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Time-triggered wireless sensor network for feedback control

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Abstract: A communication network for use in feedback control must satisfy strict requirements on the reliable and deterministic behavior. However, wireless sensor networks such as ZigBee may introduce randomly varying delays into the system, resulting in the performance degradation or even the instability. In this paper we propose a deterministic wireless network that can be used for feedback control. The proposed approach is based on a time-triggered mechanism implemented on top of the IEEE802.15.4 standard. The effectiveness of the proposed method is demonstrated through a set of experiments on feedback control of a DC motor.

Keywords: wireless sensor networks, feedback control, IEEE802.15.4, ZigBee, time triggered protocol

Classification: Science and engineering for electronics

References

[1] D. Lee, J. Allan, H. A. Thompson, and S. Bennett, "PID control for a distributed system with a smart actuator," *Control Engineering Practice*, vol. 9, pp. 1235–1244, 2001.

[2] Y. Tipsuwan and M. Y. Chow, "Control methodologies in networked control systems," *Control Engineering Practice*, vol. 11, pp. 1099–1111, 2003.

[3] T. C. Yang, "Networked control system a brief survey," *IEE Proc. Control Theory & Applications*, vol. 153, no. 4, pp. 403–412, 2006.

[4] X. Liu and A. Goldsmith, "Wireless network design for distributed control," *Proc. IEEE Conference on Decision and Control*, pp. 2823–2829, 2004.

[5] H. Thompson, "Wireless and internet communications technologies for monitoring and control," *Control Engineering Practice*, vol. 12, no. 6, pp. 781–791, 2004.

[6] IEEE, "IEEE Std. 802.15.4-2003 wireless medium access control (MAC) and physical layer (PHY) specification for low rate wireless personal area networks (LR-WPANs)," New York, IEEE Press, 2003.

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[7] ZigBee Alliance, "ZigBee specification," Dec. 2006 [Online] http://www.zigbee.org
[8] P. Baronti, P. Pillai, V. Chook, S. Chessa, A. Gotta, and Y. Hu, "Wireless sensor networks: a survey on the state of the art and the 802.15.4 and ZigBee standards," *Computer Communications*, vol. 30, no. 7, pp. 1655–1695, May 2007.
[9] TTTech Computertechnik GmbH, "Time-triggered protocol TTP/C high-level specification document (ver.1.1)," Nov. 2003 [Online] http://www.tttech.com

1 Introduction

Modern control systems employ digital communication networks to satisfy various demands on performance, maintainability, and reliability [1, 2, 3]. However, the use of a wired network causes significant limitations in terms of mobility, flexibility, and extensibility of the system. In order to avoid the complex wiring harness, several researchers [4, 5] have paid attention to wireless sensor networks such as the ZigBee stack based on IEEE802.15.4 [6, 7, 8].

However, the ZigBee protocol has several drawbacks to be used in a feedback control system. One of the critical disadvantages is the non-deterministic temporal behavior caused by the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol. The CSMA/CA protocol also presents a possibility of undetected message collisions, so called the *hidden terminal* problem; that is, nodes placed beyond the range may transmit messages simultaneously to the same node at which a collision occurs. Another drawback with CSMA/CA is the difficulty in detecting the loss of messages because the expected message arrival time is unknown to the receiving nodes. All of these problems result in the performance degradation, and even the instability of the system [2].

As an alternative to overcome these problems, this paper presents a time -triggered mechanism [9] which is implemented on top of the IEEE802.15.4 standard. The proposed method is based on the time division multiple access (TDMA) protocol, in which exclusive timeslots are allocated to each node in the system. Therefore, not only the message latency is constant over the bus load, but also the hidden terminal problem is avoided. It is also possible to detect immediately the loss of messages when the expected message has not been delivered in the designated timeslot. The effectiveness of the proposed network is verified through a set of experiments including feedback control of a DC motor.

2 IEEE 802.15.4 standard and ZigBee stack

The IEEE 802.15.4 standard [6] defines the physical (PHY) layer and the media access control (MAC) layer for wireless sensor networks with low transmission rate, low power consumption, low cost, and simple installation.

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The PHY layer supports three frequency bands: 2450 MHz, 915 MHz, and 868 MHz, among which the 2450 MHz band is used in this paper. Also the PHY layer supports various functions, such as channel selection, link quality estimation, and energy detection measurement. The MAC layer offers an arbitration mechanism based on a CSMA/CA scheme, in which every node waits for the random period of time before transmitting its message. The CSMA/CA protocol is an efficient solution to resolving message conflicts under a low level of bus load. However, in the CSMA/CA scheme, low priority messages can prevent high priority messages from accessing to the bus medium. Also it can introduce significant amount of jitter in the message latency as bus traffic is increased. Indeed these problems are the main reasons for why the IEEE802.15.4 based Zigbee stack is not suitable for feedback control systems.

