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|---|--------------------------------|---|
| 1. REPORT DATE (DD-MM-YYYY) 16-04-2023 | 2. REPORT TYPE Final Report | 3. DATES COVERED (From - To) 24-Jul-2018 - 19-Jan-2023 |
|---|--------------------------------|---|

| | |
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| 4. TITLE AND SUBTITLE Final Report: Towards End-to-End QoE Guarantees for Timely Video Delivery in Adversarial Multi-hop Battlefield Networks | 5a. CONTRACT NUMBER W911NF-18-1-0331 |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER 611102 |

| | |
|------------|----------------------|
| 6. AUTHORS | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |

| | |
|--|--|
| 7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Texas Engineering Experiment Station SRS 400 Harvey Mitchell Parkway South, Suite 300 College Station, TX 77845 -4375 | 8. PERFORMING ORGANIZATION REPORT NUMBER |
|--|--|

| | |
|--|---|
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211 | 10. SPONSOR/MONITOR'S ACRONYM(S) ARO |
| | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) 73254-NC.30 |

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|--|
| 12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution is unlimited. |
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| 13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation. |
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| 14. ABSTRACT |
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| 15. SUBJECT TERMS |
|-------------------|

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|---------------------------------|-------------------|--------------------|----------------------------------|---------------------|---|
| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT UU | 15. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON I-Hong Hou |
| a. REPORT UU | b. ABSTRACT UU | c. THIS PAGE UU | | | 19b. TELEPHONE NUMBER 979-862-1092 |

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as of 17-Apr-2023

Agency Code: 21XD

Proposal Number: 73254NC

Agreement Number: W911NF-18-1-0331

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DUNS Number: 847205572

EIN: 741974733

Report Date: 19-Apr-2023

Date Received: 16-Apr-2023

Final Report for Period Beginning 24-Jul-2018 and Ending 19-Jan-2023

Title: Towards End-to-End QoE Guarantees for Timely Video Delivery in Adversarial Multi-hop Battlefield Networks

Begin Performance Period: 24-Jul-2018

End Performance Period: 19-Jan-2023

Report Term: 0-Other

Submitted By: I-Hong Hou

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 3

STEM Participants:

Major Goals: The objective of this project is to establish a new framework for developing network algorithms that ensure both end-to-end delay and end-to-end QoE for video delivery in battlefield networks in the presence of event-driven IoT applications. Our framework will be built upon two critical components: One is an analytical model that precisely calculates a range of QoE metrics, such as the frequency and duration of video interruptions and video quality, based on the traces of packet deliveries. This enables us to translate the perceived video quality, which is a subjective matter, into measurable, and hence optimizable, network performance metrics. The other is a network model that explicitly addresses several important features of battlefield networks, including unreliable wireless transmissions, multi-hop transmissions, end-to-end delay bounds, and unpredictable, adversarial even, packet generations from event-driven IoT applications. By combining these two components, our framework can serve as the foundation to analyze the actual QoE performance of network algorithms under realistic battlefield networks.

Based on our framework, we will develop a rich suite of network algorithms, including packet scheduling, multi-hop routing, and dynamic video rate control, that optimize end-to-end QoE under end-to-end delay constraints. Our algorithms will jointly consider video flows and event-driven IoT applications, and offer provably optimal QoE performance for video flows without sacrificing the reliability of event-driven IoT applications. We will also study implementation issues of our algorithms within the framework of software-defined networking (SDN).

Our research efforts are organized in the following four thrusts:

1. QoE optimization for one-hop wireless networks: We will start by considering the case of one-hop wireless networks, where a wireless gateway delivers multiple video flows to its connected users. Building upon our recent work on minimizing video interruption duration for on-demand video, we will further address the delay constraints of live surveillance video streaming, as well as other important QoE metrics such as the interruption frequency and video bit rate.
2. End-to-end QoE for multi-hop networks: We will further investigate optimizing end-to-end QoE for multi-hop networks. We will combine our recent breakthrough on guaranteeing end-to-end delay and timely deliveries, and results from Thrust 1 to develop tractable algorithms that simultaneously support both end-to-end QoE and end-to-end delay bound. We will also focus on developing distributed algorithms that require minimum coordination between wireless nodes.
3. Coexistence with event-driven IoT applications under adversarial environments: We will study practical battlefield networks where video streaming applications need to coexist with event-driven IoT applications by

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focusing on two specific challenges: The first is network congestion due to a short burst of event-driven packets, which will be addressed by dynamic video rate control algorithms. The second is the unpredictable nature of battlefield events, for which we will develop online algorithms that ensure both end-to-end QoE for video flows and end-to-end reliability for IoT applications even under an adversarial series of events.

