2019 Final Project Report

for

Academic Consortium for the 21st Century (AC21) Special Project Fund

Towards Ultra-Reliable Low-Latency Communications for 5G UAV Ecosystems: Collaborative Research Planning among NC State, NU, and AU

Project Leader: Dr. Shih-Chun Lin, North Carolina State University

Contents

Project Leadership

Dr. Shih-Chun Lin, North Carolina State University; Dr. Kentaro Kobayashi, Nagoya University; Dr. Peng Shi, University of Adelaide; Dr. Kwang-Cheng Chen, University of South Florida.

Acknowledgment

Project Summary

As one of the 5G envisioned services, ultra-reliable and low-latency communications (URLLC) aim to provide secure data transmissions from one end to another with ultra-high reliability and deadline-based low latency requirements, enabling tactile Internet, mission-critical Internet of Things, and vehicle safety applications. Meanwhile, unmanned aerial vehicles (UAVs) for wireless communications has drawn much attention as the mass production of high-performance, low-cost, intelligent UAVs become more practical and feasible, which empowers more functional diversity for 5G networks. This SPF project, led by NC State, focused on initiating collaborative research discussion and external grant planning for introducing a holistic software-defined wireless architecture that ensures URLLC in 5G UAV ecosystems. Dr. Shih-Chun Lin (NC State), Dr. Kentaro Kobayashi (Nagoya University), Dr. Peng Shi (University of Adelaide), and Dr. Kwang-Cheng Chen (University of South Florida) joined their efforts in this project with great accomplishments. These achievements include teleconference and initial discussions, invited tutorial in IEEE ICC in Shanghai, China, six seminar talks in Taiwan, the first collaborative workshop organization with the ICMaSS at Nagoya University, Japan, and several joint grant writings. The student exchange program between NC State and Nagoya University is also planned to enhance the cross-linkage between the lines of research pursued by the participating members and strengthen the AC21 network in the long term.

Invited Tutorial Speakers in IEEE International Conference on Communications (ICC) in Shanghai, China, May 2019

In May 2019, Dr. Chen and Dr. Lin jointly gave a tutorial talk of "Ultra-Low Latency and Machine-Learning Based Mobile Networking (https://icc2019.ieee-icc.org/program/tutorials#tut-13)" in IEEE International Conference on Communications (ICC) in Shanghai, China. The IEEE ICC is one of the IEEE Communications Society's two flagship conferences dedicated to driving communications and has more than 2,900 scientific researchers each year joining the program submissions. The three-hour tutorial was a big success and had attracted more than 50 attendants in the discussion of ultra-low latency mobile networking, as shown in Figures 1-2.

This tutorial presented key and emerging technological aspects of ultra-low latency mobile networking based on machine learning (ML) network architecture: uplink and downlink air-interface, ultra-reliable and ultra-low latency communication (uRLLC) for 5G and beyond, network function virtualization (NFV) of network resources, ML-enabled anticipatory mobility management, channel estimation, and radio resource allocation based on ML, software-defined networking architecture and realization, network security, and machine-learning-based network architecture under new development by the ITU-T, toward future ultra-low latency and ML-based mobile networking. Through this tutorial, we successfully attracted many researchers and engineers into the research realm of ultra-low latency communications, which enhances the visibility of participating AC21 members and sets the initial discussion for the later workshop organization in the International Conference on Materials and Systems for Sustainability (ICMaSS) in Nagoya.

Figure 1. Dr. Lin delivered a tutorial talk in ICC in Shanghai.

Figure 2. Attendants in the ICC talk.

Six Seminar Talks in Taiwan, June-July 2019

During June-July 2019, based on initial research discussions with AC21 members, Dr. Lin also gave six seminar talks to industrial partners, universities and government agents in Taiwan, including Cyntec Co., Ltd., the Research Center of Information Technology Innovation (Academia Sinica) as in Figure 3, National Chiao Tung University, LiFT Program (Ministry of Science and Technology) in Figure 4, and National Center for High-performance Computing (National Applied Research Laboratories). The topics of these six seminars are given in below. The presentations greatly improved the international profile of the AC21 consortium and joined institutions.

"Towards a Distributed Computing Architecture for Ultra-Low Latency Vehicular Networking," *the Research Center of Information Technology Innovation, Academia Sinica*, Taipei, Taiwan, June 6, 2019.

"Towards a Distributed Computing Architecture for Ultra-Low Latency Vehicular Networking," *Department of Communication Engineering, National Chiao Tung University*, Hsinchu, Taiwan, June 10, 2019.

"5G and Beyond: Architectures and Deployment Cases," *Cyntec Co., Ltd.*, Hsinchu, Taiwan, June 10, 2019.

"Towards a Distributed Computing Architecture for Ultra-Low Latency Vehicular Networking," *Department of Computer Science, National Chiao Tung University*, Hsinchu, Taiwan, June 13, 2019.

