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Towards Real-Time Control in Future Wireless Networks: Communication-Control Co-Design

Guodong (Philip) Zhao, Muhammad Ali Imran, Zhibo Pang, Zhi Chen, and Liying Li

G. Zhao and M. Imran are with School of Engineering, University of Glasgow, Glasgow, UK
(guodong.zhao@glasgow.ac.uk, muhammad.imran@glasgow.ac.uk)
Z. Pang is with ABB Corporate Research, Vasteras, Sweden, (pang.zhibo@se.abb.com)
Z. Chen is with National Key Laboratory on Communications, University of Electronic Science and Technology of China (UESTC), Chengdu, China (chenzhi@uestc.edu.cn)
L. Li is with School of Automation Engineering, University of Electronic Science and Technology of China (UESTC), Chengdu, China (liyingli0815@gmail.com)

Abstract

Wireless networks are undergoing a transition from connecting people to connecting things, which will allow human interaction with the physical world in a real-time fashion, e.g., tactile internet, industrial automation, self-driving vehicles, and remote surgery. Therefore, future wireless networks need to support real-time control since it is the essential function enabling such emerging applications. In this article, some fundamental design capabilities needed to realize real-time control in future wireless networks are discussed, with primary emphasis given to communication-control because both communication and control systems have strong dynamics and interdependencies, and they tightly interact with each other. A case study is provided to demonstrate the necessity of such co-design.

I. INTRODUCTION

In the past two decades, the evolution of wireless networks, e.g., cellular and WiFi networks, has successfully connected people and brought us into a cyber world, which allows people to communicate with each other and access the Internet almost at anytime and anywhere. In the near future, a significant number of "things", e.g., sensors and actuators, are expected to be connected, which will allow us to interact with the physical world in a real-time fashion, e.g., tactile internet, industrial automation, self-driving vehicles, remote surgery, and smart grid. Therefore, future wireless networks need to support real-time control, also called teleoperation or remote operation, since it is the essential function that enables many emerging applications as mentioned in [1].

Unfortunately, today's wireless networks are lagging far behind in their ability to support real-time control because real-time control usually requires deterministic communication with ultra low-latency and high-reliability requirements. For example, the tactile internet and industrial automation need 1 ms end-to-end round-trip time delay and 10^{-5} ~ 10^{-7} packet loss probability [2]. Smart grid requires as low as $10\mu s$ time delay with 10^{-9} packet loss probability [3]. In contrast, conventional cellular and WiFi networks are designed for high quality video transmission and web surfing. They can provide massively high throughput wireless services, but with relative large time delay 50~150 ms and high packet loss probability 10^{-2} [4]. Conventional industrial wireless networks as summarized in [5], e.g., Zigbee, Bluetooth, Wireless HART, and ISA-100.11a, operate in the *industrial scientific medical* (ISM) bands around 2.4 GHz and 5 GHz, and have non-guaranteed performance due to strong co-channel interference, which has been mentioned in [6]. Consequently, the current applications of industrial wireless networks are limited to industrial monitoring rather than real-time control.

In practice, it is very challenging to support real-time control via a wireless communication network. A primary for this is the independent design between communication and control systems that leads to substantial wireless resource consumption. In independent design, control engineers ask for extreme communication requirements based on the worst case of a control system, e.g., the case that a controller needs to stabilize a system under the most uncertain situation, since the worst case usually causes the failure of the whole system. Then, communication engineers come up with the solutions to guarantee the extreme requirements for every single packet, which consumes substantial wireless resources.

In this article, we discuss some fundamental design aspects to realize real-time control in future wireless networks from the perspective the *physical* (PHY) layer and *media access control* (MAC) layer, where primary emphasis will be placed on communication-control co-design. Our goal is to motivate researchers to treat the wireless and control systems as a whole to design a fully integrated system, which can be widely implemented in many emerging applications. The main contributions of this article are as follows:

- We introduce the basics of a typical real-time wireless control system and summarize the state-of-the-arts of the currently techniques from the perspectives of control and wireless communications, respectively.
- We discuss communication-control co-design, which is expected to capture the tight interaction between communication and control systems. In particular, we identify some opportunities as well as technical challenges and open issues.
- We provide a case study of the co-design to demonstrate the advantages as well as the fundamental difference compared with conventional independent design.