4. Implementation and integration with software-defined networking: We will address the critical issues of realistically implementing our proposed policies. We will consider integrating our proposed policies in a SDN-based framework, where a SDN controller determines the optimal policies, while each wireless node simply carries out the prescribed policies. We will also implement and test our policies using our programmable MAC testbed that supports ultra-low latency scheduling.

Accomplishments: We have made significant progress related to the seven topics listed in Major Goals. This project has produced 8 journal articles, 20 conference papers, and one book chapter. Below is the summary of some major results related to the topics in Major Goals:

1. QoE optimization for one-hop wireless networks:

We have studied QoE optimization for three very different applications: real-time video streaming, virtual reality (VR), real-time estimation, and age-of-information (AoI).

To study real-time video streaming, we consider two most critical QoE metrics: playback latency and video interruption. We characterize the fundamental tradeoffs between playback latency and video interruption. We also develop the optimal scheduling policy under mild constraints [1].

To study QoE optimization for VR, we consider delivering VR contents of both high video quality and fast responsiveness, over wireless networks with limited bandwidth. We propose to leverage the predictability of user movements in the virtual world and develop an optimal predictive scheduling policy. In addition to our theoretical study, we demonstrate the usefulness of our policy by building a prototype system. We show that our policy can be implemented under Furion, a Unity-based VR gaming software, with minor modifications [2].

To study real-time estimation, we consider wireless networks where multiple flows are delivering status updates about their respective information sources. An end user aims to make accurate real-time estimations about the status of each information source using its received packets. We propose a new metric called loss-of-confidence (LoC) to measure how the confidence interval of the end user's estimation is impacted by packet deliveries. We develop the optimal scheduling policy for minimizing LoC under various systems [3, 4]. We also show that our policies indeed achieve the smallest estimation error for an actual estimation problem [5].

Finally, we study the optimization of AoI, a new performance metric that has gathered significant research interests. We develop a theoretical framework of designing scheduling policies for second-order optimization. We employ this framework for the optimization of AoI over Gilbert-Elliott channels [6]. We also study the information freshness in M/G/1 queueing system with a single buffer and the server taking multiple vacations. This system has wide applications in communication systems. We evaluate the information freshness in this system with both i.i.d. and non-i.i.d. vacations under three different scheduling policies. For the systems with i.i.d. vacations [7].

2. End-to-end QoE for multi-hop networks:

We study the problem of broadcasting real-time flows in multi-hop wireless networks. We propose a distributed protocol called the delegated-set routing (DSR) that incurs virtually no overhead of coordination among nodes. We also develop distributed algorithms that aim to maximize the total timely utility under DSR [8]. To address interference in multi-hop networks, we also develop a joint CSMA, routing, and scheduling policy that maximizes end-to-end timely throughputs [9]. Further, we study leveraging content caching to optimize end-to-end QoE. We propose a distributed algorithm that jointly optimizes cache-version selection and content placement for adaptive video streaming in wireless edge networks [10].

3. Coexistence with event-driven IoT applications under adversarial environments:

We have studied adversarial environments from three directions: unknown future arrivals, selfish behaviors, and compromised devices.

We study the amount of capacity needed to provide stringent timely delivery guarantees in adversarial environment. We propose a low-complexity online algorithm and prove that it only requires a small amount of redundancy to guarantee the timely delivery of most packets without any knowledge about future packet arrivals [11]. We also study a problem of jointly optimizing two important operations in mobile edge computing without knowing future requests, namely service caching, which determines which services to be hosted at the edge, and service routing, which determines which requests to be processed locally at the edge. We propose a simple online algorithm with sub-linear regrets [12].

We investigate the problem of index coding with selfish clients. Our objectives are to motivate each selfish client to reveal the correct private information and to maximize the social welfare. We develop joint coding and incentive

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schemes for achieving these two objectives [13].

Finally, we consider IoT applications where some sensors are compromised and may report false data. We develop watermarking techniques to address such vulnerability [14 – 20].

4. Implementation and integration with software-defined networking:

We have built a testbed that integrates PULS, which is our earlier work on Processor-Supported Ultra-Low Latency Scheduling, with software-defined networking (SDN), software-defined radio (SDR), and the optional usage of information-centric networking (ICN). We have used this testbed to evaluate a recent work on predictive scheduling for virtual reality. The video demo is shown in [21].

We also built a mm-wave testbed. We design and implement MAC protocols on this testbed [22 – 24].

In addition, we have many research accomplishments that are critical to battlefield networks, although not covered in Major Goals. They include employing Reward-Biased Maximum Likelihood Estimate method for reinforcement learning [25 – 28], developing learning algorithms for Whittle-based scheduling policy [29], and addressing safety in reinforcement learning [30].

