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Final Report: 10.1 Communication and Human Networks: Towards Provably Timely and Reliable Battlefield Networks

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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

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U.S. Army Research Office
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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 contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

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a. REPORT	b. ABSTRACT	c. THIS PAGE			I-Hong Hou
UU	UU	UU	UU		19b. TELEPHONE NUMBER: 979-862-1092

RPPR Final Report
as of 29-Oct-2019

Agency Code:

Proposal Number: 66749NS **Agreement Number: W911NF-15-1-0279**
INVESTIGATOR(S):

Name: I-Hong Hou
Email: ihou@tamu.edu
Phone Number: 9798621092
Principal: Y

Organization: **Texas Engineering Experiment Station**
Address: SRS, College Station, TX 778454375
Country: USA
DUNS Number: 847205572 EIN: 741974733

Report Date: 14-May-2016 Date Received: 03-Jul-2019
Final Report for Period Beginning 15-Jun-2015 and Ending 14-Jun-2018
Title: 10.1 Communication and Human Networks: Towards Provably Timely and Reliable Battlefield Networks
Begin Performance Period: 15-Jun-2015 **End Performance Period:** 14-Apr-2019
Report Term: 0-Other

Submitted By: I-Hong Hou Email: ihou@tamu.edu
Phone: (979) 862-1092

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

STEM Degrees: 2 **STEM Participants:** 5

Major Goals: Battlefield networks enable soldiers at tactical edges to communicate with command centers and nearby soldiers in real time. An important requirement of battlefield networks is that most applications, such as tactical commands, voice and video calls, etc., require stringent per-packet delay and reliability guarantees. Similar real-time requirements are also critical for intra-tank wireless networks that connect sensors and actuators inside a tank.

This project aims to establish a novel framework for developing solutions with provable timeliness and reliability guarantees for battlefield and intra-tank networks. The proposed approach differs significantly from most existing studies that aim to only develop heuristics to improve delay and throughput performance opportunistically without offering stringent performance guarantees. The proposed framework will explicitly address various practical behaviors of battlefield networks, which, in addition to stringent per-packet delay and reliability requirements, include stochastic and unreliable wireless transmissions, mobile soldiers, dynamic flows, and multihop transport.

Specifically, the following research topics will be investigated:

1. Scheduling heterogeneous unicast flows: Multiple flows coexist in battlefield networks. Different flows generate packets with different traffic patterns, have different per-packet delay bounds, and require different reliability guarantees. Novel scheduling policies that fulfill the different requirements of heterogeneous flows will be proposed and evaluated.
2. Multicasting heterogeneous flows: Many flows in battlefield networks are multicast flows, such as commands for soldiers in a certain area. Multicasting differs from unicasting in that it incurs a high overhead to gather per-transmission feedback information from all receivers. Scheduling policies with and without feedback information will be evaluated. New policies that intelligently schedule packets to meet delay and reliability constraints, as well as obtain limited feedback information will be proposed.
3. End-to-end delay bounds for multi-hop networks: Multi-hop transmissions are usually needed to communicate with soldiers that are far away from the command centers. Joint routing and scheduling policies that aim to provide end-to-end delay and reliability guarantees will be developed.
4. Direct soldier-to-soldier communications: Soldiers at the tactical edge can communicate with each other directly for fast information exchange. An important challenge for direct soldier-to-soldier communication is the lack of a centralized scheduler. Soldiers therefore need to communicate through random access. Distributed policies that achieve the optimal timeliness and reliability will be established.
5. Real-time self-configuration: Distributed rate control policies that quickly react to soldier mobility and flow dynamics will be introduced. In addition to timeliness and reliability, their convergence rate will be studied.

6. Intra-tank wireless communications: This project proposes a new architecture that connects sensors and actuators in a tank by wireless networks. To enable this architecture, new polices with provably safety properties will be developed. This architecture can potentially greatly reduce the cost of tanks and allow faster innovations.
7. Testbed implementations: All the policies developed in this project will be evaluated by testbeds. The PIs have built a wireless sensor network testbed as well as a software-defined radio testbed.

