Our system implementations leverage the programmable wireless networking testbed supported by an ARO DURIP award.

Training Opportunities:
A number of graduate students were trained on low-latency wireless networking while working on this project. One former student is now a postdoctoral fellow at Columbia University, and another is pursuing their PhDs at MIT. In addition, three undergraduate students worked with us on implementing some of our algorithms on our ARO/DURIP funded programmable wireless testbed. One of these students is now pursuing a PhD at Stanford University.

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as of 14-Dec-2022

Results Dissemination:
Our work resulted in multiple conference and journal publications. These include:

[1] Igor Kadota, Abhishek Sinha, Rahul Singh, Elif Uysal-Biyikoglu, Eytan Modjano, “Scheduling Policies for Minimizing Age of Information in Broadcast Wireless Networks,” IEEE/ACM Transactions on Networking, Vol. 26, No. 5, October 2018.

[2] Igor Kadota, Abhishek Sinha, Eytan Modiano, “Scheduling Algorithms for Optimizing Age of Information in Wireless Networks With Throughput Constraints,” IEEE/ACM Transactions on Networking, August 2019.

[3] Rajat Talak, Sertac Karaman, Eytan Modiano, "Improving Age of Information in Wireless Networks with Perfect Channel State Information," IEEE/ACM Transactions on Networking, Vol. 28, No. 4, August 2020.

[4] Rajat Talak, Sertac Karaman, Eytan Modiano, “Optimizing Information Freshness in Wireless Networks under General Interference Constraints,” IEEE/ACM transactions on Networking, Vol. 28, No. 1, February 2020.

[5] Vishrant Tripathi, Rajat Talak, Eytan Modiano, "Age Optimal Information Gathering and Dissemination on Graphs," Transactions on Mobile Computing, April 2021.

[6] Rajat Talak, Eytan Modiano, “Age-Delay Tradeoffs in Queueing Systems," IEEE Transactions on Information Theory, 2021.

[7] Igor Kadota and Eytan Modiano, “Minimizing the Age of Information in Wireless Networks with Stochastic Arrivals,” IEEE Transactions on Mobile Computing, 2020.

[8] Rajat Talak, Sertac Karaman, Eytan Modiano, “Capacity and Delay Scaling for Broadcast Transmission in Highly Mobile Wireless Networks,” IEEE Transactions on Mobile Computing, 2019.

[9] Igor Kadota, Muhammad Shahir Rahman, and Eytan Modiano, "WiFresh: Age-of-Information from Theory to Implementation," International Conference on Computer Communications and Networks (ICCCN), 2021.

Honors and Awards: Our work under this project received best paper awards at leading conferences in the field. In particular,

1) Igor Kadota, Abhishek Sinha, Eytan Modiano, "Optimizing Age of Information in Wireless Networks with Throughput Constraints," IEEE Infocom, Honolulu, HI, April 2018. Best paper award.

2) Rajat Talak, Sertac Karaman, Eytan Modiano, "Optimizing Information Freshness in Wireless Networks under General Interference Constraints," ACM MobiHoc 2018, Los Angeles, CA, June 2018. Best paper award.

3) PI Modiano received the Infocom Achievement Award for "pioneering contributions to the analysis and design of cross-layer resource allocation algorithms for wireless, optical, and satellite networks."

Protocol Activity Status:

Technology Transfer:
1) PI Modiano continues to collaborate with researchers at the Naval Research Laboratory and MIT Lincoln Laboratory on wireless networking.

2) PI Modiano is working with ARL employee, Chirag Rao, who is a graduate student at MIT, on the topic of low-latency wireless networking.

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Participant Type: Faculty
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Person Months Worked: 1.00 **Funding Support:**

Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Article Title: Optimizing Age of Information in Wireless Networks with Throughput Constraints
Authors: Igor Kadota, Abhishek Sinha and Eytan Modiano
Keywords: wireless networks, Age of Information, latency, delay, scheduling
Abstract: Age of Information (AoI) is a performance metric that captures the freshness of the information from the perspective of the destination. The AoI measures the time that elapsed since the generation of the packet that was most recently delivered to the destination. In this paper, we consider a singlehop wireless network with a number of nodes transmitting timesensitive information to a Base Station and address the problem of minimizing the Expected Weighted Sum AoI of the network while simultaneously satisfying timely-throughput constraints from the nodes. We develop three low-complexity transmission scheduling policies that attempt to minimize AoI subject to minimum throughput requirements and evaluate their performance against the optimal policy. In particular, we develop a randomized policy, a Max- Weight policy and a Whittle's Index policy, and show that they are guaranteed to be within a factor of two, four and eight, respectively, away from the minimum AoI possible. In con
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Authors: Igor Kadota, Eytan Modiano
Acknowledged Federal Support: **Y**

Partners

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I certify that the information in the report is complete and accurate:
Signature: Eytan Modiano
Signature Date: 8/31/22 4:30PM

WiFresh: An AoI-based MAC protocol

- Implementation using a software defined networking testbed

- NI USRP-2974
  - Standalone units
  - Processor: Intel Core i7
  - FPGA: Kintex-7
  - Freq. range: 10 MHz to 6 GHz
  - **Ultra-fast MAC layer implementation**

- Raspberry Pi mobile devices
  - Add-ons: Camera, GPS antenna, Inertial Measurement Unit
  - **Simple application layer implementation**