II. REAL-TIME WIRELESS CONTROL SYSTEM

In this section, we first introduce the basics of real-time wireless control systems and then discuss some critical variables that capture the tight interaction between communication and control.

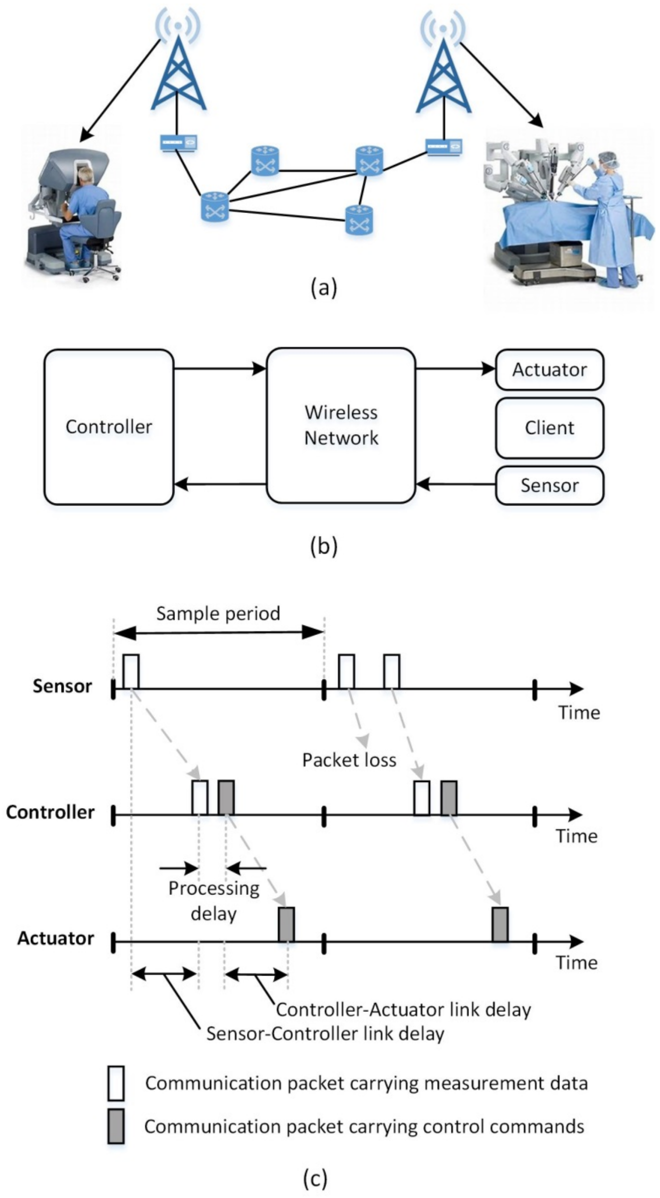

Fig. 1 A typical real-time wireless control system: a) the use case of remote surgery; b) system diagram; c) timing diagram of the wireless communication.

A. System Diagram

A typical example of a real-time wireless control system is provided in Fig. 1, where the use case is remote surgery as in Fig. 1-(a) and the basic system diagram is in Fig. 1-(b). From this example, the wireless control system is a spatially distributed system, in which a wireless network connects a sensor, an actuator, and a controller. The sensor observes the state of the client by sending its measurement data to the controller via the wireless network, which is shown in Fig. 1-(c). Then, the controller conducts calculations to obtain some control commands for the actuator, where the wireless network delivers the commands. Once the actuator receives the commands, it acts accordingly, which physically changes the state of the client. In the meantime, the sensor observes the updated state and sends new measurements to the controller for further control. This sequence continues to iterate until the desired task is completed.

The above system diagram captures the essential feature of many emerging applications in future wireless networks. For example, if a cloud center is the controller and a moving robot is the actuator, Fig. 1-(b) represents the basic system diagram of remote operation in industrial automation. If we generalize the model by considering multiple controllers, actuators, and sensors, it describes the use case of smart grid.

The overall design goal of the real-time wireless control system is to finish a control task and achieve a certain control performance. For example, in industrial automation, the design goal could be wirelessly controlling a robotic arm to grab objects with certain accuracy requirements. In future transportation systems, the design goal could be enabling the automated formation of several cars following one another closely, also called platooning, under required safety performance.

B. Critical Variables

Real-time wireless control is supported by both control system and wireless system, which tightly interact with each other via some critical variables. In this subsection, we introduce some critical variables illustrated in Fig. 1-(c) to understand the whole system.