Accomplishments: We have made significant progress related to the seven topics listed in Major Goals. This project has produced 15 journal articles, 23 conference papers, one book, and one book chapters. Below is the summary of some major results related to the topics in Major Goals:

1. Scheduling heterogeneous unicast flows: We have developed a series of work for the problem of optimizing quality of experience (QoE) for video streaming applications in wireless networks. We have precisely quantified the capacity region of achievable QoE and developed tractable and provably optimal scheduling policies.
We have also studied energy efficiency. We have considered reducing energy consumption through turning base stations into sleep mode or using dynamic transmission power control. We have developed policies that use the minimal energy to ensure the delay and reliability requirements of battlefield networks.
2. End-to-end delay bounds for multi-hop networks: We have studied the convoluted problem of packet scheduling in multi-hop networks with end-to-end delay bounds. We have proposed a decomposition technique that allows each wireless device in the network to make scheduling decisions solely based on its own network state and some minimal communications with others.
We have also studied the problem of capacity planning to guarantee end-to-end delay bounds in multi-hop networks without any knowledge of future packet arrivals. We have proposed an online algorithm, and demonstrated that, compared to existing policies, it requires much smaller wireless capacity to achieve a certain degree of reliability.
3. Direct soldier-to-soldier communications: We have proposed a feasibility-optimal decentralized algorithm for real-time wireless ad hoc networks, where a strict deadline is imposed for each packet. The algorithm is fully decentralized in the sense that every link only needs to know its own priority, and links contend for priorities only through carrier sensing. We prove that the proposed algorithm is optimal.
4. Real-time self-configuration: We have collaborated with Dr. Ananthram Swami (ARL-Adelphi) on the joint rate control and packet scheduling algorithms for wireless networks with strict per-packet delay bounds. We have established fully distributed policies where each flow controls its own rate and the base station schedules transmissions with virtually no explicit message exchange. We prove that our policy achieves the optimal system utility while satisfying the per-packet delay bounds and per-flow reliability bounds.
We also studied dynamic network where soldiers are highly mobile and may only have intermittent connection to base stations. We then propose an online policy that schedules transmissions for connected soldiers without any knowledge about their future mobility patterns.
5. Intra-tank wireless communications: We have proposed policies that ensure safety properties by minimizing the performance loss due to short-term fluctuations, both in terms of packet deliveries and inter-delivery times.
6. Testbed implementation: We have presented PULS, a processor-supported ultra-low latency scheduling implementation for testing of downlink scheduling protocols with ultra-low latency requirements. Using PULS, we implemented four different scheduling policies and provide detailed performance comparisons under various traffic loads and real-time requirements. We show that in certain scenarios, the optimal policy can maintain a loss ratio of less than 1% for packets with deadlines, while other protocols experience loss ratios of up to 65%.

In addition, we have many research accomplishments that are critical to battlefield networks, although not covered in Major Goals. They include the following:
1. Joint optimization of communication and computation at the edge: We have collaborated with Dr. Kevin Chan in ARL to propose a tractable online algorithm called retrospective download with least-requested deletion (RED/LED) that caches services dynamically without any assumptions on the arrival patterns of mobile applications.
We have also studied the problem of allocating jobs to appropriate servers in cloud computing. We study this problem for both systems with persistent jobs that do not have deadlines and systems with dynamic jobs that require stringent deadline guarantees. For both systems, we propose online job allocation policies with low complexity.
2. Control of connected vehicles: Battlefield networks will be able to connect and coordinate autonomous vehicles. We have been studying the problem of controlling connected vehicles. Our results include a trajectory-optimized linear quadratic regulator design for stochastic nonlinear systems with Gaussian noise, and a distributed policy to schedule connected vehicles in a multi-hop transportation network.
3. Provably secure connected system: We have proposed an online framework to detect cyber-attacks on Automatic Generation Control (AGC). We have also examined notions of securable and unsecurable subspaces

