Chapter 7
Conclusions and Future Directions

Abstract In this chapter, we summarize the book and provide three potential future directions for mixed-criticality industrial wireless networks.

7.1 Conclusions

In this book, we have introduced mixed criticality into industrial wireless networks, and presented analysis methods and scheduling algorithms to improve the QoS of industrial wireless networks.

In Chap. 1, we presented the concept of mixed-criticality industrial wireless networks. Industrial wireless networks have to meet the stringent QoS requirements of industrial applications. However, due to the openness of the wireless environment, the available network resources are limited. Mixed criticality is an advanced theory that makes limited resources fully utilized and can help industrial wireless networks improve their QoS.

In Chap. 2, we presented an end-to-end delay analysis method for fixed priority scheduling in mixed-criticality WirelessHART networks, which can be used to determine whether all flows can be delivered to destinations within their deadlines. In evaluations, we compared our analysis results with simulations and a testbed. The results show that the pessimism of our analysis is acceptable and reliable.

In Chap. 3, we focused on the analysis method under the EDF policy. Firstly, we proposed a novel network model that can switch routing strategies based on the criticality of networks. When errors or accidents occur, the network switches to high-criticality mode and low-level critical tasks are abandoned. Secondly, we analyzed the demand bound of mixed-criticality industrial wireless networks under the EDF policy and formulated network demand bounds in each criticality mode. Thirdly, we tightened the demand bound by analyzing carry-over jobs and classifying the number of conflicts to improve analysis accuracy. Simulation results demonstrate that the presented methods can estimate the schedulability efficiently.

Mixed-criticality data flows coexist in advanced industrial applications. They share the network resource, but their requirements for the real-time performance and reliability are different. In Chap. 4, we proposed a scheduling algorithm to guarantee

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their different requirements, and then analyzed the schedulability for this scheduling algorithm. Simulation results show that our scheduling algorithm and analysis have more performance than existing ones.

In Chap. 5, we first introduced MRI nodes into mixed-criticality networks. Then, we analyzed the transmission paths and obtained the candidate node set. Next, based on the characteristics of MRI nodes, we proposed the algorithm SAA and the algorithm PIA to guarantee the network schedulability in low-criticality mode. By considering system cost, these two algorithms help to reduce the number of MRI nodes used. Finally, we analyzed the schedulability of these two algorithms when the system switches to high criticality mode. The simulation results show that our scheduling algorithms and analysis perform better than the existing scheduling policy.

In Chap. 6, we focused on the mixed-criticality scheduling problem of 5G NR. We presented the mixed-criticality 5G NR model and formulated the problem as an OMT specification. Then, for the schedulability of the mixed-criticality scheduling problem, we analyzed its sufficient condition and necessary condition. Based on the two conditions, we proposed a scheduling algorithm. Finally, an industrial 5G testbed and extensive test cases were used to evaluate our proposed algorithm. The evaluation results indicate that our proposed algorithm can improve the real-time performance and reliability of 5G NR.

7.2 Future Directions

There are many potential future directions for mixed-criticality industrial wireless networks. Here, we list three promising directions, as follows.

- *Criticality identifier for industrial communications*. In mixed-criticality industrial wireless networks, high-criticality communications are assigned more network resources. However, which communications should be high-criticality? Criticality is not an inherent property of industrial communications and must be identified according to some rules. The identification rules determine whether there is a good match between industrial requirements and the goals of algorithms. If criticality levels are not correctly identified, even the optimal scheduling algorithm cannot meet industrial requirements.
- *Efficient scheduling algorithm when the criticality level is switched*. On the one hand, the system state space is extremely complex, and there is no way to enumerate all the switching opportunities. On the other hand, when the criticality level is switched, there is no time to invoke a scheduling algorithm again. Under these restrictions, when the criticality level is switched, only the simple scheduling rule can be applied, such as preempting resources from the nearest low-criticality transmissions (as shown in Chaps. 4, 5 and 6). There is still a gap between these simple rules and optimal solutions. Therefore, efficient and effective scheduling algorithms should be studied.

- *Testbed supporting mixed criticality*. Currently, mixed-criticality studies are evaluated based on simulations or real testbeds. Although the simulation is more flexible, it is too ideal to fully demonstrate the situation in real-world scenarios. A testbed can provide more comprehensive evaluations. However, there are no mixed-criticality hardware platforms and software protocol stacks. An easy-to-use testbed will facilitate research and development.