1) Sample Period: The sample period is the overall time consumption that a control iteration takes, including sensor's sensing, the sensor-controller communication, controller's processing, the controller-actuator communication, and actuation's execution. The sample period affects the control performance since it determines the time resolution to conduct control. On the other hand, it also affects the wireless network since it determines the volume of the traffic generated by the control system.

2) Time Delay: In the typical real-time wireless control system, there are sensor-controller link delays, controller-actuator link delays, and controller's processing delays. The communication delays usually include transmission delay, backhaul delay, and queuing delay, which are related to many factors, e.g., the communication protocol, frame or packet structure, the transmission strategy, scheduling policy, etc. Excessively long delay, including the controller's processing delay, may degrade the control performance or even cause the failure of the system.

3) Packet Loss: Due to the dynamic nature of wireless channels, wireless communication inevitably experiences deep fading or shadowing that reduces the channel capacity. If the channel capacity is too low to support the transmitted data rate, the receiver cannot decode the packet correctly, which is called packet loss. In wireless systems, the packet loss may cause re-transmission or reduce the throughput. In control systems, the packet loss may increase the control cost, e.g., the control system needs to conduct extra actions to compensate for the consequences of packet loss.

III. CONTROL AND COMMUNICATION INDEPENDENT DESIGN

In real-time wireless control systems, there are mainly two kinds of design methods, independent design and co-design, which are shown in Fig. 2. The former divides the whole system into control and communication systems, which are designed independently. The latter jointly designs both control and communication systems. In the current and next sections, we discuss them, respectively.

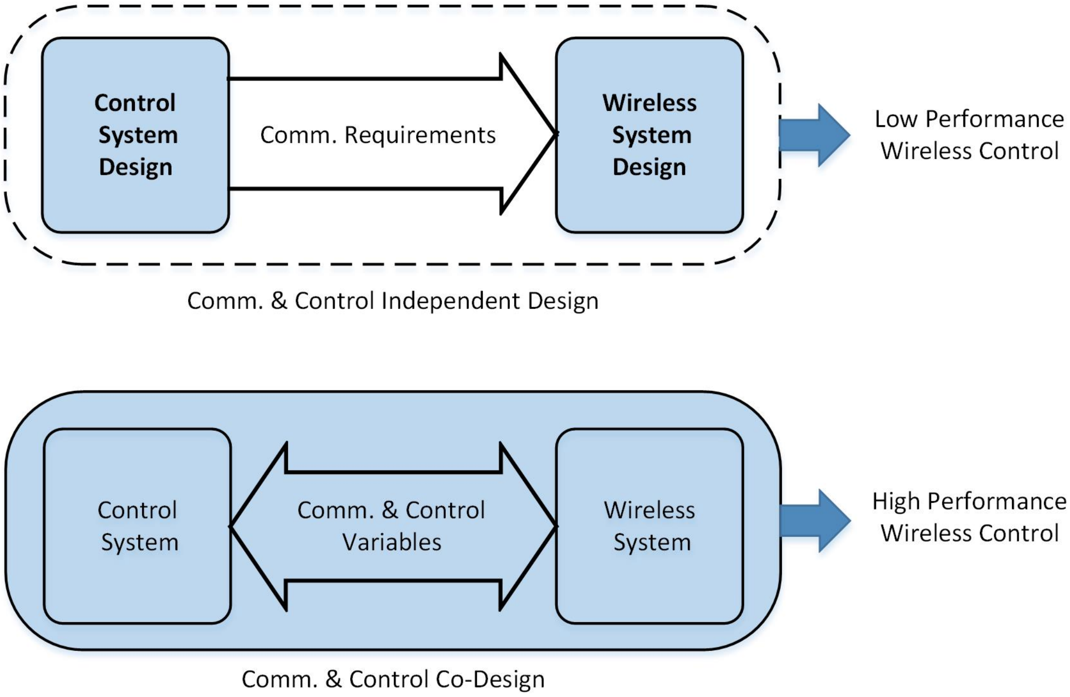

Fig. 2 Independent design versus co-design.

A. Motivation

According to [7], the independent design is based on the principle of layering as it allows an unmodified control system to operate with new communication systems as long as they meet the requirements defined by the control system. Such an arrangement is flexible, i.e., the control system is compatible with different wireless communication systems. This also simplifies the system design, where the control and communication systems can be designed separately.

