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Time Delay Characteristic of Industrial Wireless Networks Based on IEEE 802.15.4a

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Abstract: The IEEE 802.15.4a standard provides a framework for low-data-rate communication systems, typically sensor networks. In this paper, we established a realistic environment for the time delay characteristic of industrial network based on IEEE 802.15.4a. Several sets of practical experiments are conducted to study its various features, including the effects of 1) numeral wireless nodes, 2) numeral data packets, 3) data transmissions with different upper-layer protocols, 4) physical distance between nodes, and 5) adding and reducing the number of the wireless nodes. The results show that IEEE 802.15.4a is suitable for some industrial applications that have more relaxed throughput requirements and time-delay. Some issues that could degrade the network performance are also discussed.

Keywords: Time delay characteristic, IEEE 802.15.4a, industrial wireless network, performance test, sensor networks.

1 Introduction

Wireless communication has been pervading many application areas for a number of years and is affecting an ever-increasing number of aspects of daily life. New products and services concerning mobile communication (i.e., mobile audio, video, and data exchange services and the relevant devices) appear in the market almost every day, and people are getting used to relying on wireless technology in their business and entertainment activities[1]. In general, wireless networks have been widely deployed in data exchange services, such as the Internet, e-mail, and data file transfer. Their capabilities needed to deliver such services are characterized by an increasing need for data throughput. However, some filed applications, such as industrial[2], vehicular, and residential sensors[3−7], have more relaxed throughput requirements, but require lower power consumption. Moreover, these applications require lower power consumption and low complexity wireless links at a low cost (relative to the device cost). Therefore, IEEE 802.15.4a[8] is the one that satisfies these types of requirements.

The 802.15.4a physical layer is based on two different technologies: ultra wide band (UWB) and chirp signals. It defines various data rates from 110 kbps up to 27.24 Mpbs, with the mandatory data rate mode realizing 0.851 Mbps. A standard device will be capable of transmitting in at least one of three 500 MHz-wide bands centered at 499.2 MHz, 4.493 GHz, and 7.987 GHz. The error-rate performance of IEEE 802.15.4a compliant UWB radios was investigated in [9]. The impact of position information on routing was investigated by comparing a traditional solution based on the ad hoc on-demand distance vector (AODV) routing protocol with a position-based solution relying on the combination of the security protocol analyzer (SPA) distributed positioning protocol and the general packet radio service (GPRS) routing protocol[10]. Robust and energy-detection receivers for impulse radio (IR)-UWB transmission have been presented and analyzed in [11–14]. Taking the impact of the characteristics of the new physical layer on medium access into account, De Nardis and Benedetto[15] provided an overview and comparison of 802.15.4 with 802.15.4a on the media access control (MAC) layer. However, there are very few research of chirp spread spectrums based on IEEE 802.15.4a, especially for industrial applications.

Different from the mentioned literature using UWB technology, a wireless network for industrial applications based on IEEE 802.15.4a is presented in this paper, which uses the chirp spread spectrum technology. We attempt to make a preliminary performance study via several sets of practical experiments, including the effects of 1) numeral wireless nodes, 2) numeral data packets, 3) data transmissions with different high-layer protocols, 4) physical distance between devices and their coordinator, and 5) adding and reducing the number of wireless nodes. Experimental results would be beneficial to the design and deployment of the IEEE 802.15.4a wireless networks.

The rest of the paper is organised as follows. Section 2 introduces the IEEE 802.15.4a communication protocols. Next, experimental hardware and configuration are illustrated in Section 3. Then, experimental results of the performance study are described in Section 4. Finally, Section 5 gives a brief conclusion and future work.

2 IEEE 802.15.4a wireless protocol

This section provides a brief introduction of the standard, focusing on the aspects that are closely related to the present work. A more detailed description of the standard

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can be found in [10, 15, 16].