"How to Upgrade Current Taiwan Industry into Industry 4.0: AI, Big Data, and IoT System Integration," *LiFT Program, Ministry of Science and Technology*, Taipei, Taiwan, June 18, 2019.

"Latest Research on 5G Architectures and Deployment Cases," *National Center for High-performance Computing, National Applied Research Laboratories*, Hsinchu, Taiwan, July 5, 2019.

Figure 3. Dr. Lin and fellows at Academic Sinica, Taipei.

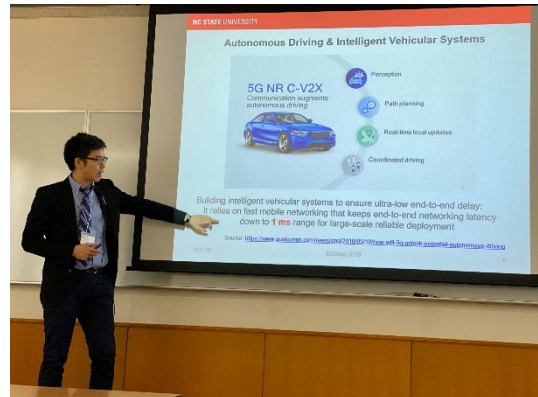**Figure 4.** Dr. Lin gave a seminar talk in LiFT program in Taipei.

First Collaborative Workshop at Nagoya University in Nagoya, Japan, November 3, 2019

Through a few rounds of discussions and thorough preparation, on November 3rd, 2019, Dr. Lin and Dr. Kobayshi successfully held "the First Collaborative Workshop Towards Ultra-Reliable Low-Latency Communications for 5G UAV (http://www.katayama.nuee.nagoya-u.ac.jp/~kobayasi/ncsu/workshop01.html)" at Nagoya University in Japan, as shown in Figure 5. The workshop is co-located with the International Conference on Materials and Systems for Sustainability (ICMaSS), which was first held in 2005. The detailed collaborative workshop schedule and papers can be found in the Appendix. Specifically, Dr. Kobayshi served as workshop chair, and there were five workshop papers from both Nagoya University and NC State. They are presented by Dr. Kobayshi's students and Dr. Lin, e.g., as shown in Figure 6.

This is the first international conference for AC21 members' joint research outcomes in ultra-reliable low-latency communications. Several great research discussions happened between the attendants and the presenters during the workshop as shown in Figure 7. After the workshop, Dr. Lin also visited the Katayama Lab and had a very constructive academic exchange with Dr. Kobayshi, as in Figures 8-9. It is our goal to continuously organize the workshop every two years with ICMaSS, which will enhance the strategic relationship between Nagoya University and NC State and also bring the scope and impact of this SPF project far beyond the grant period.

Figure 5. Dr. Lin attended and organized the workshop in ICMaSS at Nagoya University.

Figure 6. Dr. Lin presented two of workshop papers conducted by NC State team.

Figure 7. Several faculties at Nagoya University attended the workshop presentation.

Figure 8. Dr. Lin visited Dr. Masaaki Katayama and his lab.

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Figure 9. Academic exchange and research discussion between Dr. Kobayshi and Dr. Lin.

Collaborative Proposal Writings and Student Exchanges

Through active academic exchanges, the four participating AC 21 members also conducted fruitful collaborative proposal writings. These activities included the Harry C. Kelly Memorial Fund and NC State 2019-2020 Internationalization Seed Grants (NC State and Nagoya University), 2019 Faculty Research and Professional Development (NC State), and NSF SpecEES (NC State and University of South Florida). Also, Dr. Shi and Dr. Lin jointly submitted a research proposal of "Towards Scalable and Resilient Cyber Infrastructure for Mission-Critical 5G UAV Access Networks: Collaborative Research Planning between the University of Adelaide and NC State" to the University of Adelaide - NC State Starter Grants for Research Collaboration in November 2019.

Spanning from this SPF project, Dr. Lin and Dr. Kobayshi planned to establish a Ph.D. student visiting program between labs at the two institutions and are expecting the first visit will happen around the first quarter of 2020. This program will certainly enhance the cross-linkage between the lines of research pursued by the participating members and strengthen the AC21 network in the long term.