3 Implementing time-triggered mechanism on IEEE802.15.4

This section describes a wireless sensor network based on a time-triggered technique and the IEEE802.15.4 standard. The primary motivation for adopting a time-triggered technique is to achieve reliable and deterministic communications which are crucial for feedback control systems. The main idea is to allocate timeslots in which the designated nodes will have the exclusive right to use the bus medium. Therefore, latency of each message can be constant even at the maximum level of bus load.

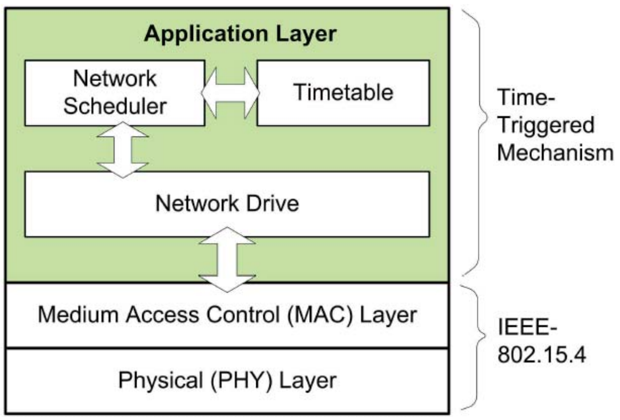

Fig. 1. Function architecture and protocol stack of the proposed network protocol.

The time-triggered mechanism is implemented on top of the MAC layer of IEEE802.15.4 as illustrated in Fig. 1. The proposed scheme consists of several software components as follow:

- *Timetable* stores the message schedule for each node in the system;
- *Network Scheduler* manages the process for message transmissions when the local time reaches to the designated timeslot defined in a timetable; and,

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– *Network Drive* is a set of application programming interfaces (APIs) to provide an interface between the network scheduler and the MAC layer.

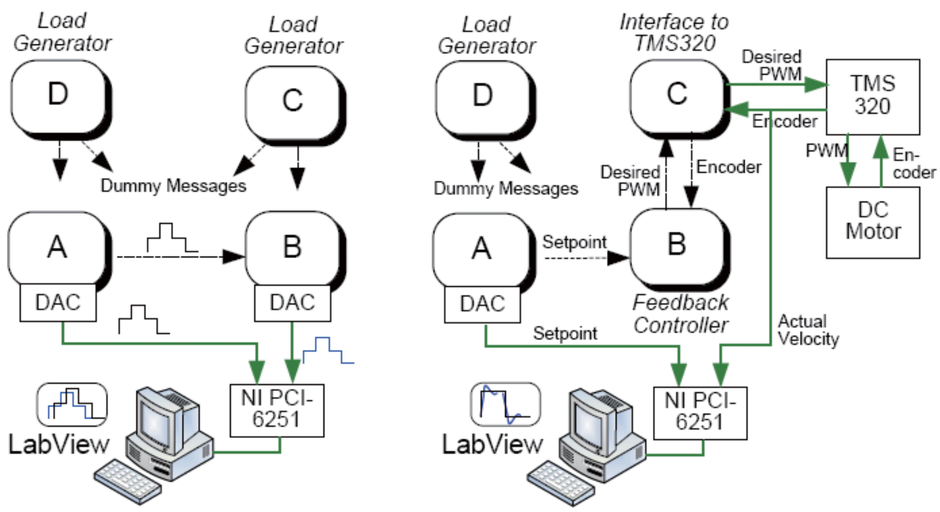
A TDMA round contains up to four message frames, and each frame is divided into up to 16 timeslots. The timeslots are implemented on the contention access period (CAP) of the IEEE802.15.4 protocol. As no contention occurs with a time-triggered protocol, the time for backoff is set to constant. The number of timeslots per frame, the size of each timeslot, and the number of frames per TDMA round can be selected as the design parameters.

The proposed protocol requires a central controller by which beacon signals are broadcast periodically. The information on the message schedule is only stored in the central controller at the design phase. The rest of nodes in the system are configured online using the schedule information included in a beacon message which is sent by the central controller. This approach is beneficial as it allows a dynamic change of the message schedule without recompiling the entire nodes.

Reliable and accurate clock synchronization is the key requirement for the success of a time-triggered protocol. In this paper, a simple synchronization strategy based on master-slave structure is used. At the start of each message frame the central controller broadcasts a beacon message to which the rest of the nodes synchronize their local clocks. That is, on the reception of a beacon message, each slave node resets its own local clock to a predefined value which is chosen to compensate for transmission delays of a beacon message.

