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Mixed scheduling with heterogeneous delay constraints in cyber-physical systems

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HIGHLIGHTS

- To support real-time communication with heterogeneous delay constraints is a challenging issue in CPS.
- The paper develops a distributed MAC strategy for the multiple-access scenarios.
- The resource allocation problem is modeled as a non-cooperative game.
- By game theoretical analysis, the proposed one-shot strategy can achieve the Nash equilibrium.
- The game model guarantees real-time performance, and shows scalability under different scenarios.

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ABSTRACT

The physical space and the cyber space are deeply coupled in Cyber-Physical Systems (CPS). The traffic flows are constrained by heterogeneous delay constraints. In order to provide real-time and predictable communication, the paper combines the distributed scheduling algorithm with game theory. A non-cooperative game is proposed to form the scheduling set in the contention-based multiple-access scenario. In the game, each player only has its delay knowledge and makes decision without the information of other competing players. The payoff function is designed to encourage players to give the transmission chance to the player with urgent packets. Simulation results demonstrate that the game-theoretic scheduling approach can improve the real-time performance compared with the existing scheduling algorithms under different scenarios.

1. Introduction

Cyber-Physical Systems (CPSs) are a kind of emerging large-scale and networked systems [1,2]. The technologies of computing, communication, control are merged in a collaborative and autonomous manner. The interactions of CPSs involve the discrete dynamics of cyber space and the continuous dynamics of physical space. The heterogeneous systems are considered as the next generation of engineered systems [3]. CPSs spread all over the time-critical and safety-critical fields, such as smart grid, unmanned aerial vehicle, high-confidence medical systems, etc. [4,5].

Communication system plays an essential role in CPSs [6]. It is provided to support distributed real-time computing and cooperative control. Communication part improves the scalability of CPSs and distinguishes CPSs from the regular control systems [7]. In order to interact in a higher frequency between the two spaces, a large number of different functional nodes are spatially scattered. As shown in Fig. 1, consider the heterogeneous systems consisting of three kinds of functional nodes A, B, C. Set A represents different kinds of sensors. They are distributed to collect the interesting data [8,9]. Then the aware data is delivered to the computing entities, which are represented as set B. Actuators, represented as set C, are assigned to execute control tasks generated by the computing systems. In the large-scale interconnecting systems, scheduling problem is very hard due to the following reasons. First, the stochastic nature of channels imposes uncertainties on the interaction. Non-deterministic delays induced by channels deteriorate the real-time performance, which could lead to potential instability in the control-loop. To connect various nodes in the two distinct spaces in a realtime and reliable manner is a main goal. Second, CPSs are large-scale systems. The network topologies dynamically change. Centralized controllers do not always exist. It is hard to gather global information for centralized

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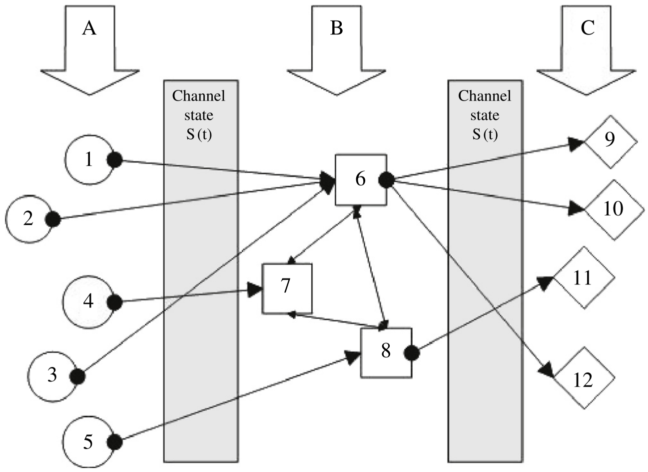

Fig. 1. A heterogeneous system with different functional nodes. The data links with arrows represent the directions of data flows.

management. Special attentions should be paid to the scenarios without infrastructures. The decentralized control policies are preferred. Third, the systems consist of multiple nodes with diverse Quality of Service (QoS) requirements, such as heterogeneous timing constraints. The correct running of CPSs not only depends on the computing results generated by the computing nodes, but also on the satisfaction with many timing requirements. Traditional best-effort service algorithms are inadequate. As a kind of event-triggered systems, the traffic must be successfully delivered before reaching its maximum-allowable delay. To allocate the communication resources among heterogeneous nodes with QoS differentiation is very challenging [10,11]. These constraints impose complexity when the resource-optimal communication protocols are designed.