Financial Report

The funding of $10,000 U.S. dollars was received on 1 April 2019. The amount was used to support the travel and subsistence costs associated with PIs' time at the partner institution, conference participation and workshop organization. Detailed spending can be found in the table below:

	Expenditure, USD
Join the NSF CISE program workshop	$867
Travel and expense to IEEE ICC, Shanghai, China	$3,584.29
Travel and expense to Taiwan plus local trips	$1,654.6
Travel and expense to ICMaSS, Nagoya, Japan	$3,076.11
ICMaSS registration fees	$368
Stationery and printing	$450
Total	**$10,000**

Timeline of Activities

April	Discuss the project and student exchanges and proposal preparation for potential external grants. • PIs discussed academic exchanges and initiating collaborative research activities.
May	Attend IEEE ICC 2019 to advertise the planning works and seek feedbacks from academic and industrial partners. • Being invited as tutorial speakers, Dr. Lin and Dr. Chen presented the initial results of AC21 collaborative work in the ICC'19 Tutorial Session: Ultra-Low Latency and Machine-Learning Based Mobile Networking https://icc2019.ieee-icc.org/program/tutorials

June	Deliver six seminar talks in Taiwan • Dr. Lin gave seminar talks to industrial partners, universities and government agents, based on initial research discussions with AC21 members.
July	Enhance the cross-linkage between the lines of research pursued by PIs' labs. • Planed the workshop details in ICMaSS. • Discussed potential collaboration opportunities with NSF proposal submissions.
August	Discuss the proposal preparation for external grants. Create a project website to disseminate and advertise the work on 5G UAV ecosystems. • Detailed working items for the project sustainability were provided, which demonstrated a plan for the scope and impact of the project beyond the AC21 grant period.
September	Discuss the feasibility of building the physical testbed for the proposed 5G UAV ecosystems. • PIs discussed working tasks for establishing an experimental testbed to test and demonstrate the research activities. • Dr. Chen and Dr. Lin jointly submitted a research proposal to an NSF program.
October	Meet at Nagoya University in Nagoya for onsite discussion. • The last in-person meeting reinforced the complementary strengths of institutions' strategic partnership. • Dr. Kobayashi and Dr. Lin prepared the workshop website in ICMass 2019 http://www.katayama.nuee.nagoya-u.ac.jp/~kobayasi/ncsu/

November	Hold an international workshop in ICMaSS 2019 in Nagoya, Japan.
	• The workshop improved the international profile of the AC21 consortium and the PIs' institutions.
December	Prepare to submit the final report.
	• This collaborative research empowered the large-scale deployment of 5G-enabled applications with the promised performance of high reliability, low latency, and cost-efficiency.
	• Final report and several technical workshop papers were produced.
	• Discussed student exchange program among PI's labs.

Contribution to AC21

The longstanding relationship and strategic partnership among NC State, NU and AU leverage complementary strengths and transdisciplinary scholarship to advance research collaboration as well as academic exchanges. Particularly, by jointly planning the collaborative research activities, the project reinforced the three university linkages through communications between PIs' teams. The PIs also used important conference forums, e.g., IEEE ICC and ICMaSS, to advance industrial partnerships and achieve funding success. The project stimulated international collaboration and had the following contributions and broader impact on the fields of research, education, management, and international exchange.

Research: The research solutions of this project systematically accomplished the initial research discussion of 5G UAV ecosystems for URLLC, which involved the multidisciplinary knowledge of UAV placement and trajectory design, software platform programming for unified control, reliable communication and wireless networking, and system management and orchestration tools. It led to the substantive engagement of researchers in the areas of transportation engineering, radio and antenna designs, system programming, telecommunications, and wireless networking.

Education: The research solutions were incorporated into Information and Network Theory, Wireless Communication and Networking, and Network Optimization courses both at undergraduate and graduate levels within the ECE Department at NC State. The PIs also trained their Ph.D. students to become experts in this fast-evolving field and involve M.S. and undergraduate students in the proposed research by assigning them sub-problems to solve.

Management: The funding was used for the organization of an international workshop in ICMaSS 2019. This workshop brought together researchers in all relevant areas and improve the international profile of NC State, NU and AU in cutting-edge telecommunication research, enabling the establishment of new research connections and interpretations.

International Exchange: By developing the visiting/exchange Ph.D. student program at the PIs' institutions, the exchanging of students will enhance the cross-linkage between the lines of research pursued by the team members and further strengthen the AC21 network.

Appendix – Collaborative Workshop Schedule and Papers in ICMaSS

1st Collaborative Workshop Towards Ultra-Reliable Low-Latency Communications for 5G UAV Ecosystems

Date:
    Novemver 3, 2019
Time:
    10:00-11:15
Venue:
    IB Building Room 011, Nagoya University
Organizers:
    Kentaro Kobayashi (Nagoya University) and Shih-Chun Lin (North Carolina State University)

This workshop was also held as a session in International Conference on Materials and Systems for Sustainability (ICMaSS) 2019 (A6-II: Information & Communication II).