In practice, the independent design usually starts from the control system, where the minimum communication requirements are obtained under certain control performance requirements. In other words, control engineers specify the communication requirements in terms of data rate, latency, reliability, etc. Then, communication engineers find solutions to meet these requirements.

B. Control System Design

In general, as indicated in [8], a control system is designed to keep the state error of the client near a set point close to zero, while minimizing the cost of control actions. Control cost is usually defined as a sum of the deviations of the state from its desired set-point and the magnitudes of the control inputs. Then, the algorithm that minimizes the control cost becomes the optimal control algorithm.

In wireless control systems, since the packet loss and time delay caused by the wireless system usually degrade the control performance or even destabilize the system, the first thing that needs to be understood is the impacts of wireless imperfections, e.g., packet loss and time delay, on control performance. Based on this, we can obtain the communication requirements for wireless system design. In algorithm design, many contributions as discussed in [9] have investigated robust control algorithms to tolerate communication imperfections. Some of them minimize the communication requirements under certain control performance, e.g., the intermediate control and distributed control. Others optimize control performance under a certain level of communication imperfections, e.g., scheduling for multiple control systems.

C. Wireless Communication System Design

A wireless communication system is designed to deliver data in sensor-controller links or/and controller-actuator links. Some requirements, such as data rate, latency, packet loss, etc., need to be achieved. Meanwhile, the wireless resource consumption needs to be minimized. Therefore, communication engineers first find use cases with specific requirements, and then they design the wireless system to meet these requirements.

A typical example is tactile internet in the *fifth generation* (5G) cellular networks [2]. Use cases are first studied, which allows people to understand the key communication requirements, e.g., data rate, latency, and reliability. Then, the performance gap is identified by comparing the target requirements with current wireless networks. Next, communication engineers investigate the basic wireless resources, e.g., time, frequency, energy, and space, to obtain technical directions that can potentially fill the gap. For example, the need to understand channel capacity with short packets motivates research on finite-block length coding and frame design as in [10]; spectrum analysis motivates research on millimeter wave techniques as in [11]; more stringent latency requirement forces communication engineers to rethink the trade-off among time, frequency, and spatial diversities as discussed in [12]. On the other hand, communication engineers may take advantages of the recent progress on software defined radio and cloud/edge computing to have some new design solutions, e.g., network slicing, cloud/edge/fog networks, etc. Many other techniques, like *non-orthogonal multiple access* (NOMA) and grant free access techniques, are also considered to reduce the latency in access and more efficient utilization of radio resources. In summary, the design goal of the wireless system is to meet the target requirements to enable real-time wireless control for different use cases.

IV. COMMUNICATION-CONTROL CO-DESIGN

The communication-control co-design is a category of system design methods that treats the wireless communication and control systems as a whole to find technical solutions to achieve the goal of wireless control. It is expected to obtain much better overall system performance compared with the independent design, since it can capture the tight interaction between communication and control systems. In the following, we first introduce the motivation behind co-design as well as the reason why we consider co-design now. Then, we discuss the new opportunities offered by co-design and the corresponding technical challenges and open issues.

A. Motivation

In real-time wireless control systems, the control performance not only depends on control algorithm but also relies on the performance of wireless communication network. The tight coupling between control and the wireless network requires us to treat the wireless and control systems as a whole to design a fully-integrated system, which is expected to achieve good control performance while consuming minimal wireless resources.

For example, the sample rate of a control system affects both control and wireless systems, which further determines the overall control performance [6]. From the control side, a low sample rate leads to poor control performance since the system cannot provide adequate control actions. A high sampling rate improves the control performance. However, if the sampling rate is too high, the control system will generate too many communication packets and cause traffic congestion in wireless networks. Then, the time delay and packet loss become high, which in turn degrades the control performance. Therefore, the optimal sampling rate should be selected by considering both control and wireless systems.

Another pertinent question is that why this time and age is most appropriate for considering the co-design challenge? This is mainly due to the trend of network virtualization in wireless networks that offers significant flexibility in system design. Originally, the flexibility was obtained from independent design, in which a control system is compatible with many wireless networks as long as required communication performance can be satisfied. This however comes with the price of low system efficiency and poor overall performance. Most of today's control systems are still based on wired communications. However, future wireless networks with rich communication and computing resources are expected to be configured dynamically according to specific scenarios and use cases. Therefore, the co-design that fully integrates the control system into wireless network is expected to achieve excellent overall performance.

