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Buffer-Aided Relay Selection for Packetized Predictive Control

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Abstract—In wireless communications, relay selection is very important to enhance the communications between the resource and destination. However, only transmission coefficients are considered in traditional relay selection. In this paper, we consider the relay selection in wireless *packetized predictive control (PPC)* systems, where our goal is to select the relay nodes by jointly considering communication sub-system and control sub-system. To achieve this goal, we propose a buffer-aided relay selection method, in which both communication performance and control performance are jointly optimized. Simulation results show the performance of our proposed method.

I. INTRODUCTION

In the coming fifth generation (5G) cellular networks, ultra-reliable and low-latency communication (URLLC) is one of the most important scenarios to enable real-time wireless control systems. To maintain the extreme high quality-of-service (QoS) requirement, relay technique is critical to enhance the communication reliability between the source and destination [1][2]. When the destination cannot receive the signal transmitted by the source via the direct link, the relay node between them can amplify the source signal and forward it to the destination. Thus, relay technique can significantly improve the communication quality-of-service (QoS) [3].

As one of the most important research in relay technique, relay selection has been sufficiently researched in the past decades [4]–[7]. For example, in [8], the authors developed a relay selection scheme with specific information rates and delay bounds to minimize the outage probability and achieve higher throughput. In [9], the authors proposed a buffer-aided relay selection scheme, where the optimal relay with the highest signal-to-interference ratio (SIR) among all available source-to-relay and relay-to-destination links was selected. Most of the existing research only focus on the communication aspect, and only communication coefficients are considered in optimal relay selection. When we consider the real-time control system that the relay assisted communication serves, the control performance is very important in the whole system and should be considered to evaluate the system performance [10][11].

In this paper, we consider the buffer-aided relay selection design for packetized predictive control (PPC) in real-time wireless control systems. To maintain the control stability, each PPC packet contains the predictive future commands. When

packet loss happens, the predictive commands can be used. When we jointly consider the PPC with buffer-aided relays, the data cached in each buffer at the relay may be different since some relay nodes may fail in packet receiving at certain transmission time slots. To select the suitable relay nodes to obtain the optimal whole system performance, we propose a co-design selection method, where the data freshness and availability from the control aspect and the resource consumption from the communication aspect are jointly considered. In the proposed method, we deal with the relay selection by communication and control co-design with optimizing the above three factors. With our co-design method, the optimal whole system performance, i.e., control sub-system performance and communication sub-system performance, can be obtained.

The rest of this paper is organized as follows. Section II provides the system model of this paper. Section III formulates a optimization problem to select relay nodes. Section IV provides simulation results to show the advantages of the proposed method. Finally, Section V concludes the paper.

II. SYSTEM MODEL

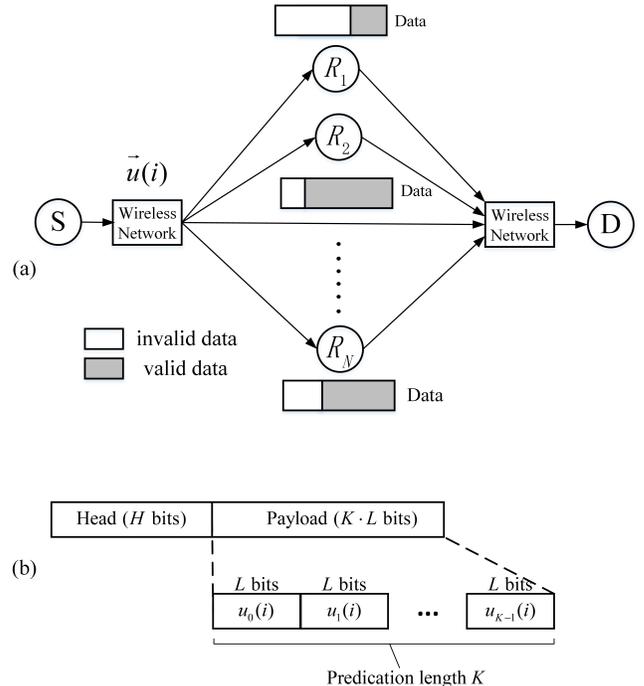


Fig. 1. (a) System model; (b) packet structure.