Program

Chair: Kentaro Kobayashi (Nagoya University)

1. **A Study on Cross-layer Combination of Predictive Control and Error Correction Coding for Wireless Feedback Control**
   Kohei Kasai, Kentaro Kobayashi, Hiraku Okada, and Masaaki Katayama (Nagoya University)
2. **A Study on Broadcast of Operation Information for IEEE802.15.4-Based Wireless Control of Multiple Machines**
   Yasuhiro Umemura, Kentaro Kobayashi, Hiraku Okada, and Masaaki Katayama (Nagoya University)
3. **A Study on Flight Models in Wireless Relay Networks Using Drones for LargeScale Disasters**
   Hiroki Yanai, Hiraku Okada, Kentaro Kobayashi, and Masaaki Katayama (Nagoya University)
4. **A Study on Delay-Optimal Scheduling Policy for Ultra-Low Latency Vehicular Networking**
   Weiqi Sun and Shih-Chun Lin (NC State University)
5. **A Study on User-Centric Virtual-Cell Design in Software-Defined Vehicular Networks**
   Weiqi Sun and Shih-Chun Lin (NC State University)

[HOME]

A Study on Cross-layer Combination of Predictive Control and Error Correction Coding for Wireless Feedback Control

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Introduction   In wireless feedback control systems, control quality deteriorates due to wireless channel error and packet loss. As techniques to improve the control quality, there are techniques such as error correction coding to reduce wireless channel error in the communication layer and packetized predictive control to compensate packet loss in the control layer. The purpose of this study is improvement of the control quality using both predictive control and error correction coding. We propose a method that combines redundancy of predictive control and error correction coding and show that the proposal improves tolerance to channel error compared to the single use of either of them.

Wireless Feedback Control System   Figure 1 shows the proposed wireless feedback control system. The discrete time representation of the plant is given as $\mathbf{x}[k+1]=\mathbf{A}\mathbf{x}[k]+\mathbf{B}\mathbf{v}[k]+\mathbf{w}[k]$, where $\mathbf{x}[k]$, $\mathbf{v}[k]$, and $\mathbf{w}[k]$ are state, control input, and disturbance vectors at time $t=kT_s$ (T_s:control period, k=0, 1, ...), respectively; and $\mathbf{A}$ and $\mathbf{B}$ are

Figure 1 Proposed wireless feedback control system

coefficient matrices. A model predictive controller is used to calculate control input up to N_p cycles ahead with a reference $\mathbf{x}_{ref}$, i.e., $\vec{\mathbf{u}}[k]=\text{MPC}(\mathbf{x}-\mathbf{x}_{ref})= [\mathbf{u}[k|k], \mathbf{u}[k+1|k], …, \mathbf{u}[k+N_p|k]]$, where $\mathbf{u}[k|k]$ is a control input vector to be input at k and the others are predictive input vectors. A packet of $\mathbf{u}[k|k]$ with redundancy given by the proposed method is sent to the plant through a channel with bit error rate P_b. If uncorrectable error occurs, the received control input packet is discarded (i.e., packet loss) and instead the plant uses a predictive input vector previously stored in the buffer.
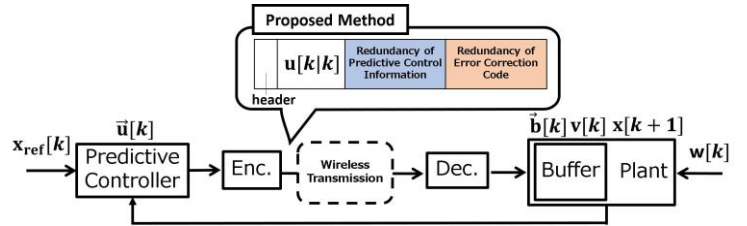
Redundancy Combination   The proposed method combines redundancy of predictive control and error correction coding. Here, let the size of control input $\mathbf{u}[k|k]$ be B_u bytes. In the proposed method, the predictive controller adds $N \times B_u$-byte redundancy of $\mathbf{u}[k+1|k], … , \mathbf{u}[k+N|k]$ to $\mathbf{u}[k|k]$, and in addition, the encoder adds $P \times B_u$-byte redundancy of error correction codes to the packet of the predictive controller; therefore, the total redundancy length added to $\mathbf{u}[k|k]$ is $(N+P) \times B_u$ bytes. Under a fixed total redundancy length, there is a trade-off in N and P: a longer N of the predictive controller can cope with continuous packet loss using buffered predictive input vectors, but the packet error rate becomes higher; on the other hand, a longer P of the error correction coding decrease the packet error rate but cannot cope with continuous packet loss.