B. Opportunities

1) New Applications and Markets: Conventionally, the design goal of wireless communication systems is to approach the performance of wired communication systems in terms of data rate, latency, reliability, etc. Then, in control systems, we can safely replace communication cables by wireless links. However, the past ten-year development shows the constraints in the performance of wireless links and limitations in many scenarios. This is because the dynamic nature of wireless channels contradicts the deterministic communication required by conventional control systems. In contrast, the co-design is expected to address the problem by exploiting the strong dynamics and tight interaction between wireless and control systems. Thus, the co-design is not for upgrading the conventional control system by removing communication cables. Instead, it is targeted for new applications and markets that did not exist before, e.g., remote surgery in advanced medical systems, moving robots in industrial automation, and connected cars in future transportation systems.

2) New Techniques: Conventional control system design requires deterministic communication link since control system does not collaborate with wireless system. Then, the communication time delay and packet loss become the side effects that the control system tries to avoid. However, in co-design, the control system may take advantages of communication imperfections, which becomes new design freedoms. For example, it has been shown in [13] that the communication delay can help to stabilize control system; the dynamics of wireless channels can enhance the security of wireless control systems; the distribution of wireless nodes can provide guidance to deploy drones for wireless coverage. Therefore, the co-design that fully integrates the wireless and control systems offers many opportunities for developing new techniques.

3) Discussion: Compared with the conventional independent design, the co-design integrates both control and communication, which makes the system much complicated and raises some potential risks. For example, (1) the co-design would have more chance of system failure due to its complication. It also becomes relatively difficult to diagnose the system and identify the problem. (2) The co-design would have more degrees of freedom (i.e., parameter setting) to configure the system. Then, it becomes difficult to guarantee that the system runs in the optimal mode, which risks the benefits of the co-design. (3) The co-design would also suffer from obtaining the promised performance in practical scenarios, since all the parts in the system, e.g., model, theory, and algorithm, need to be verified by running the real co-designed system.

C. Technical Challenges and Open Issues

As indicated in the introduction, the performance gap between control requirements and current wireless systems is huge. It needs to reduce the packet loss probability from 10^{-2} to $10^{-5} \sim 10^{-9}$ and the time delay from 50 ~ 150 ms to 1 ms. In the following, we discuss the main technical challenges and open issues in co-design, from modeling and theories to enabling techniques in different aspects.

1) Modeling: In communication-control co-design, the first challenge is to obtain a good abstraction of the wireless control system, which is expected to hide the system complexity, keep the critical aspects, and be mathematically tractable. Generally, there are two categories of methods. The first one divides the whole system into control and wireless systems, and models them separately. The second one treats the wireless control system as a whole and models the communication network itself as the controller. In most of existing systems with independent design, they use the first category modeling method and treat the critical variables between two subsystems as design requirements rather than design variables. In the future, the new modeling methods for co-design becomes challenging since there are many types of controllers, wireless networks, scenarios, and use cases.

2) Information and Control Theories: Even though the control and communication theories are relatively mature, they cannot effectively serve the co-design. Currently, there are some progresses on co-design theories, but many problems are still open. For example, the relationship between control stability and information processing rate has recently been studied. The fundamental limits of the control over noisy channels and packet dropping networks have been established. However, in real-time wireless control systems with short packet communication, the fundamental limits of wireless control are still open. Furthermore, if we consider predictive control, where each communication packet carries not only the current control information but also the future control information, then the fundamental limits become more complicated since it is related to aging information networks.

3) Interaction between Control and Wireless Network: Currently, the interaction between control and wireless network is mainly studied by control engineers with oversimplified communication models. To fully understand the interaction, communication engineers still need to answer many fundamental questions. For example, to achieve a control task with certain control performance, does each packet have the same importance and require to be served under the same communication *quality of service* (QoS), e.g., the time delay and packet loss probability? What is the tradeoff between them? The answers are critical since the wireless resource consumption increases dramatically as the QoS requirement grows. Rather than serving each packet with identical QoS, the co-design may use different QoS levels or trade off points to serve different packets. In summary, understanding the tight interaction between control and communication systems is not trivial and it provides important guidance on co-design.