Training Opportunities: This project partially supported eight graduate students. The PIs provide one-on-one mentoring to these students. Three of the students have received their Ph.D. degrees in the duration of this project.

Results Dissemination: Our research results have been promptly disseminated through conference/journal publications. PI Hou has presented invited talks in Information Theory and Applications Workshop in 2019 and 2020.

Honors and Awards: 1. PI Kumar received the IEEE Alexander Graham Bell Medal, 2022. “For seminal contributions to the modeling, analysis, and design of wireless networks.”

2. PI Kumar was elected as a Fellow of International Federation of Automatic Control (IFAC), July 29, 2022. “For seminal contributions to adaptive control and analysis of wireless networks”

3. Best Paper Award in ACM MobiHoc 2020 for the paper: Ping-Chun Hsieh, Xi Liu, and I-Hong Hou, “Fresher Content or Smoother Playback? A Brownian- Approximation Framework for Scheduling Real-Time Wireless Video Streams,” in ACM MobiHoc 2020.

4. Runner-up for Best Paper Award in WiOpt 2019 for the paper: Daojing Guo and I-Hong Hou, “On the Credibility of Information Flows in Real-Time Wireless Networks.”

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI

Participant: I-Hong Hou

Person Months Worked: 3.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Co PD/PI

Participant: P. R. Kumar

Person Months Worked: 3.00

Project Contribution:

National Academy Member: Y

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Hyunwook Kang

Person Months Worked: 5.00

Project Contribution:

Funding Support:

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as of 17-Apr-2023

National Academy Member: N

Participant Type: Staff Scientist (doctoral level)

Participant: Woo Hyun Ko

Person Months Worked: 2.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Graduate Student (research assistant)

Participant: Bharadwaj Satchidanandan

Person Months Worked: 2.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Graduate Student (research assistant)

Participant: Daojing Guo

Person Months Worked: 10.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Graduate Student (research assistant)

Participant: Narges Zarnaghinaghsh

Person Months Worked: 7.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Graduate Student (research assistant)

Participant: Siqi Fan

Person Months Worked: 15.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Graduate Student (research assistant)

Participant: Akshay Rajiv Mete

Person Months Worked: 11.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Graduate Student (research assistant)

Participant: Tao Liu

Person Months Worked: 5.00

Funding Support:

Project Contribution:

National Academy Member: N

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as of 17-Apr-2023

Participant Type: Graduate Student (research assistant)

Participant: Tzu Hsiang Lin

Person Months Worked: 1.00

Funding Support:

Project Contribution:

National Academy Member: N

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: IEEE Control Systems Letters

Publication Identifier Type: DOI

Publication Identifier: 10.1109/LCSYS.2019.2925278

Volume: 4

Issue: 2

First Page #: 307

Date Submitted: 5/20/20 12:00AM

Date Published: 4/1/20 5:00AM

Publication Location:

Article Title: On the Design of Security-Guaranteeing Dynamic Watermarks

Authors: Bharadwaj Satchidanandan, P. R. Kumar

Keywords: Cyber-physical systems, security, dynamic watermarking, non-Gaussian systems.

Abstract: Dynamic watermarking is a defense mechanism to secure cyberphysical systems from arbitrary sensor attacks. The approach involves the actuators of a plant superimposing on the control policy-specified input a “small” random signal called the dynamic watermark (DW), and conducting certain carefully designed tests to detect the presence of adversarial sensors. Prior works on this topic have restricted attention to systems where the process and measurement noises affecting the system are Gaussian random processes. In this letter, we go beyond the class of Gaussian systems and address the problem of designing watermarks for linear systems affected by arbitrarily distributed noise. We first show how the fundamental security guarantee of DW can fail when the statistics of the watermark are not chosen appropriately taking into account the parameters of the noise process that affects the system. Subsequently, we address the problem of how security-guaranteeing DWs should be designed.

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: IEEE/ACM Transactions on Networking

Publication Identifier Type: DOI

Publication Identifier: 10.1109/TNET.2019.2917393

Volume: 27

Issue: 3

First Page #: 1258

Date Submitted: 5/20/20 12:00AM

Date Published: 6/1/19 5:00AM

Publication Location:

Article Title: Online Routing and Scheduling With Capacity Redundancy for Timely Delivery Guarantees in Multihop Networks

Authors: Han Deng, Tao Zhao, I-Hong Hou

Keywords: Competitive ratio, cyber-physical systems, multi-hop networks, online algorithms, optimal scheduling.