Unfortunately, current scheduling algorithms cannot satisfy the communication requirements in CPS. Most of the algorithms focus on the throughput [12–15]. The real-time performance is poor. Although some works try to deal with delay issues, there are some additional assumptions. These assumptions can be categorized in three classes. The first class of assumptions involves network topology [16]. These algorithms are proposed for specified scenarios. Whether they are still effective in other scenarios is uncertain. The second class of assumptions involves packet arrival and packet timing characteristics [17–19]. These works group time slot into frames. Packets arriving in that frame expire before the end of the frame. The third assumption category involves packet delay [20]. Delay bounds are the same for all the traffic. The assumption could be seen as a variant of the second assumption. However, as a kind of event-triggered systems, some packets are generated due to physical phenomena. It is hard to predict the arriving time and the deadline of a packet. Meanwhile, node joins or quits as the system evolves. The network topology changes dynamically. An allocation algorithm for a particular topology is not suitable for CPS. These assumptions limit the applied range of existing algorithms, which motivates the need for a practical scheduling protocol that ensures per-packet meet its own deadline and can be implemented with low complexity.

The main motivation of the paper is to provide a decentralized mechanism for resource allocation in contention-based multiple-access scenario while providing real-time guarantees among heterogeneous nodes. As the traffic is characterized by real-time, each packet to be transmitted has a maximum-allowable delay. The packet is discarded if it is not successfully received before reaching its allowable delay. Each individual node hopes to improve its own payoff by accessing the spectrum frequently in the distributed environment. However, the behaviors of selfish nodes increase the probabilities of transmission collisions, which deteriorate the overall throughput. CPSs focus on that individual autonomy and whole cooperation. Individual node takes autonomous actions based on its own preference and goal. Non-cooperative game theory is a natural choice to deal with conflicting interest in the competitive situation. It provides a framework to characterize the interactions among self-interested nodes. It helps each node to execute a more rational decision-making process. It guides the node to "cooperate" spontaneously without communication among nodes in a decentralized manner [21]. In order to random access the channel in the decentralized manner and achieve a low complexity, the paper considers the issues of resource allocation from the MAC layer based on game theory. Game theory firstly originated from the economics [22]. In the past decades it has been successfully applied in the fields of distributed resource allocation [23]. It has been demonstrated that game theory is a powerful tool to model and analyze the problems in the distributed resource-limited systems [24–26]. Many previously-published studies proposed the improved strategies for multiple access and resource allocation on the basis of game model [27,28]. In the scenario with QoS requirements, game-theoretic approaches are also very effective [24].

The paper combines distributed scheduling algorithms with the game theory to guarantee the real-time performance. A non-cooperative game is proposed to form the scheduling set in the contention-based multiple-access scenario. In the game, the node has only its allowable delay knowledge. Each node makes decision according to his own metrics. As the competitors are selfish, the objective of each node is to maximize its payoff. To encourage the competitors to cooperate and give the transmission chance to the urgent nodes, in our model the cost for transmission is designed to be a function of timing parameters. The transmission parameters, such as contention window, are determined by cost. In order to optimize his own payoff, each node is willing to cooperate with limited information. The game guides each self-interested node to play the best response according to the maximum-allowable delay constraint. A global equilibrium is achieved. Based on the game model, the goal of delay-guarantee is satisfied. Meanwhile, system-wide social optimum is achieved. We show that the game-theoretic approach improves the real-time performance compared with the existing scheduling algorithms under different scenarios.

We focus on one-shot Nash equilibrium strategy. As the saturation condition is not always satisfied in the scenario constrained by real-time requirements, we deal with the scheduling issue that the packet-arriving rates are in the capacity region of the network. Under the saturation scenario, the proposed algorithms have to prove the best response dynamics eventually converge to Nash equilibrium [29,30]. As the idea presented by [31], the symmetric feature of the game drives all the players play the best response in the game. No player can profit by unilaterally deviating his strategy. Therefore, all the players are willing to play the best response under the strategy. The one-shot strategy can achieve the Nash equilibrium of the game [31].

The key contributions of our work are as follows:

- We present a non-cooperative game-theoretic MAC strategy to schedule nodes for CPSs, which perceives and allocates the available communication resource based on the real-time constraints. The strategy guides each player to make a rational decision individually. The game is easy to implement in a distributed manner.
- Without message passing among players, each player can maximize his payoff based on Nash equilibrium solution. We show the one-shot game achieves good real-time guarantees in the contention-based multiple-access scenario.
- By applying the game model to different scenarios, the proposed model shows good scalability and flexibility.