Numerical Results   We evaluated the performance of the proposed method by computer simulation. A rotary inverted pendulum is employed as the plant, and the control performance is evaluated by pendulum fall rate. The performance evaluation is performed for several combinations of the redundancy length N of the predictive control and the redundancy length P of the error correction codes, namely Polar codes. Figure 2 shows the pendulum fall rate for $N+P$=4. This result shows that control quality can be improved by combining redundancy of predictive control and error correction coding, and the best performance is obtained in the case of N =1 and P =3. The reason is that if P is large, the packet error rate is effectively reduced, and therefore small N is enough to compensate packet loss.
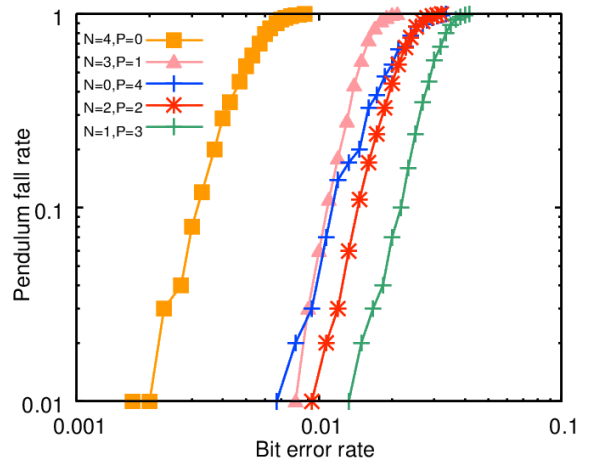

Figure 2 Pendulum fall rate

A Study on Broadcast of Operation Information
for IEEE802.15.4-Based Wireless Control of Multiple Machines

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Introduction

This study considers an efficient communication method to control multiple machines using IEEE802.15.4 communication standard. In wireless control of multiple machines, it is necessary to communicate with more machines within a control period. We propose a method of aggregating operation information of multiple machines and simultaneously transmitting them using broadcast communication. The effectiveness of the proposed method is shown by evaluating the control quality.

Wireless Feedback Control System with Multiple Machines

Figure 1 shows a wireless feedback control system with multiple machines (plants), where a controller and plants communicate via a beacon-enabled IEEE802.15.4 network. The controller sends operation information $u_i[k]$, which is calculated for time kTs (Ts beacon interval, $k = 0, 1, 2, ...$), to each plant. State information of each plant is given by $x_i[k+1]=Ax_i[k]+B\hat{u}_i[k]+w_i[k]$, where $x_i[k]$, $\hat{u}_i[k]$ and $w_i[k]$ are state information, received operation information and disturbance, and A and B are determined by the plamts. Each plant feedback observed state information to the controller. For the next time index, the controller estimates state information using the received state information and calculates operation information as $u_i[k]=K_i(x_{ref}[k]-x_{esti}[k])$, where $x_{ref}[k]$, $x_{esti}[k]$, and K_i are reference, estimated state information and feedback gain.
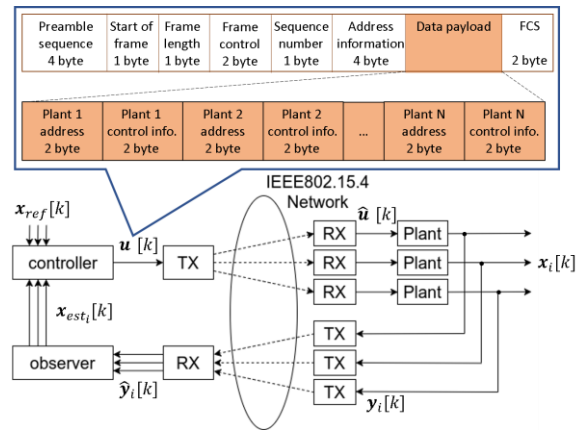

Figure 1 System model

Broadcast of Operation Information

In the beacon-enable IEEE802.15.4, there are two periods, a contention access period (CAP) for communicating by carrier sense multiple access and a contention free period (CFP) for communicating by time division multiple access with guaranteed time slots (GTSs). The proposed method combines a broadcast of operation information in the CAP and the conventional GTS allocation method. As shown in Fig. 1, the controller aggregates the addresses and operation information of plants to be broadcast into the payload part of a packet, and then broadcasts the packet at the beginning of the CAP. In addition, the controller allocates all GTSs to the transmission of state information of each plant based on the control quality. Note that the information of the existence of the broadcast and the GTS allocation is delivered to all plants by the beacon according to the IEEE802.15.4 standard.

Numerical Results

We evaluated the performance of the proposed method by computer simulation. A rotary inverted pendulum is used as the plant, and the pendulum fall rate is used to evaluate the control quality. The control quality of the proposal is compared with no broadcast case. Figure 2 shows that the proposed method effectively improves the control quality for larger number of plants compared to the case without broadcast. This is because operation information and state information that can be communicated within one control period are increased by broadcasting aggregated operation information.
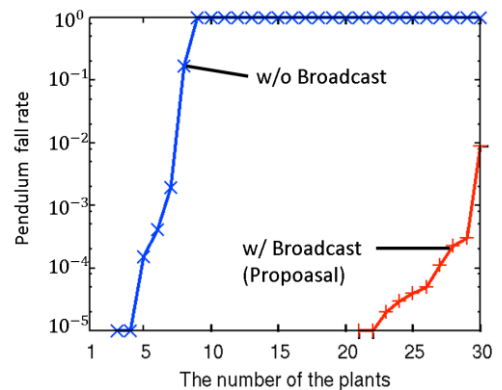