from the standpoint of a fully-observed stochastic linear dynamical system, and establish operational meanings for them in this context.
4. Provably secure networks: Security is obviously critical to battlefield networks. We have proposed a clean slate approach for building wireless networks that is provably resilient to ANY attack schemes that aim to reduce network performance.
5. A new MAC protocol for mmWave communications: We have proposed TrackMAC, a directional MAC protocol that (i) has the property that it continuously tracks the direction of every associated station which, in general, is mobile, and (ii) can be implemented squarely within the specifications of the IEEE 802.11ad standard for mm-wave WLAN.

Training Opportunities: This project partially support five graduate students. The PIs provide one-on-one mentoring to these students. Two 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. In addition, we have been invited to present our research results in several invited/plenary/keynote talks. They are listed below:

PI Hou:
1. Invited talk, International Conference on Signal Processing and Communications (SPCOM), Bangalore, India, June 12 – 15, 2016.
2. Invited talk, European Conference on Queueing Theory (ECQT), Toulouse, France, July 18 – 20, 2016.
3. Invited talk, Information Theory and Applications Workshop, San Diego, CA, February 11 – 16, 2018.
4. Invited talk, Information Theory and Applications Workshop, San Diego, CA, February 10 – 15, 2019.

PI Kumar:
1. Distinguished Keynote, 2nd IEEE International Conference on Data Science in Cyberspace (IEEE DSC 2017), Shenzhen, China, June 26-29, 2017.
2. Keynote Address, 1st Cyber-Physical Systems Symposium, (CyPhySS 2017), Robert Bosch Centre for Cyber-Physical Systems, Indian Institute of Science, Bangalore, India, 19-21 July 2017.
3. Distinguished Mercer Lecture, Rensselaer Polytechnic Institute, November 30, 2016.
4. Zhu Kezhen Distinguished Lectures, Zhejiang University, November 17–18, 2016, Hangzhou, China.
5. Semi-Plenary Speaker, 4th International Conference on Sustainable Energy Technologies (ICSET 2016), November 14–17, 2016, Hanoi, Vietnam.
6. Keynote Speaker, the 13th IEEE International Conference on Mobile Ad hoc and Sensor Systems (IEEE MASS 2016), October 10–13, 2016, Brasilia, Brazil.
7. Plenary Lecture, 6th IFAC Workshop on Distributed Estimation and Control in Networked Systems (NecSys 2016), September 8-9, 2016, Tokyo, Japan.
8. Keynote Presentation, CPS Applications to Power Systems Engineering, IEEE Power and Energy Society General Meeting July 16, 2016, Boston.
9. Kwan Chao-Chih Distinguished Lecture, Chinese Academy of Sciences, Beijing, April 13, 2018.

Honors and Awards: 1. Best Paper Award at 9th International Conference on Communication Systems and Networks (COMSNETS 2017) for the paper: Bharadwaj Satchidanadnan and P. R. Kumar, “On Minimal Tests of Sensor Veracity for Dynamic Watermarking-Based Defense of Cyber-Physical Systems.”
2. Best Paper Award at the Eighteenth International Conference on Mobile Ad Hoc Networking and Computing (ACM MobiHoc 2017) for the paper: Ping-Chun Hsieh, Xi Liu, Jian Jiao, I-Hong Hou, Yunlong Zhang and P. R. Kumar, “Throughput-Optimal Scheduling for Multi-Hop Networked Transportation Systems With Switch-Over Delay.”
3. PhD student Ping-Chun Hsieh received the Outstanding Student Award from the ECE Department of Texas A&M University.
4. PhD student Han Deng receives Best-in-Session Presentation Award in IEEE Infocom 2016 for her paper “Online Job Allocation with Hard Allocation Ratio Requirement.”
5. Winner of the Global Cyber Challenge Peace-a-thon (International), Nov 23, 2017.
6. PI Kumar is elected as a Foreign Fellow, Indian National Academy of Engineering, Nov 1, 2017.