2.1 Network organization

The IEEE 802.15.4a standard defines two classes of devices: full-function devices (FFD), in which all network functionalities are implemented, and reduced-function devices (RFD), which only support a reduced set of functionalities, e.g., sensor nodes that measure a physical parameter and can execute simple commands. RFD and FFD devices organize themselves in personal area networks (PANs). A PAN is controlled by a PAN coordinator setting up and maintaining the PAN. The role of PAN coordinator can only be taken by an FFD device, while RFD devices can only join an existing PAN by communicating with its coordinator. A PAN can adopt either of the two following network organizations:

1) Star topology-devices can only exchange information with the PAN coordinator (see Fig. 1).

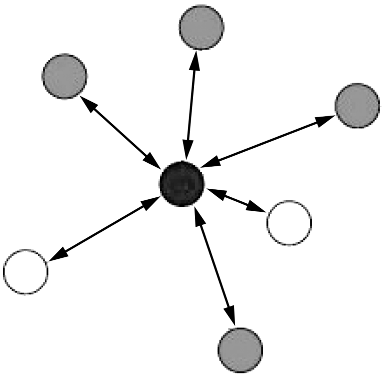

Fig. 1 Example of star topology (dark grey circle: PAN coordinator; light grey circle: FFD device; white circle: RFD device)

2) Peer-to-peer topology-FFD devices can communicate directly as long as they are within physical reach; while RFD devices, due to their limitations, can only connect with the PAN coordinator (see Fig. 2).

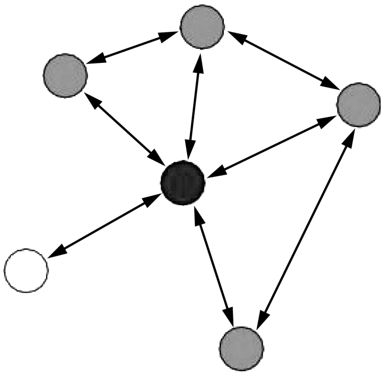

Fig. 2 Example of peer-to-peer topology (dark grey circle: PAN coordinator; light grey circle: FFD device; white circle: RFD circle)

2.2 Access strategies

Medium access within a PAN is controlled by the PAN coordinator that may choose either beacon-enabled or non-beacon-enabled modality.

In the beacon-enabled modality, the PAN coordinator broadcasts a periodic beacon. The period between two consecutive beacons defines a superframe structure divided in 16 slots. The first slot is always occupied by the beacon, while the other slots are used for data communication by means of random access and form the so-called contention access period (CAP). The beacon contains information related to PAN identification, synchronization, and superframe structure. The beacon-enabled modality is only adopted when the PAN has a star topology. In this case, two data transfer modes are available:

1) Transfer from a device to the coordinator. A device willing to transfer data to the coordinator uses either ALOHA or slotted carrier sensing multiple access with collision avoidance (CSMA-CA) to access the medium.

2) Transfer from the coordinator to a device. When the coordinator has data pending for a device, it is announced in the beacon. The interested device selects a free slot and sends a data request to the coordinator, indicating that it is ready to receive the data. When the coordinator receives the data request message, it selects a free slot and sends data using either ALOHA or CSMA-CA.

In order to support low-latency applications, the PAN coordinator can reserve one or more slots for those devices running such applications, thus avoiding contention with other devices. Reserved slots are referred to as guaranteed time slots (GTS), and they form the contention free period (CFP) of the superframe.

In the non-beacon-enabled modality, there is no explicit synchronization provided by the PAN coordinator. This modality is particularly suited for PANs adopting the peer-to-peer topology but can be adopted in a star network as well.

3 Performance experiments

In this section, we carry out experiments to examine the network performance of the IEEE 802.15.4a wireless networks.

3.1 Experimental hardware

As shown in Fig. 3, seven nanoNET TRX IEEE 802.15.4a development boards[17] are used as a coordinator and six network devices, respectively, continuously transferring the data so as to perform the measurements. The key product features of nanoNET TRX included the following:

1) An IEEE 802.15.4a chirp spread spectrum transceiver with integrated MAC controller;

2) Operation in the industrial, scientific and medical (ISM) band at 2.45 GHz;

3) Output power of −25 dB·m to 10 dB·m;

4) Range of 900 m (free space) and 60 m (indoors);

5) Four channel digital I/O (bidirectional);

6) Integrated power management.