Abstract: It has been shown that it is impossible to achieve stringent timely delivery guarantees in a large network without having complete information of all future packet arrivals. In order to maintain desirable performance in the presence of uncertainty of future, a viable approach is to add redundancy by increasing link capacities. This paper studies the amount of capacity needed to provide stringent timely delivery guarantees. We propose a low-complexity online algorithm and prove that it only requires a small amount of redundancy to guarantee the timely delivery of most packets. Further, we show that in large networks with very high timely delivery requirements, the redundancy needed by our policy is at most twice as large as a theoretical lower bound. For practical implementation, we propose a distributed protocol based on this centralized policy. Without adding redundancy, we further propose a low-complexity order-optimal online policy for the network.

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: Y

RPPR Final Report

as of 17-Apr-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: IEEE Journal on Selected Areas in Communications

Publication Identifier Type: DOI

Publication Identifier: 10.1109/JSAC.2021.3065093

Volume: 39

Issue: 5

First Page #: 1339

Date Submitted: 8/31/21 12:00AM

Date Published: 5/1/21 5:00AM

Publication Location:

Article Title: Scheduling Real-Time Information-Update Flows for the Optimal Confidence in Estimation

Authors: Daojing Guo, I-Hong Hou

Keywords: Wireless networks , packet scheduling , optimization , information-update systems , real-time estimation

Abstract: This paper considers a wireless network where multiple flows are delivering status updates about their respective information sources. An end-user aims to make accurate real-time estimations about the status of each information source using its received packets. As the accuracy of estimation is most impacted by events in the recent past, we propose to measure the Confidence-in-Estimation by the number of timely deliveries in a window of the recent past, and say that a flow suffers from a Loss-of-Confidence (LoC) if this number is insufficient for the end user to make a reliable estimation with small confidence intervals. We then study the problem of minimizing the system-wide LoC in wireless networks where each flow has a different requirement and link quality. We show that the problem of minimizing the system-wide LoC requires the control of the temporal variance of timely deliveries for each flow.

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: IEEE/ACM Transactions on Networking

Publication Identifier Type: DOI

Publication Identifier: 10.1109/TNET.2021.3063626

Volume: 29

Issue: 3

First Page #: 1224

Date Submitted: 8/31/21 12:00AM

Date Published: 6/1/21 5:00AM

Publication Location:

Article Title: Adaptive CSMA for Decentralized Scheduling of Multi-Hop Networks With End-to-End Deadline Constraints

Authors: Rahul Singh, P. R. Kumar

Keywords: Scheduling algorithms , wireless networks , multi-armed bandits , real-time systems

Abstract: This paper considers a wireless network where multiple flows are delivering status updates about their respective information sources. An end-user aims to make accurate real-time estimations about the status of each information source using its received packets. As the accuracy of estimation is most impacted by events in the recent past, we propose to measure the Confidence-in-Estimation by the number of timely deliveries in a window of the recent past, and say that a flow suffers from a Loss-of-Confidence (LoC) if this number is insufficient for the end user to make a reliable estimation with small confidence intervals. We then study the problem of minimizing the system-wide LoC in wireless networks where each flow has a different requirement and link quality. We show that the problem of minimizing the system-wide LoC requires the control of the temporal variance of timely deliveries for each flow.

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: Y

RPPR Final Report as of 17-Apr-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: IEEE Transactions on Communications

Publication Identifier Type: DOI

Publication Identifier: 10.1109/TCOMM.2021.3049123

Volume: 69

Issue: 4

First Page #: 2176

Date Submitted: 8/31/21 12:00AM

Date Published: 4/1/21 5:00AM

Publication Location:

Article Title: Joint Index Coding and Incentive Design for Selfish Clients

Authors: Yu-Pin Hsu, I-Hong Hou, Alex Sprintson

Keywords: Network coding , game theory , incentive design

Abstract: This paper considers a wireless network where multiple flows are delivering status updates about their respective information sources. An end-user aims to make accurate real-time estimations about the status of each information source using its received packets. As the accuracy of estimation is most impacted by events in the recent past, we propose to measure the Confidence-in-Estimation by the number of timely deliveries in a window of the recent past, and say that a flow suffers from a Loss-of-Confidence (LoC) if this number is insufficient for the end user to make a reliable estimation with small confidence intervals. We then study the problem of minimizing the system-wide LoC in wireless networks where each flow has a different requirement and link quality. We show that the problem of minimizing the system-wide LoC requires the control of the temporal variance of timely deliveries for each flow.