Protocol Activity Status:

Technology Transfer: Nothing to Report

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PARTICIPANTS:

Participant Type: PD/PI
Participant: I-Hong Hou
Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Co PD/PI
Participant: P. R. Kumar
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: Y
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Han Deng
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Shuai Zuo
Person Months Worked: 9.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Tao Zhao
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Ping-Chun Hsieh
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Daojing Guo
Person Months Worked: 10.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

BOOKS:

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Publication Identifier Type: Publication Identifier:
Book Edition: Volume: Publication Year: Date Received: 29-Aug-2018
Publication Location:
Publisher: Springer
Book Title: Defending Cyber-Physical Systems from Sensor Attacks
Authors: Bharadwaj Satchidanandan, P. R. Kumar
Editor:
Acknowledged Federal Support: Y

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: IEEE INFOCOM 2016
Date Received: 15-Jul-2016 Conference Date: 10-Apr-2016 Date Published:
Conference Location: San Francisco, USA
Paper Title: Heavy-Traffic Analysis of QoE Optimality for On-Demand Video Streams Over Fading Channels
Authors: Ping-Chun Hsieh, I-Hong Hou
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: IEEE INFOCOM 2016
Date Received: 15-Jul-2016 Conference Date: 10-Apr-2016 Date Published:
Conference Location: San Francisco, USA
Paper Title: On the Modeling and Optimization of Short-Term Performance for Real-Time Wireless Networks
Authors: I-Hong Hou
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: IEEE INFOCOM 2016
Date Received: 15-Jul-2016 Conference Date: 10-Apr-2016 Date Published:
Conference Location: San Francisco, USA
Paper Title: Online Job Allocation with Hard Allocation Ratio Requirement
Authors: Hang Deng, I-Hong Hou
Acknowledged Federal Support: **Y**

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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: the 17th ACM International Symposium
Date Received: 15-Jul-2016 Conference Date: 05-Jul-2016 Date Published:
Conference Location: Paderborn, Germany
Paper Title: Asymptotically optimal algorithm for online reconfiguration of edge-clouds
Authors: I-Hong Hou, Tao Zhao, Shiqiang Wang, Kevin Chan
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2016 IEEE International Conference on Robotics and Automation (ICRA)
Date Received: 15-Jul-2016 Conference Date: 16-May-2016 Date Published:
Conference Location: Stockholm, Sweden
Paper Title: Feedback motion planning under non-Gaussian uncertainty and non-convex state constraints
Authors: Mohammadhussein Rafieisakhaei, Amirhossein Tamjidi, Suman Chakravorty, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2016 8th International Conference on Communication Systems and Networks (COMSNETS)
Date Received: 15-Jul-2016 Conference Date: 05-Jan-2016 Date Published:
Conference Location: Bangalore, India
Paper Title: Towards safety of transportation systems with a mixture of automated and human-driven vehicles
Authors: Xi Liu, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: the 18th ACM International Symposium on Mobile Ad Hoc Networking and Computing (ACM MobiHoc)
Date Received: 16-Aug-2017 Conference Date: 10-Jul-2017 Date Published:
Conference Location: Chennai, India
Paper Title: Throughput-Optimal Scheduling for Multi-Hop Networked Transportation Systems With Switch-Over Delay
Authors: Ping-Chun Hsieh, Xi Liu, Jian Jiao, I-Hong Hou, Yunlong Zhang, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2016 American Control Conference (ACC)
Date Received: 16-Aug-2017 Conference Date: 06-Jul-2016 Date Published: 01-Aug-2017
Conference Location: Boston, MA, USA
Paper Title: Cross-layer design for cyber-physical systems of coordinated networked vehicles over bi-directional middleware
Authors: Woo-Hyun Ko, P.R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2016 IEEE 55th Conference on Decision and Control (CDC)
Date Received: 16-Aug-2017 Conference Date: 12-Dec-2016 Date Published:
Conference Location: Las Vegas, NV, USA
Paper Title: Secure control of networked cyber-physical systems
Authors: Bharadwaj Satchidanandan, P. R. Kumar
Acknowledged Federal Support: **Y**