A USB port is provided for easy connection to a PC or a notebook, where the real-time data could be stored. The other six boards are served as the network devices (devices 2–7). The boards contain a microcontroller, a printed circuit board (PCB) antenna, as well as buttons and light emitting diodes (LEDs) as the user interface.

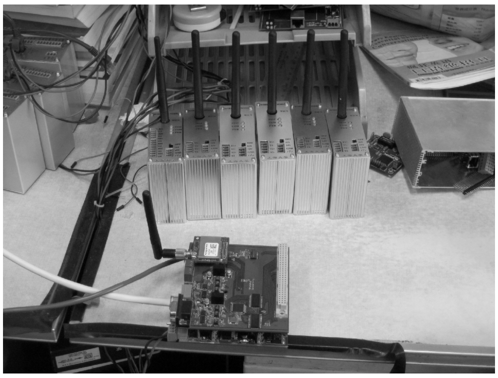

Fig. 3 Experimental equipment

3.2 Experimental configuration

Four sets of experiments are designed to evaluate the various performances of IEEE 802.15.4a, including the effects of 1) numeral wireless nodes, 2) numeral data packets, 3) data transmissions with different high-layer protocol, and 4) physical distance between each node. The experiments were run in a one-hop star topology, as shown in Fig. 4.

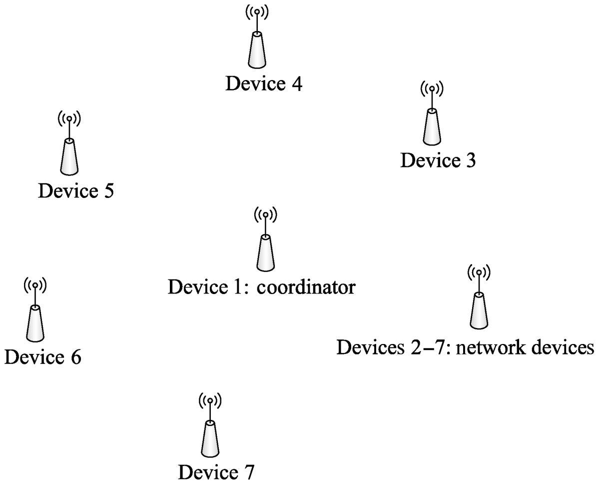

Fig. 4 Experimental network structure (star topology)

Device 1 is the coordinator continuously sending or receiving data packets to or from the network node. The other devices 2–7 are the network devices to send data in the following experiment A–D (as shown in Fig. 4). The physical distance between coordinator and devices is 1 m except in Section 4.4. The performance study was for a steady state network, i.e., after all the devices finish channels canning and the relevant procedure joins the PAN.

4 Results and discussion

In this section, the time-delay is incorporated in the mentioned experimental sets. In these experiments, the time-delay is defined as the time slot between coordinator received signals from the same network device:

$$t_{\text{time}-\text{delay}} = t_{n,k+1} - t_{n,k} \tag{1}$$

where n means the n-th network device, which means that the n-th time is the coordinator accessing the n-th device.

4.1 Effects of numeral wireless nodes

In this experiment, we change the numbers of wireless nodes to observe the effect on time-delay with the token-ring protocol which was designed by our group[18]. First of all, we test the time-delay with only one network device, and then add the network device one by one, until the total number of network devices is six. Each test has been lasting for 15 min at least. All the wireless nodes send only one packet when they get the token-ring to access the wireless channel. For some industrial applications, the communication traffic is very low, for example, the value of temperature or pressure. The data size of packet is set to 168 byte[17]. The results are shown in Fig. 5.