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Proceedings of the IEEE

Publication Identifier Type:

Publication Identifier:

Volume: 109

Issue: 4

First Page #: 495

Date Submitted: 8/31/21 12:00AM

Date Published: 4/15/21 5:00AM

Publication Location:

Article Title: A Survey of Cybersecurity of Digital Manufacturing

Authors: Priyanka Mahesh, Akash Tiwari, Chenglu Jin, Panganamala R. Kumar, A. L. Narasimha Reddy, Satish T

Keywords: Digital Manufacturing

Abstract: —The Industry 4.0 concept promotes a digital manufacturing (DM) paradigm that can enhance quality and productivity, that reduces inventory and the lead-time for delivering custom, batch-of-one products based on achieving convergence of Additive, Subtractive, and Hybrid manufacturing machines, Automation and Robotic Systems, Sensors, Computing, and Communication Networks, Artificial Intelligence, and Big Data. A DM system consists of embedded electronics, sensors, actuators, control software, and inter-connectivity to enable the machines and the components within them to exchange data with other machines, components therein, the plant operators, the inventory managers, and customers. This paper presents the cybersecurity risks in the emerging DM context, assesses the impact on manufacturing, and identifies approaches to secure DM.

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: IEEE Transactions on Network Science and Engineering

Publication Identifier Type: DOI

Publication Identifier: 10.1109/TNSE.2021.3138340

Volume: 9

Issue: 3

First Page #: 1198

Date Submitted: 9/25/22 12:00AM

Date Published: 5/1/22 5:00AM

Publication Location:

Article Title: Age of Information for Single Buffer Systems With Vacation Server

Authors: Jin Xu, I-Hong Hou, Natarajan Gautam

Keywords: Age of information , performance analysis , polling system , queues with server vacations

Abstract: In this research, we study the information freshness in M/G/1 queueing system with a single buffer and the server taking multiple vacations.

Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: Y

RPPR Final Report as of 17-Apr-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 2-Awaiting Publication
Journal: IEEE Transactions on Wireless Communications
Publication Identifier Type: **Publication Identifier:**
Volume: **Issue:** **First Page #:**
Date Submitted: 9/25/22 12:00AM **Date Published:** 5/5/22 5:00AM
Publication Location:
Article Title: BeamSurfer: Minimalist Beam Management of Mobile mm-Wave Devices
Authors: Venkata Siva Santosh Ganji, Tzu-Hsiang Lin, Francisco A. Espinal, and P. R. Kumar
Keywords: Base stations , Wireless communication , Receivers , Synchronization , Protocols , Transient analysis , Gain
Abstract: Management of narrow directional beams is critical for mm-wave communication systems. Translational or rotational motion of the user can cause misalignment of transmit and receive beams with the base station losing track of the mobile. Reacquiring the user can take about one second in 5G New Radio systems and significantly impair performance of applications, besides being energy intensive. It is therefore important to manage beams to continually maintain high received signal strength and prevent outages. It is also important to be able to recover from sudden but transient blockage caused by a hand or face interposed in the Line-of-Sight (LoS) path. This work presents a beam management protocol called BeamSurfer that is targeted to the use case of users walking indoors near a base station. It is designed to be minimalistic, employing only in-band information, and not requiring knowledge such as location or orientation of the mobile device or any additional sensors.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: Y

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: 2019 11th International Conference on Communication Systems & Networks (COMSNETS)
Date Received: 20-May-2020 **Conference Date:** 07-Jan-2019 **Date Published:**
Conference Location: Bengaluru, India
Paper Title: Iris: A Directional MAC Protocol With Applications to Millimeter-Wave Mobile Ad-Hoc Networks
Authors: Bharadwaj Satchidanandan, Venkata Siva Santosh Ganji, P. R. Kumar
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 17th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks, WIOPT 2019
Date Received: 20-May-2020 **Conference Date:** 04-Jun-2019 **Date Published:**
Conference Location: Avignon, France
Paper Title: Broadcasting Real-Time Flows in Integrated Backhaul and Access 5G Networks
Authors: Aria HasanzadeZonuzy, I-Hong Hou, Srinivas Shakkottai
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: 17th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks, WIOPT 2019
Date Received: 20-May-2020 **Conference Date:** 04-Jun-2019 **Date Published:**
Conference Location: Avignon, France
Paper Title: Cache-Version Selection and Content Placement for Adaptive Video Streaming in Wireless Edge Networks
Authors: Archana Sasikumar, Tao Zhao, I-Hong Hou, Srinivas Shakkottai
Acknowledged Federal Support: Y