4) Network Slicing and Edge Computing: Network slicing and edge computing are effective tools to implement real-time wireless control. This is because future wireless networks are expected to use common communication infrastructures to support different use cases with diverse and extreme requirements. For each control task or a group of control tasks, network slicing can provide a set of network resources to customize a visualized end-to-end network. In addition, it is natural to integrate controller into wireless network and use edge computing to realize wireless control, since current wireless infrastructures, e.g., base station, usually have strong computing ability. Currently, the network slicing and edge computing are the major trends in wireless communications. Next, integrating these techniques to specific control applications would be the future and the main challenging is how to efficiently schedule wireless and computing resources to meet the required control performance in different use cases.

5) Security and Privacy: Security and privacy issues are crucial since the wireless control system interacts with the physical world. The failure of the system may cause severe consequences. Then, security and privacy schemes should be deeply integrated into the whole system, including radio access, authentication, data transmission, controller design, etc. Current security and privacy solutions are lagging far behind since they are based on classical secrecy and authentication methods for long packet transmission. Future solutions for real-time control should be simple but with

high performance. This raises significant challenges on using limited resource to achieve both high security and high control performance.

6) Other Challenges: Sensors and actuators as well as the controller may have limited energy source (battery) and/or stochastic energy supplies (renewables). Hence, the challenge of optimal trade-off between the latency and energy consumption becomes relevant for the co-design of communication and control systems. In addition, it is very challenging to achieve reliability (and guaranteed latency) over unreliable channels, unlicensed spectrum, and unpredictable resource availability.

V. A CASE STUDY OF COMMUNICATION-CONTROL CO-DESIGN

In this section, we take *packetized predictive control* (PPC) as an example to demonstrate the importance of the co-design, where more technical details can be found in [14]. Specifically, we first describe the system to show how PPC works and interacts with a communication system. Then, we provide the results to show the basic relationship between wireless resource consumption and prediction length. Finally, we discuss the insights obtained from the case study.

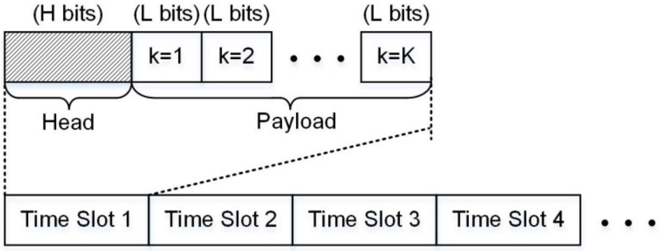

Fig. 3 Communication frame structure for the controller-actuator link in PPC.

A. System Description

In this example, we adopt the system model in Fig. 1-(b), where PPC and short packet wireless communication (Footnote: In real-time wireless control, communication packets usually carry several control commands that can be very short. For example, in industrial automation, each command for an actuator may have only several bits to turn on and off a switch or a valve. In 3GPP Release 14 [15], the packet length of short packet communications is defined as 20-32 bytes, i.e., 160 - 256 bits.) are used for real-time control. For simplicity, we assume that only the controller-actuator communication is wireless and experiences packet loss, and provide Fig. 3 to show the communication frame structure. From the figure, the controller sends a packet to the actuator in each time slot, where each control iteration takes up one time slot and the time duration of each time slot is identical. Furthermore, K is denoted as the prediction length, which means that in each iteration, the controller generates K control commands for the actuator. The first one is for the current iteration and the rest of them are for the future K-1 iterations. As a result, each communication packet for the controller-actuator link carries K control commands. The larger the value of K is, the more bits the wireless network needs to deliver, which leads to heavier wireless traffic. At the actuator side, once it receives the packet, it acts according to the first command and caches K-1 future commands at the buffer. Then, the system becomes robust to handle the packet loss in the future.

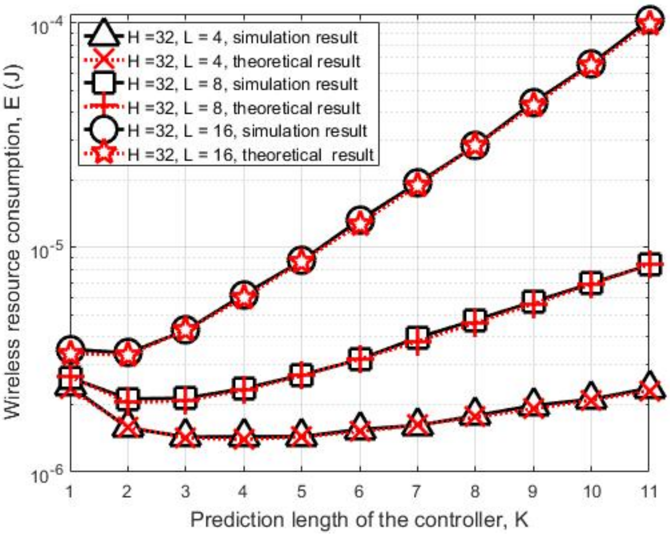

Fig. 4 The relationship between the resource consumption *E* in the wireless communication network and the prediction length *K* in the control system, where *H* and *L* represent the numbers of bits for the header and payload of a communication packet, respectively.