Figure 2 Pendulum fall rate

Acknowledgement

A Study on Flight Models in Wireless Relay Networks Using Drones for Large-Scale Disasters

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Introduction

For large-scale disasters, it is important to secure communications to confirm safety and disaster situation. However, communication disturbance may occur due to destruction of communication infrastructure. Then, a wireless relay network using drones has been proposed. In the wireless relay network, a packet can be transmitted even if there are not drones enough to cover the stricken area. The increase in delay time depends on the manner in which the drones fly. We discuss flight models to reduce delay time for this network. Moreover, we consider maintenance stops of drones due to their battery exhaustion because it is impossible for the drones to fly permanently. Considering exhaustion of drones' batteries makes the feasibility of the system to increase. To consider the exhaustion of drones' batteries, we introduce a stop duration.

Figure 1 Wireless network using drones.

Wireless Relay Network Using Drones

Figure 1 depicts a wireless relay network using drones as an emergency communication system. This network consists of user nodes and drones. Drones construct the wireless relay network in the sky to cover the stricken area, and accommodate user nodes on the ground. When a drone has a neighbor drone within its communication range, the two drones connect wirelessly and the drone forwards a packet to the neighbor drone. If the drone does not have any neighbor drones within its communication range, we employ the concept of delay torellant network (DTN) to enable packet transmissions. In the emergency communication system of the stricken area, an arbitrary user node in the wireless relay network transmits a packet to another arbitrary user node. Drones can fly during the flight duration, but they stop flying when their batteries run out.Drones drop out from the network during the stop duration and then their batteries are exchanged. After the exchange, drones return to the network again.
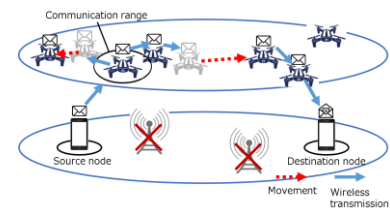
Numerical Results

We evaluate the delay time considering drones' stops for the flight models by simulations. In the simulation, we consider three timing of drones' stops; random, ordering, simultaneous stop timings, and two cases of maintenance points; a fixed point at (2000, 2000) and any points which indicate that drones stop at the location where their batteries exhaust.

The simulation area is 4000 m × 4000 m. A source node and a destination node are located at (500, 500) and (3500, 3500), respectively. The communication range and speed of the drones are 500 m and 10 m/s, restictively. The rebounding-flight model is used as a flight model. We measure the delay time of packet transmissions from the source node to the destination node in terms of the total number of drones.

Figure 2 The delay performance for stop timings considering maintenance points.

Figure 2 shows the average delay time for stop timings considering maintenance points. Compared with the case of any maintenance points, when drones stop at the fixed maintenance point, the delay time increases for any stop timings. The delay time of the simultaneous stop timing is longer than that of the other two timings for the case of the fixed maintenance point. There is no significant difference in the delay time between the random and ordering stop timings. Then it is not necessary to adjust the stop timing so as to be in order. From the results, we conclude that the random stop timing is effective to reduce the delay time for the wireless relay networks using drones, taking account of drones' stops.
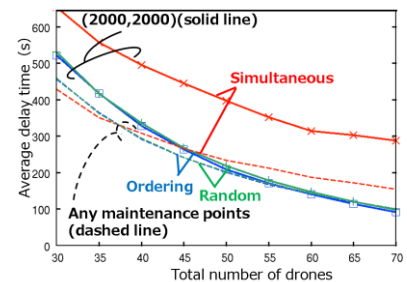
Acknowledgement

A Study on Delay-Optimal Scheduling Policy for Ultra-Low Latency Vehicular Networking

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Introduction

Safety and reliable deployment of autonomous vehicles (AVs) in massive scale is important and challenging, which requires the end-to-end latency down to 1 ms range. In this study, we focus on ultra-low latency mobile networking in our designated software-defined vehicular networks. A time-average queueing delay minimization problem is formulated, where the head-of-line packet waiting time is modeled as the worst-case constraint. To solve the problem, a delay-optimal scheduling policy is proposed via the Lyapunov optimization. Numerical results confirm the superior performance of the proposed policy.