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Fig. 1-(a) provides the PPC model with buffer-aided relays. The source S is a controller of the PPC system, and can estimate the current and future states for the plant, denoted as the destination D. Then in each time slot, S transmits the packet $\vec{u}(i)$ to D with relays aided. For simplicity, we assume that N relays are placed on the midline of the link from the source S to the destination D, and they are distributed on the vertical axis uniformly. $d(S, R_j)$ represents the distance from S to the relay R_j , and $d(R_j, D)$ represents the distance from the relay R_j to D. Therefore, we can obtain

$$d(S, R_j) = d(R_j, D) \quad (1)$$

Fig. 1-(b) provides the packet structure in the PPC system. Each packet $\vec{u}(i)$ consists of K control commands and can be expressed as $\vec{u}(i) = [u_0(i), u_1(i), \dots, u_{K-1}(i)]$, where u_0 denotes the current command, and u_1, u_2, \dots, u_{K-1} denote the commands of the future time slots. After multiple transmissions, the data cached in each relay will be very different because of different transmission conditions, e.g., the white area and the gray area represent the invalid data and valid data, respectively in Fig. 1-(a). Invalid data represents the data which is outdated, and valid data represents the data which can be used now and later. At the time slot i , the data from the source and relays is fundamentally different, because the data from the source is actual while the data cached in the relays is predictive.

As shown in Fig. 1-(a), we consider a wireless network in the process of packet transmission, where the wireless channel consists of path-loss and Rayleigh fading. The path-loss can be expressed as follows

$$g_{p[dB]} = -128.1 - 37.6 \log_{10}(d), \quad (2)$$

where d represents the distance, and $d \geq 0.035$ km. Then the formulation of channel capacity can be obtained as follows

$$C = \log_2 \left(1 + \frac{P_0 g_p h^2}{N_0} \right), \quad (3)$$

where P_0 is the transmission power, and N_0 is the power of the additive white Gaussian noise (AWGN). In addition, h denotes the Rayleigh fading coefficient which obeys the Rayleigh distribution with the unit variance.

III. OPTIMAL RELAY SELECTION

Most existing researches on relay selection just consider the transmission coefficients [4]–[7]. However, the relay selection cannot maintain the whole system performance considering only the communication factors. In this paper, we consider the buffer-aided relay selection design for packetized predictive control (PPC) in real-time wireless control systems. To select the suitable relay nodes to obtain the optimal whole system performance, we propose a co-design selection method, where the data freshness and availability from the control aspect and the resource consumption from communication aspect are jointly considered.

In the following of this section, we first formulate the above problem as an optimization problem. Then, we develop a

solution to obtain results.

A. Problem Formulation

In principle, the related factors play an important role in the relay selection method. In this paper, we consider data freshness, the number of valid data and signal-noise ratio (SNR) as the related factors. In addition, data freshness and the number of valid data are considered from the control aspect, as each packet consists of the current data and the future data. And signal-noise ratio (SNR) is considered from the communication aspect, which directly determines the channel quality. In the following, we introduce the above three factors in detail.

First, the data freshness indicates the differences between the data which cached in relays and the data from S at the current time slot, and the data freshness can be expressed as follows

$$U_j(i) = \frac{\|X_s(i) - X_j(i-1)\|^2}{\|X_s(i)\|^2}, \quad (4)$$

where $X_s(i)$ represents the data from the source at the time slot i , and $X_j(i-1)$ represents the data from the j th relay at the time slot $i-1$. In addition, $\|n\|$ represents l_2 -Norm. According to (4), the data freshness $U_j(i)$ should be as small as possible.

Second, the number of valid data indicates the number of data which can be used now and later. Thus, the number of valid data can be expressed as follows

$$N_{valid} = N_{current} + N_{future}, \quad (5)$$

where $N_{current}$ denotes the number of the current data, and N_{future} denotes the number of the predictive future data.

Third, the channel quality is determined by SNR, and we denotes SNR as S , which can be expressed as

$$S = \frac{P_0 g_p h^2}{N_0}. \quad (6)$$

From (4), (5) and (6), SNR and the number of valid data are positive factors to measure the transmission performance, and it means that the larger the value is, the better the transmission efficiency is. On the contrary, the data freshness is a retrorse factor, and it means that the smaller the value is, the better the transmission efficiency is.