As can be seen in Fig. 5, the time-delay is increasing with the number of wireless nodes. The increasing value changes a few when adding one node, expect the first one. In order to study the law of time-delay varying, we calculate the average value of the time-delay from the experiment results (see Table 1, where TR P. denotes token-ring protocol, and M/S P. denotes master/slave protocol). Ignoring the disturbance of environment and the error of test, we can describe the law of the time-delay following the number of wireless nodes changing as follows:

$$t_{\text{time}-\text{delay}} = t_{n,k+1} - t_{n,k} = \Delta t + n t_{\text{time}-\text{slot}} \tag{2}$$

where $t_{\text{time}-\text{slot}}$ is the increasing time when adding a node, $\Delta t = 1.45$ ms and $t_{\text{time}-\text{slot}} = 4.16$ ms.

Table 1 Average value of time-delay (ms) in the experiment

Nodes	1	2	3	4	5	6
TR P.	5.6	9.8	13.7	17.9	22.0	26.4
M/S P.	5.8	11.2	16.6	22.3	27.9	33.5
50 pkt	69.8	142.8	207.8	288.3	353.4	419.3
100 pkt	134.3	314.7	483.1	607.7	771.9	887.7
Distance 5 m	5.7	9.6	13.9	17.9	22.4	26.7

4.2 Effects of numeral data packets

During the CSMA/CA, data packets may be undeliverable as the channel is extremely busy, erroneous, or even lost. In this token-ring protocol, we adopt the mechanism of retransmission when the data packet lost, and send it again until becomes successful. Therefore, the rate of packet loss is zero. In this section, the effect of numeral data packets is studied.

In this experiment, the packet size is fixed to 168 byte. There were 50 packets and 100 packets transmitted from devices 2–7 to the coordinator, respectively. Figs. 6 and 7 show the effects of numeral data packets between the coordinator and the devices with varied packets. Comparing with Fig. 5, we can see that time-delay became big, even unstable when the number of packets increases. The results in Fig. 7 and Table 1 show that the IEEE 802.15.4a is only suitable for systems with low-data-rate communication. The applications with high traffic load (i.e., audio/video monitoring system) may adopt other IEEE standard (i.e., IEEE 802.11).