Queueing Model

For downlink transmissions to AVs $\mathcal{U} = \{1, 2, \ldots, U\}$, an anchor node (AN) holds U traffic queues $\mathbf{Q}(t) = [Q_1(t), Q_2(t), \ldots, Q_U(t)]$. The traffic arrival process is modeled by a sequence of independent and identically distributed (i.i.d.) non-negative random variables $\{A_u(t), u \in \mathcal{U}\}$ with $\mathbb{E}[A_u(t)] = \lambda_u$. The queue dynamic for VU u can be captured by $Q_u(t+1) = [Q_u(t) - \pi_u(t) S_u(t)]^+ + A_u(t)$, where $\pi_u(t)$ indicates scheduling decision that is 1 if $Q_u(t)$ is served and is 0 otherwise. $S_u(t)$ is the number of packets served at time t. Let $H_u(t)$ represent the head-of-line packet waiting time in queue u at time t and define $H_u(t) = 0$ if there is no packet in the queue. Define $\alpha_u(t)$ as an indicator variable that is 1 if $Q_u(t) > 0$ and is 0 otherwise and T_i as the inter-arrival time between the head-of-line packet and the subsequent packet, which follows geometric distribution with $\mathbb{E}[T_i] = 1/\lambda_i$. We can observe that $H_u(t)$ satisfies $H_u(t+1) = \alpha_u(t) \left[H_u(t) + 1 - \sum_{i=1}^{S_u(t)} T_i \right]^+ + (1 - \alpha_u(t)) A_u^+(t)$.
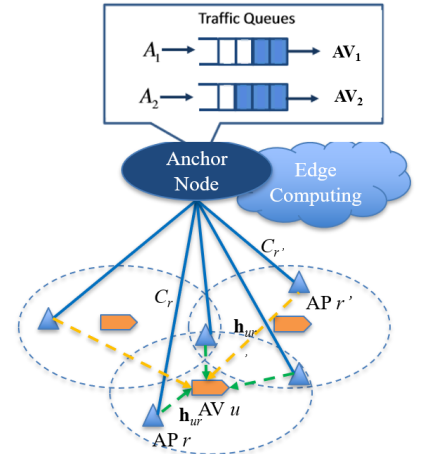
Figure 1 Downlink system: AN-APs-AVs

Delay-Optimal Scheduling Policy

We aim at finding the optimal scheduling decision and service rate for each AV to minimize the time-average of queueing delay while ensuring the stability of queue length and the bound on the head-of-line packet waiting time. The queue-aware problem can be formulated as follows:

$$\textit{Find}: \qquad \pi_u(t), S_u(t), \forall u \in \mathcal{U}$$

$$\textit{Minimize}: \quad \lim_{T \to \infty} \sum_{t=1}^{T} \mathbb{E}\left[\sum_{u=1}^{U} D_u(t) \right] \Big/ T$$

$$\textit{Subject to}: \quad \lim_{T \to \infty} \sum_{t=1}^{T} Q_u(t) \Big/ T < \infty, \forall u \in \mathcal{U}$$

$$\lim_{T \to \infty} \sum_{t=1}^{T} H_u(t) \Big/ T < \infty, \forall u \in \mathcal{U}$$

The original stochastic optimization problem can be transformed to a per-slot deterministic one using Lyapunov optimization. Define $\mathbf{\Theta}(t) \overset{\Delta}{=} [\mathbf{Q}(t); \mathbf{H}(t)]$ and Lyapunov function $\mathcal{L}(\mathbf{\Theta}(t)) \overset{\Delta}{=} \left[\sum_{u=1}^{U} Q_u(t)^2 + \sum_{u=1}^{U} \lambda_u H_u(t)^2 \right] \Big/ 2$. The one-step conditional Lyapunov drift is $\Delta \mathcal{L}(\mathbf{\Theta}(t)) \overset{\Delta}{=} \mathbb{E}\left[\mathcal{L}(\mathbf{\Theta}(t+1)) - \mathcal{L}(\mathbf{\Theta}(t)) | \mathbf{\Theta}(t) \right]$. Based on Lyapunov optimization, with positive constants V, η and B, for all time t and $Q_u(t)$, the Lyapunov drift-plus-penalty function satisfies $\Delta \mathcal{L}(\mathbf{\Theta}(t)) + V \mathbb{E}[D(t) | \mathbf{\Theta}(t)] \leq B + \sum_{u=1}^{U} Q_u(t) [A_u(t) - S_u(t) | \mathbf{\Theta}(t)] + \sum_{u=1}^{U} H_u(t) [\lambda_u(t) - S_u(t) | \mathbf{\Theta}(t)] + VD^*$. To minimize the bound of the Lyapunov drift, the delay-aware scheduling policy is proposed as

$$\textit{Find}: \qquad \pi_u(t), S_u(t), \forall u \in \mathcal{U}$$

$$\textit{Minimize}: \quad \sum_{u=1}^{U} \left\{ \pi_u(t) S_u(t) \min\left[Q_u(t), H_u(t) \right] - VD_u(t) \right\}$$

The proposed on-line policy only depends on real-time system parameters without the need of statistic information.