Therefore, we can obtain Γ which measures the performance of relays, and we formulate the following optimization problem:

$$\begin{aligned} & \max_{\Gamma \in \{\Gamma_1, \Gamma_2, \dots, \Gamma_N\}} : \Gamma, \\ & s.t. \end{aligned} \quad (7)$$

$$\Gamma_j = eS_j - wU_j + (1 - e - w)N_j,$$

where S_j , U_j and N_j represent SNR, the data freshness and the number of valid data of the j th relay, respectively. e , w , and $1 - e - w$ are the weights corresponding to the above three factors.

The key of this optimization problem is to determine the

weights of the above three factors, then provide a relay selection method to achieve the optimal overall performance.

B. Solution

In this subsection, we solve the optimization problem (7) in the following two steps. In the first step, we change the weights of the above three factors, then obtain the all values of Γ , and Γ can be expressed as follows

$$\Gamma = eS - wU + (1 - e - w)N. \quad (8)$$

In the second step, we select the optimal relay according to the bubble sort algorithm that repeatedly steps through the list, compares adjacent values of Γ and swaps them if they are in the wrong order. The pass through the list is repeated until the list is sorted. When the pass is completed, we can obtain the maximum of Γ . And the above bubble sort algorithm can be expressed as follows

Algorithm 1 Bubble Sort Algorithm

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1: Input:  $\Gamma = \{\Gamma_1, \Gamma_2, \dots, \Gamma_N\}$ ,  $i = 1$ ,  $j = 1$ 
2: While  $i \leq N - 1$ 
3:   While  $j \leq N - 1 - i$ 
4:     if  $\Gamma[j] > \Gamma[j + 1]$ 
5:        $\text{temp} = \Gamma[j]$ 
6:        $\Gamma[j] = \Gamma[j + 1]$ 
7:        $\Gamma[j + 1] = \text{temp}$ 
8:     end
9:      $j = j + 1$ 
10:  end
11:   $i = i + 1$ 
12: end
13: Output: The maximum of  $\Gamma$ , where  $\Gamma \in \{\Gamma_1, \Gamma_2, \dots, \Gamma_N\}$ 

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Thus, in the above method, the problem how to allocate the weights is solved, and we can select the optimal relay to forward data, which can improve the overall performance of the system.

IV. SIMULATION RESULTS

In this section, we demonstrate the performance of the proposed method. We assume that the transmission power is 8 dBm, and the power of the additive white Gaussian noise (AWGN) is set as $N_0 = -114$ dBm. The number of relays is 10, the distance between S and D is 200 m, and the distance between every two adjacent relays is 100 m. In PPC, we set the prediction length $K = 10$. In addition, the weights that used in our simulations are shown in Tab. I.

Tab. I. The weights that used in simulations

weight	e	w	$(1-w-e)$
value	0.5	0.1	0.4
	0.5	0.2	0.3
	0.5	0.3	0.2
	0.5	0.4	0.1
	0.6	0.1	0.3
	0.6	0.2	0.2
	0.6	0.3	0.1
	0.7	0.1	0.2
	0.7	0.2	0.1
	0.8	0.1	0.1

To verify our proposed method, we compare the non-relay method, the traditional method and the proposed method in our simulation, then we obtain four figures.

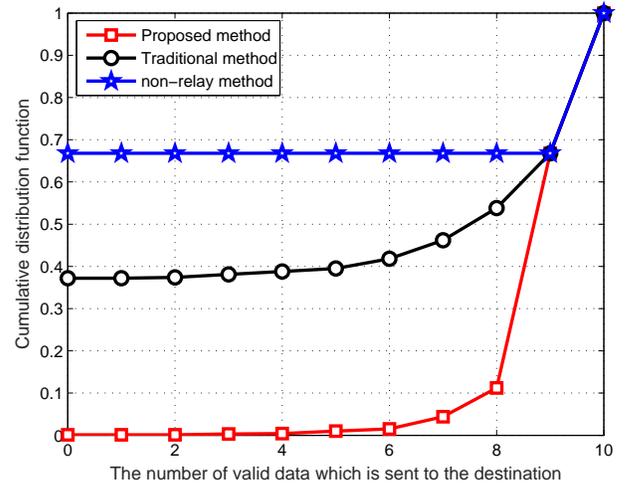


Fig. 2. The cumulative distribution function of the number of valid data which is sent to the destination.