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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 14th IEEE Annual Consumer Communications & Networking Conference (CCNC)
Date Received: 16-Aug-2017 Conference Date: 08-Jan-2017 Date Published:
Conference Location: Las Vegas, NV, USA
Paper Title: Outlier rejection for networked control systems based on middleware
Authors: Woo-Hyun Ko, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2016 IEEE Conference on Communications and Network Security (CNS)
Date Received: 16-Aug-2017 Conference Date: 17-Oct-2016 Date Published:
Conference Location: Philadelphia, PA, USA
Paper Title: Theory and implementation of dynamic watermarking for cybersecurity of advanced transportation systems
Authors: Woo-Hyun Ko, Bharadwaj Satchidanandan, P R Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 9th International Conference on Communication Systems and Networks (COMSNETS)
Date Received: 16-Aug-2017 Conference Date: 04-Jan-2017 Date Published:
Conference Location: Bengaluru, India
Paper Title: On minimal tests of sensor veracity for dynamic watermarking-based defense of cyber-physical systems
Authors: Bharadwaj Satchidanandan, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 IEEE International Conference on Robotics and Automation (ICRA)
Date Received: 16-Aug-2017 Conference Date: 29-May-2017 Date Published:
Conference Location: Singapore, Singapore
Paper Title: T-LQG: Closed-loop belief space planning via trajectory-optimized LQG
Authors: Mohammadhussein Rafieisakhaei, Suman Chakravorty, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 IEEE International Conference on Robotics and Automation (ICRA)
Date Received: 16-Aug-2017 Conference Date: 29-May-2017 Date Published:
Conference Location: Singapore, Singapore
Paper Title: MT-LQG: Multi-agent planning in belief space via trajectory-optimized LQG
Authors: Mohammadhussein Rafieisakhaei, Suman Chakravorty, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: the 2017 ACM SIGMETRICS / International Conference
Date Received: 16-Aug-2017 Conference Date: 05-Jun-2017 Date Published:
Conference Location: Urbana-Champaign, Illinois, USA
Paper Title: On the Capacity Requirement for Arbitrary End-to-End Deadline and Reliability Guarantees in Multi-hop Networks
Authors: Han Deng, I-Hong Hou
Acknowledged Federal Support: **Y**

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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: ACM MobiHoc 2018
Date Received: 21-Aug-2018 Conference Date: 26-Jun-2018 Date Published:
Conference Location: Los Angeles, CA, USA
Paper Title: PULS: Processor-Supported Ultra-Low Latency Scheduling
Authors: Simon Yau, Ping-Chun Hsieh, Rajarshi Bhattacharyya, Kartic Bhargav K. R., Srinivas Shakkottai, I-Hong
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2018 IEEE 38th International Conference on Distributed Computing Systems (ICDCS)
Date Received: 21-Aug-2018 Conference Date: 02-Jul-2018 Date Published:
Conference Location: Vienna
Paper Title: A Decentralized Medium Access Protocol for Real-Time Wireless Ad Hoc Networks With Unreliable Transmissions
Authors: Ping-Chun Hsieh, I-Hong Hou
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 IEEE 56th Annual Conference on Decision and Control (CDC)
Date Received: 21-Aug-2018 Conference Date: 12-Dec-2017 Date Published:
Conference Location: Melbourne, Australia
Paper Title: On the use of the observability gramian for partially observed robotic path planning problems
Authors: Mohammadhussein Rafieisakhaei, Suman Chakravorty, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 IEEE 56th Annual Conference on Decision and Control (CDC)
Date Received: 21-Aug-2018 Conference Date: 12-Dec-2017 Date Published:
Conference Location: Melbourne, Australia
Paper Title: A near-optimal decoupling principle for nonlinear stochastic systems arising in robotic path planning and control
Authors: Mohammadhussein Rafieisakhaei, Suman Chakravorty, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Proceedings of Workshop on POMDPs in Robotics in Robotics: Science and Systems (RSS-2017)
Date Received: 21-Aug-2018 Conference Date: 12-Jul-2017 Date Published:
Conference Location: Cambridge, Massachusetts
Paper Title: Near-Optimal Belief Space Planning via T-LQG
Authors: Mohammadhussein Ra♀eisakhaei, Suman Chakravorty, P. R. Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 55th Annual Allerton Conference on Communication, Control, and Computing (Allerton)
Date Received: 21-Aug-2018 Conference Date: 03-Oct-2017 Date Published:
Conference Location: Monticello, IL, USA
Paper Title: The securable subspace of a linear stochastic system with malicious sensors and actuators
Authors: Bharadwaj Satchidanandan, P. R. Kumar
Acknowledged Federal Support: **Y**