B. Results and Discussions

Fig. 4 shows the relationship between the wireless resource consumption *E* and the prediction length *K*. Here, the wireless resource consumption *E* is the multiplication of three terms, i.e., the time duration of the packet transmission, the bandwidth of the wireless system, and the power density of the wireless signal. From the figure, as the prediction length *K* grows and each communication packet carries more bits, the corresponding wireless resource consumption first decreases and then increases. Here, the decreasing part means that delivering more bits with heavier payload can even consume less wireless resource. This phenomenon is a very unique and different from conventional one where the wireless resource consumption monotonously increases as the growth of the communication traffic.

The above result is reasonable since the real-time wireless control requires short packet communication and consumes a significant amount of wireless resource. This is mainly due to the big gap between short packet capacity and Shannon capacity. Using PPC can effectively reduce the capacity gap. As a result, the whole system becomes efficient so that it can handle more wireless traffic with less wireless resource consumption. However, if we keep on increasing the prediction length *K*, we observe the conventional monotonous trend, i.e., the wireless resource consumption grows as the traffic increases. This is because when *K* is large, the capacity gap becomes small and has minor impacts on wireless resource consumption.

C. Discussion

This example demonstrates that the conventional independent design that minimizes the wireless communication traffic may not be equivalent to minimizing the wireless resource consumption. The co-design that captures the tight interaction between control and communication is expected to achieve the minimum wireless resource consumption and enjoy good overall performance.

VI. CONCLUSIONS

In this article, we have discussed the fundamental design capabilities needed to realize real-time wireless control in future wireless networks, which is the essential function enabling many emerging applications. In particular, we have introduced communication-control co-design, which is expected to significantly reduce the gap between the requirements of real-time control systems and the performance of today's wireless systems. We intend to obtain new integrated systems to achieve the required control performance objectives. We have also identified the opportunities offered by co-design as well as the corresponding technical challenges and open issues. In addition, a case study has been provided to demonstrate the importance of the co-design.

VII. ACKNOWLEDGMENT

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REFERENCES

[1] L. L. Bello, J. Akerberg, M. Gidlund, and E. Uhlemann, “Guest editorial special section on new perspectives on wireless communications in automation: From industrial monitoring and control to cyber-physical systems,” IEEE Trans. Industrial Informatics, vol. 13, no. 3, pp. 1393- 1397, June 2017.

[2] M. Simsek, A. Aijaz, M. Dohler, J. Sachs, and G. Fettweis, “5G-enabled tactile internet,” IEEE J. Selected Area Comm., vol. 34, no. 3, pp. 460-473, Feb. 2016.

[3] M. Luvisotto, Z. Pang, and D. Dzung, “Ultra high performance wireless control for critical applications: challenges and directions,” IEEE Trans. Industrial Informatics, vol. 13, no. 3, pp. 1448-1459, June 2017.

[4] 3GPP TR 36.881 3GPP Technical Specification Group Radio Access Network E-UTRA (Release 14), June 2016.

[5] Q. Wang and J. Jiang, “Comparative examination on architecture and protocol of industrial wireless sensor network standards,” IEEE Comm. Surveys & Tutorials, vol. 18, no. 3, pp. 2197-2219, third quarter, 2016.

[6] P. Park, S. C. Ergen, C. Fischione, C. Lu, and K. H. Johansson, “Wireless network design for control systems: A survey,” IEEE Comm. Surveys & Tutorials, vol. 20, no. 2, pp. 978-1013, second quarter, 2018.

[7] V. Kawadia and P. R. Kumar, “A cautionary perspective on cross-layer design,” IEEE Wireless Comm., vol. 12, no. 1, pp. 3-11, Mar. 2005.