Fig. 2 shows the cumulative distribution function of the number of valid data which is sent to the destination. Here, in the non-relay method, the data is directly sent to the destination from the source, and the probability of successful transmission is about 0.33. In the traditional method, the probability can be increased to 0.62. And in the proposed method, the probability of successful transmission is close to 1, which greatly improves the performance of the system.

Fig. 3 shows the total number of valid data which is sent to the destination. Here, the total number of valid data in the proposed method is nearly twice as that of the non-relay method and the traditional method. This indicates that the proposed method could improve the transmission efficiency of the system.

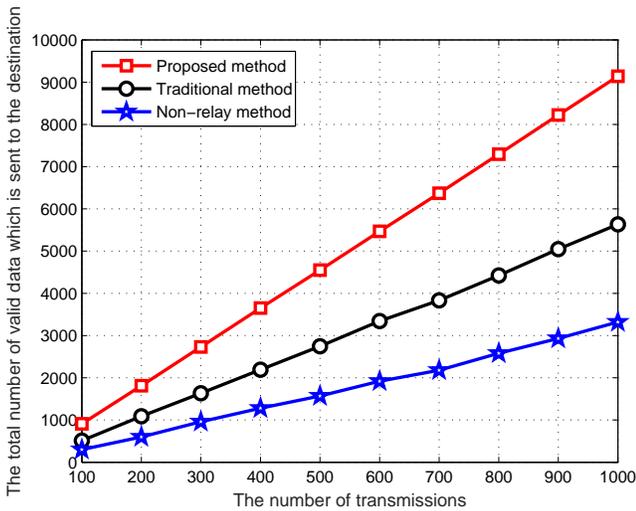


Fig. 3. The total number of valid data which is sent to the destination.

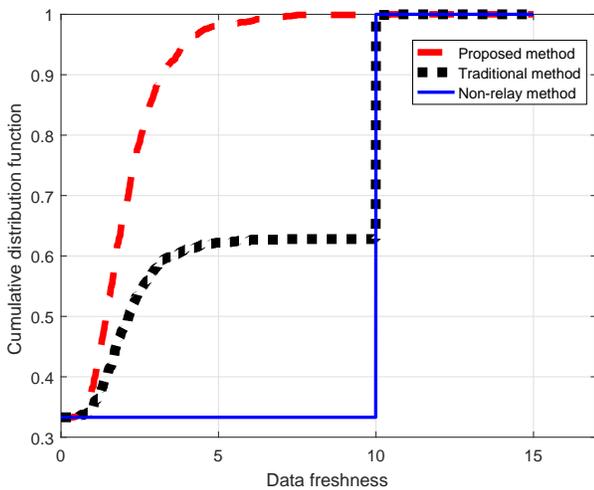


Fig. 4. The cumulative distribution function of data freshness.

Fig. 4 shows the cumulative distribution function of the data freshness. When the data freshness is 0, it means that the data from the source is sent to the destination successfully, and 10 means the transmission failure. In addition, with the increase of the data freshness, it indicates that the data cached in the relays is away from the actual data. In our simulation, we discuss a situation where the value of the data freshness is between 0 and 5. Then, we obtain that the probability are about 0.98, 0.33 and 0.62 under the proposed method, the non-relay method and the traditional method, respectively. Therefore, in the proposed method, the data sent to the destination could be closer to that of the actual situation, and the final results will be more accurate.

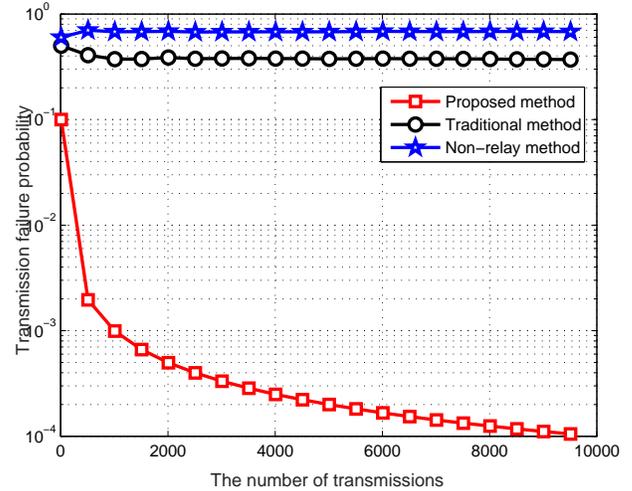


Fig. 5. The relationship between the transmission failure probability and the number of transmissions.