Acknowledgement

A Study on User-Centric Virtual-Cell Design in Software-Defined Vehicular Networks

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Introduction

Leveraging software-defined network and edge computing is a promising solution for the sharing and processing of sensor data in ultra-low latency vehicular networks. In this study, we focus on the user-centric virtual-cell based software-defined vehicular networks where coordinated multipoint and open-loop transmission are integrated to minimize the latency for handover and retransmission. A downlink network capacity maximization problem is proposed to optimize virtual cell association and transmit power allocation, while satisfying the system-level constraints from the vehicular network architecture. Performance evaluation validates the efficiency of our design.

Virtual-Cell Based Software-Defined Vehicular Network

In Figure 1, the virtual-cell based software-defined vehicular network consists of (i) an anchor node (AN) with edge computing ability, (ii) multiple access points (APs) $\mathcal{R} = \{1, 2, \ldots, R\}$ connected to the AN via the fronthaul links, and (iii) multiple vehicular users (VUs) $\mathcal{U} = \{1, 2, \ldots, U\}$. To mitigate the multi-access interference incurred by open-loop transmission, non-orthogonal multiple access (NOMA) is used based on power domain division and successive interference cancellation (SIC) is applied at receivers. The received signal at VU u is $r_u = \sum_{u' \in \mathcal{U}} h_u \sqrt{P_{u'}} s_{u'} + n_u$, where s_u is the desired signal for VU u, P_u is the transmit power allocated to s_u at each AP. $h_u = \sum_{r \in \mathcal{R}} h_{ur}$ is the equivalent channel coefficient to VU

Figure 1 An illustration of downlink transmission in the virtual-cell based software-defined vehicular network

u and $h_{ur} = \sqrt{r_{ur}^{-\alpha}} g_{ur}$ is the channel gain from AP r to VU u with the association distance r_{ur}, the path loss exponent α and the fast fading vector g_{ur} which follows $\mathcal{CN}(0,1)$. $n_u \sim \mathcal{CN}(0, \sigma^2)$ is the additive white Gaussian noise. Assume each VU can decode the signals of the VUs in the weaker channels faultlessly. Denote $V_u = \{r \in \mathcal{R} | l_{ur} = 1\}$ as the set of APs that forms the virtual cell serving VU u, and $W_r = \{u \in \mathcal{U} | l_{ur} = 1\}$ as the set of VUs served by AP r. With the knowledge of statistical channel state information (CSI), the ergodic signal-to-interference-plus-noise ratio (SINR) is
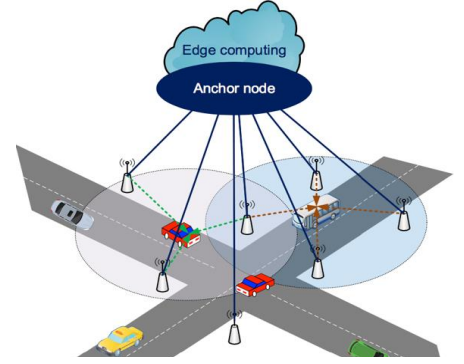
$$\gamma_u = \left| \mathbb{E}\left[\sum_{r \in V_u} h_{ur} \sqrt{P_u} \right] \right|^2 \Bigg/ \left\{ \mathrm{var}\left[\sum_{r \in V_u} h_{ur} \sqrt{P_u} \right] + \mathbb{E}\left[\left| \sum_{r \in V_u} h_{ur} \sqrt{\sum_{m \in W_r, m > u} P_m} \right|^2 \right] + \mathbb{E}\left[\left| \sum_{r \in \{R/V_u\}} h_{ur} \sqrt{\sum_{m \in W_r} P_m} \right|^2 \right] + \sigma^2 \right\}.$$

Problem Formulation

Given a software-defined vehicular network with the AP set $\mathcal{R} = \{1, 2, \ldots, R\}$ and the VU set $\mathcal{U} = \{1, 2, \ldots, U\}$, the association matrix $\boldsymbol{l}$ and the power allocation matrix $\boldsymbol{P}$, the network capacity maximization problem is

$$\begin{aligned}
Find: \quad & l_{ur}, P_u, \forall u \in \mathcal{U}, r \in \mathcal{R} \\
Maximize: \quad & \sum_{u=1}^{U} R_u \\
Subject\ to: \quad & 1 \le \sum_{r=1}^{R} l_{ur} \le V_{max}, R_u \ge R_u^{min}, \forall u \in \mathcal{U} \\
& \sum_{u \in W_r} P_u \le P_r^{max}, \sum_{u=1}^{U} l_{ur} R_u \le C_r, \forall r \in \mathcal{R}
\end{aligned}$$

The proposed framework aims at finding the optimal virtual cell formation according to the dynamic VU distribution, in such a way that the network capacity is maximized by jointly mitigating the impact of (i) the intra-cell interference, (ii) the inter-cell interference, and (iii) the pilot contamination induced interference. The optimal design highly depends on the cooperation among APs and belongs to an NP-complete problem. An effective learning algorithm will be proposed to provide satisfactory solutions by only few searching iterations.

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