[8] J. P. Hespanha, P. Naghshtabrizi, and Y. Xu, “A survey of recent results in networked control systems,” Proc. IEEE, vol. 95, no. 1, pp. 138-162, Jan. 2007.

[9] M. S. Mahmoud, Control and Estimation Methods over Communication Networks, Springer, 2014.

[10] G. Durisi, T. Koch, and P. Popovski, “Towards massive, ultrareliable, and low-latency wireless communication with short packets,” Proc. IEEE, vol. 104, no. 9, pp. 1711-1726, Sept. 2016.

[11] R. Ford, M. Zhang, M. Mezzavilla, S. Rangan, and M. Zorzi, “Achieving ultra-low latency in 5G millimeter wave cellular networks,” IEEE Comm. Mag., vol. 55, no. 3, pp. 196-203, Mar. 2017.

[12] C. She, C. Yang, and T. Quek, “Radio resource management for ultrareliable and low-latency communications,” IEEE Comm. Mag., vol. 55, no. 6, pp. 72-78, June 2017.

[13] D. Zhang, Q. Han, and X. Jia, “Network-based output tracking control for a class of T-S fuzzy systems that cannot be stabilized by nondelayed output feedback controllers,” IEEE Trans. Cybernetics, vol. 45, no. 8, pp. 1511-1524, Aug. 2015.

[14] X. Tong, G. Zhao, M. A. Imran, Z. Pang, and Z. Chen, “Minimizing wireless resource consumption for packetized predictive control in real-time cyber physical systems,” in Proc. IEEE International Conf. Comm. (ICC 2018), Kansas City, USA, May 2018, pp. 1-6.

[15] 3GPP TR 38.913 version 14.3.0 Release 14, “Study on scenarios and requirements for next generation access technologies,” Oct. 2017.

AUTHORS

GUODONG (PHILIP) ZHAO [SM'16] (guodong.zhao@glasgow.ac.uk) received his Ph.D. Degree from Beihang University, Beijing, China, in 2011 and his B.E. degree from Xidian University, Xi'an, China, in 2005. In 2011-2018, he worked as an associate professor at University of Electronic Science and Technology of China (UESTC). Now, he works as a lecturer (assistant professor) at University of Glasgow, UK. His current research interests are within the areas of wireless communications and control.

MUHAMMAD Ali IMRAN [SM'12] (muhammad.imran@glasgow.ac.uk) received his M.Sc. (Distinction) and Ph.D. degrees from Imperial College London, UK, in 2002 and 2007, respectively. He is a professor in communication systems in University of Glasgow and vice dean of Glasgow College UESTC. He is the head of communications, sensing and imaging research group and lead the 5G research activities in Glasgow. He has been awarded IEEE Comsoc’s Fred Ellersick award 2014, FEPS Learning and Teaching award 2014, Sentinel of Science Award 2016, and twice nominated for Tony Jean’s Inspirational Teaching award.

ZHIBO PANG (pang.zhibo@se.abb.com) received his B.Eng. degree from Zhejiang University, China, in 2002, his M.B.A. degree from the University of Turku, Finland, in 2012, and his Ph.D. degree from the Royal Institute of Technology (KTH), Stockholm, Sweden, in 2013. He is currently a senior scientist and project manager on the Industrial Internet of Things at ABB Corporate Research, Vasteras, Sweden, leading research projects on real-time industrial wireless communications, high-accuracy localization, Internet protocol-based convergence of communications, and vertical solutions for smart homes, buildings, factory, manufacturing, and power systems.

ZHI CHEN [SM'16] (chenzhi@uestc.edu.cn) received his B.Eng, M.Eng., and Ph.D. degrees in electrical engineering from the University of Electronic Science and Technology of China (UESTC), in 1997, 2000, and 2006, respectively. In 2006, he joined the National Key Lab of Science and Technology on Communications, UESTC, and worked as a professor in this lab from 2013. He was a visiting scholar at the University of California, Riverside, in 2010-2011. His current research interests include 5G mobile communications, tactile internet, and Terahertz communication.

LIYING LI (liyingli0815@gmail.com) received her B.E. and Ph.D. Degrees from University of Electronic Science and Technology of China (UESTC) in 2005 and 2011. She visited Georgia Institute of Technology, GA, USA, in 2008-2010 and Lehigh University, PA, USA, in 2016. Since 2011, she has been with the School of Automation Engineering at UESTC, where she is currently an Associate Professor. Her research interests are within the areas of wireless communications and smart grid.