4 Experimental results

Fig. 2 illustrates the experimental setups used to examine the proposed network. It consists of a central controller (node-A), three slave nodes (B, C, and D), and a TMS320 module which is directly wired to a DC motor. The



(a) (b)

Fig. 2. Experimental setup; (a) for message latency, and (b) for feedback control.

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TMS320 module is used only for driving the DC motor with pulse width modulation (PWM) and reading the encoder outputs. Each node is equipped with a digital-to-analog converter (DAC) to which a LabView® based data logger is connected.

The effectiveness of the proposed method is investigated in terms of message latency and the control performance with a DC motor. All experiments are carried out under the condition of approximately 80% of bus load which is generated by node-C and node-D.

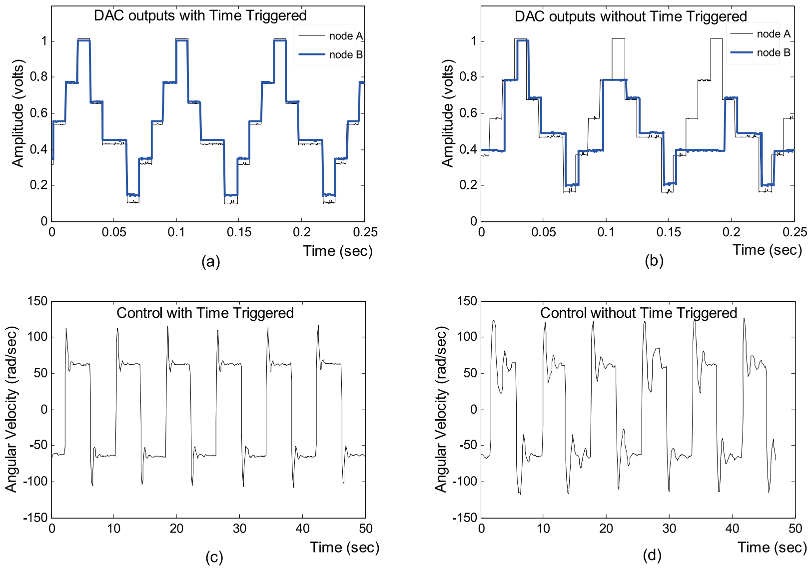

Fig. 3. Experimental results. (a) DAC outputs with time-triggered scheme, (b) DAC outputs without time-triggered scheme, (c) angular velocity of DC motor with time-triggered scheme, and (d) angular velocity of DC motor without time-triggered scheme.

Results for message latency

The ability of delivering messages in a reliable and deterministic manner is examined by measuring the phase difference between the outputs of DACs on node-A and node-B. Firstly, node-A transmits predefined signals to node-B. Then both nodes update their DAC outputs to show the latest state of the signal. By using the proposed network, as shown in Fig. 3 (a), DAC outputs of both nodes are closely matched. This fact implies that all the messages have been delivered on time without a large delay or losing any packets. In contrast, the result in Fig. 3 (b) presents a big discrepancy between the outputs of both nodes. This result indicates that node-B has failed frequently to receive the messages from node-A due to a large number of message collisions with a standard IEEE802.15.4 network.

Results for feedback control of DC motor

In these experiments, the desired motor speed being generated by node-

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A is transmitted to the motor controller (node-B) through a wireless network. Node-C offers a wireless interface between the motor controller and the TMS320 module of which a PWM port drives the DC motor. The encoder outputs are fed back to node-B via node-C, forming a closed feedback control loop. The control algorithm used in this work is a simple proportional controller.

Fig. 3 (c) and 3 (d) show the trajectories of the motor velocity. As depicted in Fig. 3 (c), using the proposed network could achieve relatively stable and time-invariant control performance. In contrast, Fig. 3 (d) shows that feedback control using a standard IEEE802.15.4 network presents a large overshoot and time-varying characteristics due to excessive jitter in the message latency.

5 Conclusion

A communication network for feedback control must have highly reliable and deterministic characteristics. In this paper we have proposed an IEEE802.15.4 based wireless sensor network that can be used in a feedback control system. The ability of delivering messages in a deterministic and reliable manner is achieved by employing a time-triggered scheme. The proposed protocol is implemented with a set of software components on top of the MAC layer of IEEE802.15.4. Using the proposed approach it is possible to avoid the problems with undetected message collisions and the message latency which is randomly varying with time. The effectiveness of the proposed method is examined through a series of experiments using DC motors. The experimental results show that not only does the proposed method provide deterministic and reliable message transmissions, but also it achieves the desired control performance using a simple control strategy.

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