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Flexible IEEE 802.15.4 deadline-aware scheduling for DPCSs using priority-based CSMA-CA

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ABSTRACT

The IEEE 802.15.4 protocol offers great potential in several application fields, such as industrial Wireless Sensor Networks (WSNs). An industrial automation cell (field level) is characterized mostly by periodic traffic flows. Using the IEEE 802.15.4 protocol, it is necessary to manage Guaranteed Time Slots (GTSs) allocation and at the same time ensure adequate performance both to other periodic traffic flows and network management/control flows. For these reasons, this paper shows a flexible approach in order to improve GTSs assignment and medium access performance. Analytical results are shown in order to demonstrate benefits introduced by deadline-aware algorithm (for guaranteed access to reserved slots) and CSMA-CA-priority based (for latencies reduction during medium access attempts). Otherwise, obtained results show that the proposed technique improves the number of deadlines met and the probability to find the channel free for transmissions.

1. Introduction

In recent years, WSNs have become more and more used in industrial process control systems [1–3] characterized by Quality of Service (QoS) and real-time constraints [4,5]. Transmission errors and packet loss on the wireless channel are inevitable due to noise, multipath delay, interference, etc. These phenomena characterize industrial environments and significantly affect the transmission of information over the wireless channel. As a result, wireless communication technologies in factory automation environments are mainly used in monitoring [6] and surveillance [7] applications where some data loss can be tolerated. The IEEE 802.11 [8] and Bluetooth [9,10] technologies, which are widely used to support communication between personal computers and/or peripheral devices, are not suitable for monitoring purposes, which require low-power and low-cost wireless connectivity and relaxed throughput. In the IEEE 802.11 family, nodes compete for the medium access according to the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. Anyhow, contention-based approaches are not able to guarantee an upper bound on the medium access delay, so they are not adequate for time-constrained traffic. On the other hand, Bluetooth uses a Master/Slave protocol through which it is possible to connect up to 7 active slaves for each wireless cell and adopts a combination of frequency hopping and time division multiplexing. For these reasons, along with lower power consumption, the IEEE 802.15.4 [11] technology is more appropriate for Distributed Process Control Systems (DPCSs) applications especially if used in harsh environments, where it is really important to reduce maintenance as much as possible.

1.1. The IEEE 802.15.4 protocol

The IEEE 802.15.4 standard provides the Physical (PHY) layer and Medium Access Control (MAC) sub-layer specifications for low data rate (up to 250 kbps in ISM frequencies – 2.4 GHz) wireless connectivity. It fits well the typical requirements which can be found in several deadline-aware application scenarios like, industrial process control, home automation and road monitoring to mention some. Typically, these applications do not require high data transfer rates, but are time-critical. In other words, in soft real time contexts, [12], applications must be characterized by timeliness [13] in reaction of unpredictable events [14]. A system is "soft real time" if its tasks miss their deadlines producing a performance degradation without compromise the operation of the system. The IEEE 802.15.4 standard specification, however, provides a limited support for real-time communications. In the beacon-enabled operating mode (the more suitable for real-time traffic management) the PAN-Coordinator (PC) can allocate/deallocate up to seven Guaranteed Time Slots (GTS) in each

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superframe (which consists in sixteen time slots). As a result, the Contention-Free Period (CFP) length, which can be used for real-time transmissions, is limited up to seven nodes, one for each GTS. At the same time, it is important to underline that the IEEE 802.15.4 standard protocol provides a GTS allocation based on First In First Out (FIFO) technique. This is not tolerable in industrial environments characterized by real-time constraints. The remaining part of the superframe is characterized by the Contention Access Period (CAP), which implements the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol. Fig. 1 shows the IEEE 802.15.4 superframe structure. In CAP, collisions and the backoff mechanism make the network access time highly variable and unpredictable.

1.2. Motivations and main aim

The state of art analysis, concerning the communication among sensors and their use in applications requiring a certain Quality of Service (QoS), has allowed to define an approach in order to reduce transmission latencies. This approach is characterized by specific strategies which allow sensors to transmit with different probabilities based on traffic flow priorities. In DPCSs most of the traffic is periodic. So, this work proposes a GTS allocation in CFP using the Earliest Deadline First (EDF) algorithm. At the same time, this paper proposes an algorithm that improves the CSMA/CA standard. Several simulation campaigns have been conducted in which, by varying CW (Contention Window) and BE (Exponential Backoff) parameters, it has been possible to produce a traffic flows classification in terms of priority classes. In order to show the feasibility of the proposed approach using COTS (Commercial off-the-shelf) hardware, we implemented it on TinyOS operating system [15] and tested it using IRIS and MTS300 boards from Crossbow/Memsic. Obtained results show how nodes with higher priority achieve better performance than those with lower priority. Furthermore, measured performance are better than the IEEE 802.15.4 standard which does not differentiate traffic flows of various nodes. The article is organized as follow: Section 2 reports main literature works about approaches to improve QoS transmissions over IEEE 802.15.4. Section 3 describes the proposed approach. Section 4 proposes a probabilistic analysis of the IEEE 802.15.4 transmission through the Priority-Based CSMA-CA. Section 5 proposes a test-bed scenario showing obtained results while Section 6 summarizes the paper reporting conclusions.