RPPR Final Report
as of 17-Apr-2023

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: 17th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks, WIOPT 2019
Date Received: 20-May-2020 Conference Date: 03-Jun-2019 Date Published:
Conference Location: Avignon, France
Paper Title: On the Credibility of Information Flows in Real-Time Wireless Networks
Authors: Daojing Guo, I-Hong Hou
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2019 Sixth Indian Control Conference (ICC)
Date Received: 26-Aug-2020 Conference Date: 18-Dec-2019 Date Published:
Conference Location: Hyderabad, India
Paper Title: On the Watermark-Securable Subspace of a Linear Stochastic System
Authors: Bharadwaj Satchidanandan, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: 2020 International Conference on COMmunication Systems & NETworkS (COMSNETS)
Date Received: 26-Aug-2020 Conference Date: 07-Jan-2020 Date Published:
Conference Location: Bengaluru, India
Paper Title: The Watermark-Securable Subspace of a Linear System Containing a Single Malicious Actuator
Authors: Bharadwaj Satchidanandan, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: 2019 57th Annual Allerton Conference on Communication, Control, and Computing (Allerton)
Date Received: 26-Aug-2020 Conference Date: 24-Sep-2019 Date Published:
Conference Location: Monticello, IL, USA
Paper Title: Optimal Information Updating based on Value of Information
Authors: Rahul Singh, Gopal Krishna Kamath, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: IEEE INFOCOM 2020 - IEEE Conference on Computer Communications
Date Received: 26-Aug-2020 Conference Date: 06-Jul-2020 Date Published:
Conference Location: Toronto, ON, Canada
Paper Title: Predictive Scheduling for Virtual Reality
Authors: I-Hong Hou, Narges Zarnaghi Naghsh, Sibendu Paul, Y. Charlie Hu, Atilla Eryilmaz
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: ACM MobiHoc 2020
Date Received: 15-Oct-2020 Conference Date: 11-Oct-2020 Date Published:
Conference Location: Online
Paper Title: Fresher Content or Smoother Playback? A Brownian-Approximation Framework for Scheduling Real-Time Wireless Video Streams
Authors: Ping-Chun Hsieh, Xi Liu, I-Hong Hou
Acknowledged Federal Support: **Y**

RPPR Final Report as of 17-Apr-2023

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2019 AIChE Annual Meeting (Topical Conference: Next-Gen Manufacturing)
Date Received: 27-Aug-2020 Conference Date: 10-Nov-2019 Date Published:
Conference Location: Orlando
Paper Title: Cyber-Security with Dynamic Watermarking for Process Control Systems
Authors: Jaewon Kim, Woo Hyun Ko, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: Proceedings of the 21st IFAC World Congress
Date Received: 27-Aug-2020 Conference Date: 12-Jul-2020 Date Published:
Conference Location: Berlin, Germany
Paper Title: Security of Control Systems with Erroneous Observations
Authors: Jaewon Kim, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: ICML 2020
Date Received: 31-Aug-2021 Conference Date: 13-Jul-2020 Date Published: 13-Jul-2020
Conference Location: Online
Paper Title: Exploration Through Reward Biasing: Reward-Biased Maximum Likelihood Estimation for Stochastic Multi-Armed Bandits
Authors: Xi Liu, Ping-Chun Hsieh, Anirban Bhattacharya, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: L4DC 2021
Date Received: 31-Aug-2021 Conference Date: 07-Jun-2021 Date Published: 07-Jun-2021
Conference Location: Online
Paper Title: Reward Biased Maximum Likelihood Estimation for Reinforcement Learning
Authors: Akshay Mete, Rahul Singh, Xi Liu, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: AAAI 2021
Date Received: 31-Aug-2021 Conference Date: 09-Feb-2021 Date Published: 09-Feb-2021
Conference Location: Online
Paper Title: Reward-Biased Maximum Likelihood Estimation for Linear Stochastic Bandits
Authors: Yu-Heng Hung, Ping-Chun Hsieh, Xi Liu, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2021 International Conference on Unmanned Aircraft Systems (ICUAS)
Date Received: 31-Aug-2021 Conference Date: 15-Jun-2021 Date Published:
Conference Location: Athens, Greece
Paper Title: Cyber-Security through Dynamic Watermarking for 2-rotor Aerial Vehicle Flight Control Systems
Authors: Jaewon Kim, Woo-Hyun Ko, P. R. Kumar
Acknowledged Federal Support: **Y**

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Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: IEEE ICC 2022
Date Received: 25-Sep-2022 Conference Date: 16-May-2022 Date Published:
Conference Location: Online
Paper Title: Online Service Caching and Routing at the Edge with Unknown Arrivals
Authors: Siqi Fan, I-Hong Hou, Van Sy Mai, Lotfi Benmohamed
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: IEEE Infocom 2022
Date Received: 25-Sep-2022 Conference Date: 02-May-2022 Date Published:
Conference Location: Online
Paper Title: A Theory of Second-Order Wireless Network Optimization and Its Application on AoI
Authors: Daojing Guo, Khaled Nakhleh, I-Hong Hou, Sastry Kompella, and Clement Kam
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: NeurIPS 2021
Date Received: 25-Sep-2022 Conference Date: 06-Dec-2021 Date Published:
Conference Location: Online
Paper Title: NeurWIN: Neural Whittle Index Network For Restless Bandits Via Deep RL
Authors: Khaled Nakhleh, Santosh Ganji, Ping-Chun Hsieh, I-Hong Hou, and Srinivas Shakkottai
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Thirty-Fifth Conference on Neural Information Processing Systems (NeurIPS 2021)
Date Received: 25-Sep-2022 Conference Date: 06-Dec-2021 Date Published:
Conference Location: Online
Paper Title: Learning Policies with Zero or Bounded Safety Violation for Constrained MDPs
Authors: Tao Liu, Ruida Zhou, Dileep Kalathil, P. R. Kumar and Chao Tian
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: 56th Annual Conference on Information Sciences and Systems (CISS 2022)
Date Received: 25-Sep-2022 Conference Date: 09-Mar-2022 Date Published:
Conference Location: Princeton, New Jersey
Paper Title: The RBMLE method for Reinforcement Learning
Authors: Akshay Mete, Rahul Singh and P. R. Kumar
Acknowledged Federal Support: **Y**