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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2018 10th International Conference on Communication Systems & Networks (COMSNETS)
Date Received: 21-Aug-2018 Conference Date: 03-Jan-2018 Date Published:
Conference Location: Bengaluru
Paper Title: TrackMAC: An IEEE 802.11ad-compatible beam tracking-based MAC protocol for 5G millimeter-wave local area networks
Authors: Bharadwaj Satchidanandan, Simon Yau, P. R. Kumar, Ahsan Aziz, Amal Ekbal, Nikhil Kundargi
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2018 IEEE International Symposium on Information Theory (ISIT)
Date Received: 21-Aug-2018 Conference Date: 17-Jun-2018 Date Published:
Conference Location: Vail, CO, USA
Paper Title: Preserving Privacy and Fidelity via Ehrhart Theory
Authors: Arun Padakandla, P. R. Kumar, Wojciech Szpankowski
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: Texas A&M University
Date Received: 16-Aug-2017 Completion Date: 8/11/17 5:00AM
Title: A NEW COMPETITIVE RATIO FOR NETWORK APPLICATIONS WITH HARD PERFORMANCE GUARANTEE
Authors: Han Deng
Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation
Institution: Texas A&M University
Date Received: 03-Jul-2019 Completion Date: 12/1/17 10:13PM
Title: IOT-ORIENTED NETWORK ALGORITHMS: THEORY AND IMPLEMENTATION
Authors: Ping-Chun Hsieh
Acknowledged Federal Support: **N**

Major Goals

Battlefield networks enable soldiers at tactical edges to communicate with command centers and nearby soldiers in real time. An important requirement of battlefield networks is that most applications, such as tactical commands, voice and video calls, etc., require stringent per-packet delay and reliability guarantees. Similar real-time requirements are also critical for intra-tank wireless networks that connect sensors and actuators inside a tank.

This project aims to establish a novel framework for developing solutions with provable timeliness and reliability guarantees for battlefield and intra-tank networks. The proposed approach differs significantly from most existing studies that aim to only develop heuristics to improve delay and throughput performance opportunistically without offering stringent performance guarantees. The proposed framework will explicitly address various practical behaviors of battlefield networks, which, in addition to stringent per-packet delay and reliability requirements, include stochastic and unreliable wireless transmissions, mobile soldiers, dynamic flows, and multihop transport.

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6. Intra-tank wireless communications: This project proposes a new architecture that connects sensors and actuators in a tank by wireless networks. To enable this architecture, new polices with provably safety properties will be developed. This architecture can potentially greatly reduce the cost of tanks and allow faster innovations.
7. Testbed implementations: All the policies developed in this project will be evaluated by testbeds. The PIs have built a wireless sensor network testbed as well as a software-defined radio testbed.