Fig. 5 shows the relationship between the transmission failure probability and the number of transmissions. As shown in Fig. 5, in the proposed method, the failure probability is lower than that of the non-relay method and the traditional method. In addition, with the increase of the number of transmissions, the failure probability of the proposed method decreases, while the failure probabilities of the other two methods won't be changed greatly and keeping at a large value.

In summary, considering the number of valid data, the data freshness, and the failure probability of data transmission, the proposed method can achieve a better performance among the three methods.

V. CONCLUSIONS

In this paper, we proposed a buffer-aided relay selection design for PPC system in real-time wireless control systems, where we jointly considered the communication and control performance in relay selection. In the proposed method, the number of valid data, the data freshness and channel state information were considered to select the optimal relay. The simulation results showed the performance gain of the co-design of relay system and PPC. With our method, the overall system performance can be optimized by the proposed buffer-aided relay selection.

REFERENCES

- [1] G. Chen, Z. Tian, Y. Gongm, and J. Chambers, "Decode-and-Forward Buffer-Aided Relay Selection in Cognitive Relay Networks," in IEEE Transactions on Vehicular Technology, vol. 63, no. 9, pp. 4723-4728, Nov. 2014.
- [2] Y. Gao, J. Ge, and C. Han, "Performance Analysis of Differential Modulation and Relay Selection with Detect-and-Forward Cooperative Relaying," in IEEE Communications Letters, vol. 15, no. 3, pp. 323-325, Mar. 2011.
- [3] G. Chen, Y. Gong, and J. Chambers, "Study of Relay Selection in a Multi-Cell Cognitive Network," in IEEE Wireless Communications Letters, vol. 2, no. 4, pp. 435-438, August 2013.

- [4] N. Nomikos and T. Charalambous, I. Krikidis, D. N. Skoutas, D. Vouyioukaset, and M. Johansson, "A Survey on Buffer-Aided Relay Selection," in *IEEE Communications Surveys and Tutorials*, vol. 18, no. 2, pp. 1073-1097, Secondquarter 2016.
- [5] K. Shamganth and M. J. N. Sibley, "A survey on relay selection in cooperative device-to-device (D2D) communication for 5G cellular networks," 2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS), Chennai, 2017, pp. 42-46.
- [6] D. Q. Qiao and M. C. Gursoy, "Buffer-Aided Relay Systems under Delay Constraints: Potentials and Challenges," in *IEEE Communications Magazine*, vol. 55, no. 9, pp. 168-174, Sept. 2017.
- [7] Z. Tian, Y. Gong, and G. Chen, "Buffer-Aided Relay Selection With Reduced Packet Delay in Cooperative Networks," *IEEE Trans. Vehicular Technology*, vol. 66, no. 3, pp. 2567-2575, Mar. 2017.
- [8] A. A. M. Siddig and M. F. M. Salleh, "Buffer-Aided Relay Selection for Cooperative Relay Networks With Certain Information Rates and Delay Bounds," in *IEEE Transactions on Vehicular Technology*, vol. 66, no. 11, pp. 10499-10514, Nov. 2017.
- [9] G. Chen, Z. Tian, Y. Gongm, and J. Chambers, "Decode-and-Forward Buffer-Aided Relay Selection in Cognitive Relay Networks," in *IEEE Transactions on Vehicular Technology*, vol. 63, no. 9, pp. 4723-4728, Nov. 2014.
- [10] Q. Wang, Y. Zou, and Y. Niu, "Event-triggered model predictive control for wireless networked control systems with packet losses," in *proc. 2015 IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER)*, June, 2015, pp. 1281-1286.
- [11] J. H. C. Huang, M. F. R. Lee, M. J. Tsai, and S. F. H. Chiu, "Generalized Predictive Control in a Wireless Networked Control System," in *proc. 9th World Congress on Intelligent Control and Automation (WCICA)*, Oct. 2011, pp. 870-875.