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Partners

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I certify that the information in the report is complete and accurate:

Signature: I-Hong Hou

Signature Date: 4/16/23 3:59PM

Major Goals

The objective of this project is to establish a new framework for developing network algorithms that ensure both end-to-end delay and end-to-end QoE for video delivery in battlefield networks in the presence of event-driven IoT applications. Our framework will be built upon two critical components: One is an analytical model that precisely calculates a range of QoE metrics, such as the frequency and duration of video interruptions and video quality, based on the traces of packet deliveries. This enables us to translate the perceived video quality, which is a subjective matter, into measurable, and hence optimizable, network performance metrics. The other is a network model that explicitly addresses several important features of battlefield networks, including unreliable wireless transmissions, multi-hop transmissions, end-to-end delay bounds, and unpredictable, adversarial event, packet generations from event-driven IoT applications. By combining these two components, our framework can serve as the foundation to analyze the actual QoE performance of network algorithms under realistic battlefield networks.

Based on our framework, we will develop a rich suite of network algorithms, including packet scheduling, multi-hop routing, and dynamic video rate control, that optimize end-to-end QoE under end-to-end delay constraints. Our algorithms will jointly consider video flows and event-driven IoT applications, and offer provably optimal QoE performance for video flows without sacrificing the reliability of event-driven IoT applications. We will also study implementation issues of our algorithms within the framework of software-defined networking (SDN).

Our research efforts are organized in the following four thrusts:

1. QoE optimization for one-hop wireless networks: We will start by considering the case of one-hop wireless networks, where a wireless gateway delivers multiple video flows to its connected users. Building upon our recent work on minimizing video interruption duration for on-demand video, we will further address the delay constraints of live surveillance video streaming, as well as other important QoE metrics such as the interruption frequency and video bit rate.
2. End-to-end QoE for multi-hop networks: We will further investigate optimizing end-to-end QoE for multi-hop networks. We will combine our recent breakthrough on guaranteeing end-to-end delay and timely deliveries, and results from Thrust 1 to develop tractable algorithms that simultaneously support both end-to-end QoE and end-to-end delay bound. We will also focus on developing distributed algorithms that require minimum coordination between wireless nodes.
3. Coexistence with event-driven IoT applications under adversarial environments: We will study practical battlefield networks where video streaming applications need to coexist with event-driven IoT applications by focusing on two specific challenges: The first is network congestion due to a short burst of event-driven packets, which will be addressed by dynamic video rate control algorithms. The second is the unpredictable nature of battlefield events, for which we will develop online algorithms that ensure both end-to-end QoE for video flows and end-to-end reliability for IoT applications even under an adversarial series of events.

4. Implementation and integration with software-defined networking: We will address the critical issues of realistically implementing our proposed policies. We will consider integrating our proposed policies in a SDN-based framework, where a SDN controller determines the optimal policies, while each wireless node simply carries out the prescribed policies. We will also implement and test our policies using our programmable MAC testbed that supports ultra-low latency scheduling.

Accomplished

We have made significant progress related to the seven topics listed in Major Goals. This project has produced 8 journal articles, 20 conference papers, and one book chapter. Below is the summary of some major results related to the topics in Major Goals:

1. QoE optimization for one-hop wireless networks:

We have studied QoE optimization for three very different applications: real-time video streaming, virtual reality (VR), real-time estimation, and age-of-information (AoI).

To study real-time video streaming, we consider two most critical QoE metrics: playback latency and video interruption. We characterize the fundamental tradeoffs between playback latency and video interruption. We also develop the optimal scheduling policy under mild constraints [1].

To study QoE optimization for VR, we consider delivering VR contents of both high video quality and fast responsiveness, over wireless networks with limited bandwidth. We propose to leverage the predictability of user movements in the virtual world and develop an optimal predictive scheduling policy. In addition to our theoretical study, we demonstrate the usefulness of our policy by building a prototype system. We show that our policy can be implemented under Furion, a Unity-based VR gaming software, with minor modifications [2].