Accomplished

We have made significant progress related to the seven topics listed in Major Goals. This project has produced 15 journal articles, 23 conference papers, one book, and one book chapters. Below is the summary of some major results related to the topics in Major Goals:

1. Scheduling heterogeneous unicast flows: We have developed a series of work for the problem of optimizing quality of experience (QoE) for video streaming applications in wireless networks. We have precisely quantified the capacity region of achievable QoE and developed tractable and provably optimal scheduling policies.

   We have also studied energy efficiency. We have considered reducing energy consumption through turning base stations into sleep mode or using dynamic transmission power control. We have developed policies that use the minimal energy to ensure the delay and reliability requirements of battlefield networks.

2. End-to-end delay bounds for multi-hop networks: We have studied the convoluted problem of packet scheduling in multi-hop networks with end-to-end delay bounds. We have proposed a decomposition technique that allows each wireless device in the network to make scheduling decisions solely based on its own network state and some minimal communications with others.

   We have also studied the problem of capacity planning to guarantee end-to-end delay bounds in multi-hop networks without any knowledge of future packet arrivals. We have proposed an online algorithm, and demonstrated that, compared to existing policies, it requires much smaller wireless capacity to achieve a certain degree of reliability.

3. Direct soldier-to-soldier communications: We have proposed a feasibility-optimal decentralized algorithm for real-time wireless ad hoc networks, where a strict deadline is imposed for each packet. The algorithm is fully decentralized in the sense that every link only needs to know its own priority, and links contend for priorities only through carrier sensing. We prove that the proposed algorithm is optimal.
4. Real-time self-configuration: We have collaborated with Dr. Ananthram Swami (ARL-Adelphi) on the joint rate control and packet scheduling algorithms for wireless networks with strict per-packet delay bounds. We have established fully distributed policies where each flow controls its own rate and the base station schedules transmissions with virtually no explicit message

exchange. We prove that our policy achieves the optimal system utility while satisfying the per-packet delay bounds and per-flow reliability bounds.

We also studied dynamic network where soldiers are highly mobile and may only have intermittent connection to base stations. We then propose an online policy that schedules transmissions for connected soldiers without any knowledge about their future mobility patterns.

5. Intra-tank wireless communications: We have proposed policies that ensure safety properties by minimizing the performance loss due to short-term fluctuations, both in terms of packet deliveries and inter-delivery times.
6. Testbed implementation: We have presented PULS, a processor-supported ultra-low latency scheduling implementation for testing of downlink scheduling protocols with ultra-low latency requirements. Using PULS, we implemented four different scheduling policies and provide detailed performance comparisons under various traffic loads and real-time requirements. We show that in certain scenarios, the optimal policy can maintain a loss ratio of less than 1% for packets with deadlines, while other protocols experience loss ratios of up to 65%.

In addition, we have many research accomplishments that are critical to battlefield networks, although not covered in Major Goals. They include the following:

1. Joint optimization of communication and computation at the edge: We have collaborated with Dr. Kevin Chan in ARL to propose a tractable online algorithm called retrospective download with least-requested deletion (RED/LED) that caches services dynamically without any assumptions on the arrival patterns of mobile applications.

   We have also studied the problem of allocating jobs to appropriate servers in cloud computing. We study this problem for both systems with persistent jobs that do not have deadlines and systems with dynamic jobs that require stringent deadline guarantees. For both systems, we propose online job allocation policies with low complexity.