2. Related works

Wireless Sensor Networks have recently found application in several areas, including industrial automation. In particular, WSNs provide flexible, reliable, cost-effective solutions to monitor the real-time status of automated manufacturing facilities. However, the distributed WSN systems should be designed in order to overcome various constraints such as limited energy, bandwidth limit, and unexpected failure of communication under disturbances. Moreover, the network topology must be managed with designated communication protocols.

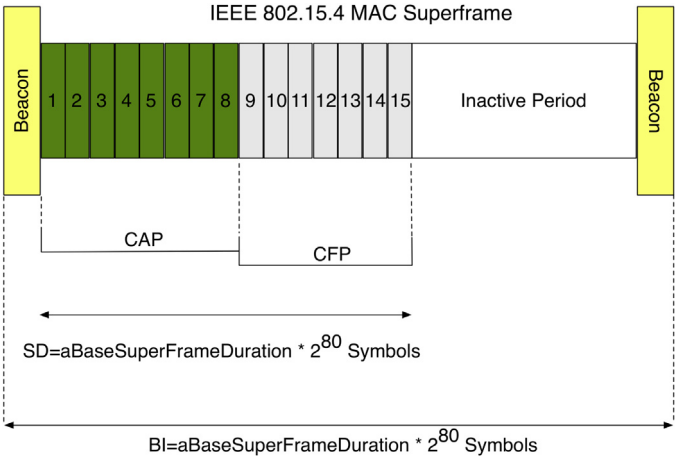

Fig. 1. IEEE 802.15.4 MAC superframe structure.

For this reason, the authors of [19] describe the main factors that affect the performance of sensor network systems in the design of wireless micro-sensor network protocols. In fact, they propose a micro-sensor network protocol evaluation tool through which the performance of various network communication models and architectures can be effectively evaluated by using the node response time, which provides timely and reliable communication. Considering sensor networks with time constraints in automated manufacturing facilities, evaluation results show that the proposed tool helps in selecting optimal network protocols in order to minimize inter-communication time and energy consumption. The same authors propose in [20] an approach to reliable real-time facility monitoring by WSNs. The application of the proposed approach to a facility sensor network improves the wireless data transmission in terms of strength against noise and electromagnetic interference. The authors highlight that a proper deployment strategy combined with their proposed protocol can facilitate the use of WSNs in industrial automation application. The conclusions obtained in [19,20] clearly describe how it is possible to overcome flow and environmental dynamics of wireless protocols inside factories.

As mentioned above, this work proposes a GTS allocation in CFP using the Earliest Deadline First (EDF) algorithm and also an improvement of the CSMA/CA standard. The following subsections report main literature works about approaches to improve QoS transmissions over IEEE 802.15.4. Specifically, literature works dealing with the IEEE 802.15.4 protocol for real-time data transmission will be analysed. Subsequently, a description of slotted CSMA/CA models will be carried out and, finally, scheduling approaches for industrial communication will be analysed.

2.1. The IEEE 802.15.4 protocol for real-time data transmission

WSNs are characterized by several devices used for data detection also in time-critical contexts which need real-time and secure communication systems. Based on network needs, several solutions have been discussed in the literature. The authors of [21] discuss how a sensor network need real-time communications. The failure reception of a packet with real-time constraints may compromise the entire system. It is therefore important to study network traffic flows, although it is not always easy to predict when and which node will send data traffic. A consideration to do regards the delay introduced by transmission of the single packet: decreasing its size, transmission times will consequently decrease, and therefore also the possibility of a collision during transmission. The proposed idea [21] is the Transmission Pipelining: if a node could start its actual transmission at the end of another one, it could be possible to have the maximum channel utilization, although a solution of this type entails a big problem in terms of nodes synchronization and the requirement that the receiver is able to read the packets received one behind the other.

As known, the IEEE 802.15.4 standard protocol does not natively support real-time data transmission management which characterize the industrial process control systems. The study carried out by the authors of [18] is based on the consideration that the GTS have a specific waiting time, and that it is possible to know a priori the packet delay, analyzing the network in worst condition. The waiting time will be given by the beacon interval added to the data transmission time. Removing the idle time in the superframe