To study real-time estimation, we consider wireless networks where multiple flows are delivering status updates about their respective information sources. An end user aims to make accurate real-time estimations about the status of each information source using its received packets. We propose a new metric called loss-of-confidence (LoC) to measure how the confidence interval of the end user's estimation is impacted by packet deliveries. We develop the optimal scheduling policy for minimizing LoC under various systems [3, 4]. We also show that our policies indeed achieve the smallest estimation error for an actual estimation problem [5].

Finally, we study the optimization of AoI, a new performance metric that has gathered significant research interests. We develop a theoretical framework of designing scheduling policies for second-order optimization. We employ this framework for the optimization of AoI over Gilbert-Elliott channels [6]. We also study the information freshness in M/G/1 queueing system with a single buffer and the server taking multiple vacations. This system has wide applications in communication systems. We evaluate the information freshness in this system with both i.i.d. and non-i.i.d. vacations under three different scheduling policies. For the systems with i.i.d. vacations [7].

2. End-to-end QoE for multi-hop networks:

We study the problem of broadcasting real-time flows in multi-hop wireless networks. We propose a distributed protocol called the delegated-set routing (DSR) that incurs virtually no overhead of coordination among nodes. We also develop distributed algorithms that aim to maximize the total timely utility under DSR [8]. To address interference in multi-hop networks, we also develop a joint CSMA, routing, and scheduling policy that maximizes end-to-end timely throughputs [9]. Further, we study leveraging content caching to optimize end-to-end QoE. We propose a distributed algorithm that jointly optimizes cache-version selection and content placement for adaptive video streaming in wireless edge networks [10].

3. Coexistence with event-driven IoT applications under adversarial environments:

We have studied adversarial environments from three directions: unknown future arrivals, selfish behaviors, and compromised devices.

We study the amount of capacity needed to provide stringent timely delivery guarantees in adversarial environment. We propose a low-complexity online algorithm and prove that it only requires a small amount of redundancy to guarantee the timely delivery of most packets without any knowledge about future packet arrivals [11]. We also study a problem of jointly optimizing two important operations in mobile edge computing without knowing future requests, namely service caching, which determines which services to be hosted at the edge, and service routing, which determines which requests to be processed locally at the edge. We propose a simple online algorithm with sub-linear regrets [12].

We investigate the problem of index coding with selfish clients. Our objectives are to motivate each selfish client to reveal the correct private information and to maximize the social welfare.

We develop joint coding and incentive schemes for achieving these two objectives [13].

Finally, we consider IoT applications where some sensors are compromised and may report false data. We develop watermarking techniques to address such vulnerability [14 – 20].

4. Implementation and integration with software-defined networking:

We have built a testbed that integrates PULS, which is our earlier work on Processor-Supported Ultra-Low Latency Scheduling, with software-defined networking (SDN), software-defined radio (SDR), and the optional usage of information-centric networking (ICN). We have used this testbed to evaluate a recent work on predictive scheduling for virtual reality. The video demo is shown in [21].

We also built a mm-wave testbed. We design and implement MAC protocols on this testbed [22 – 24].

In addition, we have many research accomplishments that are critical to battlefield networks, although not covered in Major Goals. They include employing Reward-Biased Maximum Likelihood Estimate method for reinforcement learning [25 – 28], developing learning algorithms for Whittle-based scheduling policy [29], and addressing safety in reinforcement learning [30].

Training

This project partially supported eight graduate students. The PIs provide one-on-one mentoring to these students. Three of the students have received their Ph.D. degrees in the duration of this project.

Dissemination

Our research results have been promptly disseminated through conference/journal publications. PI Hou has presented invited talks in Information Theory and Applications Workshop in 2019 and 2020.

Honors

1. PI Kumar received the **IEEE Alexander Graham Bell Medal**, 2022. "For seminal contributions to the modeling, analysis, and design of wireless networks."
2. PI Kumar was elected as a **Fellow of International Federation of Automatic Control (IFAC)**, July 29, 2022. "For seminal contributions to adaptive control and analysis of wireless networks"
3. **Best Paper Award** in ACM MobiHoc 2020 for the paper: Ping-Chun Hsieh, Xi Liu, and I-Hong Hou, "Fresher Content or Smoother Playback? A Brownian- Approximation Framework for Scheduling Real-Time Wireless Video Streams," in ACM MobiHoc 2020.
4. **Runner-up for Best Paper Award** in WiOpt 2019 for the paper: Daojing Guo and I-Hong Hou, "On the Credibility of Information Flows in Real-Time Wireless Networks."

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