2. Control of connected vehicles: Battlefield networks will be able to connect and coordinate autonomous vehicles. We have been studying the problem of controlling connected vehicles. Our results include a trajectory-optimized linear quadratic regulator design for stochastic nonlinear systems with Gaussian noise, and a distributed policy to schedule connected vehicles in a multi-hop transportation network.
3. Provably secure connected system: We have proposed an online framework to detect cyber-attacks on Automatic Generation Control (AGC). We have also examined notions of securable and unsecurable subspaces from the standpoint of a fully-observed stochastic linear dynamical system, and establish operational meanings for them in this context.
4. Provably secure networks: Security is obviously critical to battlefield networks. We have proposed a clean slate approach for building wireless networks that is provably resilient to ANY attack schemes that aim to reduce network performance.
5. A new MAC protocol for mmWave communications: We have proposed TrackMAC, a directional MAC protocol that (i) has the property that it continuously tracks the direction of every associated station which, in general, is mobile, and (ii) can be implemented squarely within the specifications of the IEEE 802.11ad standard for mm-wave WLAN.

Training

This project partially support five graduate students. The PIs provide one-on-one mentoring to these students. Two 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. In addition, we have been invited to present our research results in several invited/plenary/keynote talks. They are listed below:

PI Hou:

1. Invited talk, International Conference on Signal Processing and Communications (SPCOM), Bangalore, India, June 12 – 15, 2016.
2. Invited talk, European Conference on Queueing Theory (ECQT), Toulouse, France, July 18 – 20, 2016.
3. Invited talk, Information Theory and Applications Workshop, San Diego, CA, February 11 – 16, 2018.
4. Invited talk, Information Theory and Applications Workshop, San Diego, CA, February 10 – 15, 2019.

PI Kumar:

1. Distinguished Keynote, 2nd IEEE International Conference on Data Science in Cyberspace (IEEE DSC 2017), Shenzhen, China, June 26-29, 2017.
2. Keynote Address, 1st Cyber-Physical Systems Symposium, (CyPhySS 2017), Robert Bosch Centre for Cyber-Physical Systems, Indian Institute of Science, Bangalore, India, 19-21 July 2017.
3. Distinguished Mercer Lecture, Rensselaer Polytechnic Institute, November 30, 2016.
4. Zhu Kezhen Distinguished Lectures, Zhejiang University, November 17–18, 2016, Hangzhou, China.
5. Semi-Plenary Speaker, 4th International Conference on Sustainable Energy Technologies (ICSET 2016), November 14–17, 2016, Hanoi, Vietnam.
6. Keynote Speaker, the 13th IEEE International Conference on Mobile Ad hoc and Sensor Systems (IEEE MASS 2016), October 10–13, 2016, Brasilia, Brazil.
7. Plenary Lecture, 6th IFAC Workshop on Distributed Estimation and Control in Networked Systems (NecSys 2016), September 8-9, 2016, Tokyo, Japan.
8. Keynote Presentation, CPS Applications to Power Systems Engineering, IEEE Power and Energy Society General Meeting July 16, 2016, Boston.

9. Kwan Chao-Chih Distinguished Lecture, Chinese Academy of Sciences, Beijing, April 13, 2018.

Honors

1. **Best Paper Award** at 9th International Conference on Communication Systems and Networks (COMSNETS 2017) for the paper: Bharadwaj Satchidanadnan and P. R. Kumar, "On Minimal Tests of Sensor Veracity for Dynamic Watermarking-Based Defense of Cyber-Physical Systems."
2. **Best Paper Award** at the Eighteenth International Conference on Mobile Ad Hoc Networking and Computing (ACM MobiHoc 2017) for the paper: Ping-Chun Hsieh, Xi Liu, Jian Jiao, I-Hong Hou, Yunlong Zhang and P. R. Kumar, "Throughput-Optimal Scheduling for Multi-Hop Networked Transportation Systems With Switch-Over Delay."
3. PhD student Ping-Chun Hsieh received the **Outstanding Student Award** from the ECE Department of Texas A&M University.
4. PhD student Han Deng receives **Best-in-Session Presentation Award** in IEEE Infocom 2016 for her paper "Online Job Allocation with Hard Allocation Ratio Requirement."
5. **Winner** of the Global Cyber Challenge Peace-a-thon (International), Nov 23, 2017.
6. PI Kumar is elected as a **Foreign Fellow**, Indian National Academy of Engineering, Nov 1, 2017.