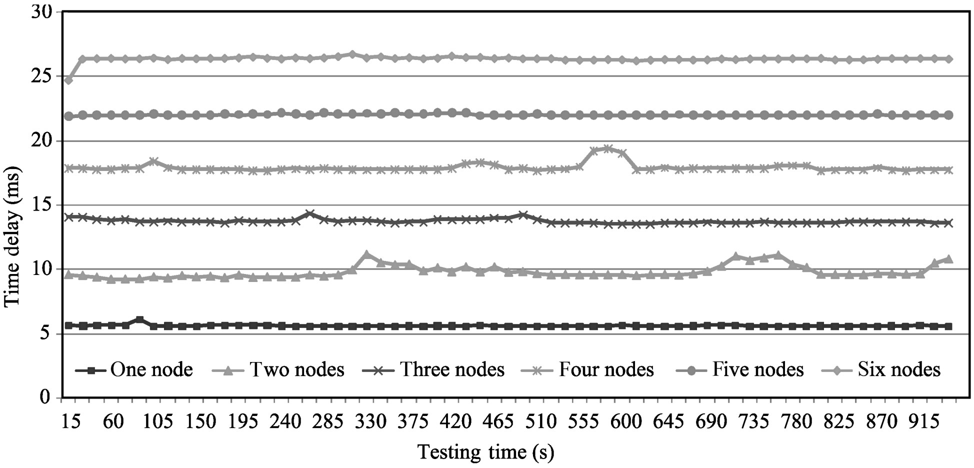

Fig. 5 Effects of numeral wireless nodes

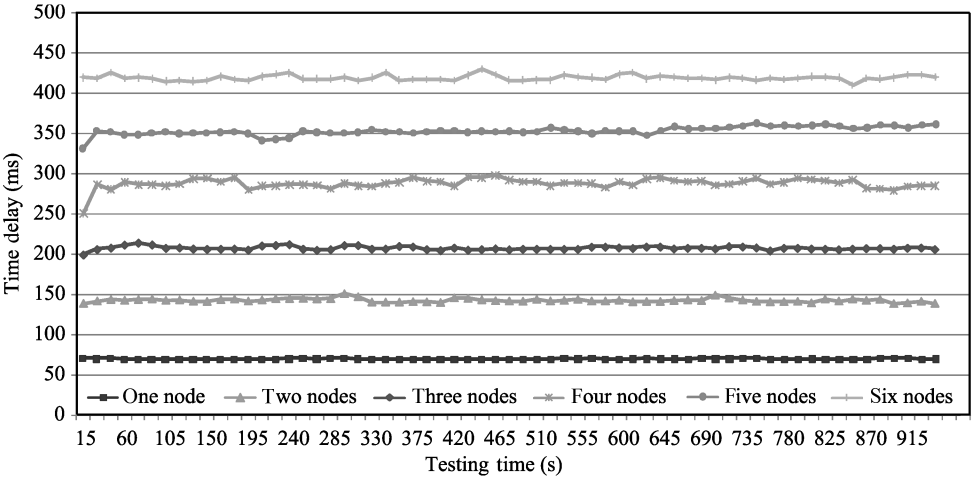

Fig. 6 Effects of numeral packets (50 packets)

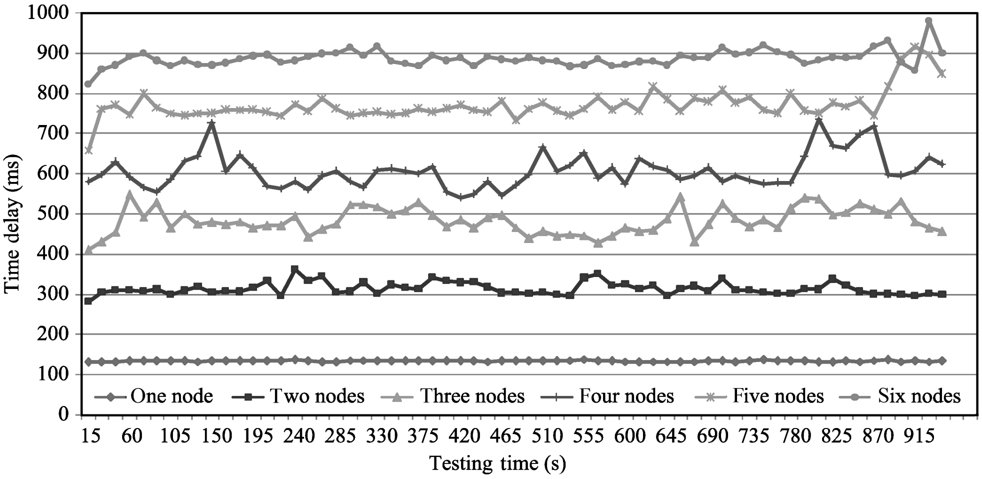

Fig. 7 Effects of numeral packets (100 packets)

4.3 Effects of different upper-layer protocols

As IEEE 802.15.4a only defines the physical layer (PHY) and the MAC layer, different high-layer protocols may affect the wireless network's performance. In this experiment, we compared the master/slave protocol with a token-ring protocol.

Fig. 8 shows the result adopting master/slave architecture. In this protocol, the coordinator is also the master to manage the slave nodes (devices 2–7). We can see that not only the value of time-delay but also the law of time-delay are different from token-ring protocol. First of all, the value of time-delay is bigger than that in Section 4.1, which adopted token-ring protocol. In Table 1, we can find that there is a positive relationship between time-delay and numeral nodes. Ignoring the disturbance of environment and the error of test, we can describe the law of the time-delay following the number of wireless nodes changing as follows:

$$t_{\text{time}-\text{delay}} = t_{n,k+1} - t_{n,k} = nt_{\text{time}-\text{slot}} \tag{3}$$

where $t_{\text{time}-\text{slot}}$ will increase in time when adding a node. In this experiment, we can see in Table 1 that $t_{\text{time}-\text{slot}} =$ 5.52 ms, which is the average value of $t_{n,k+1} - t_{n,k}$.

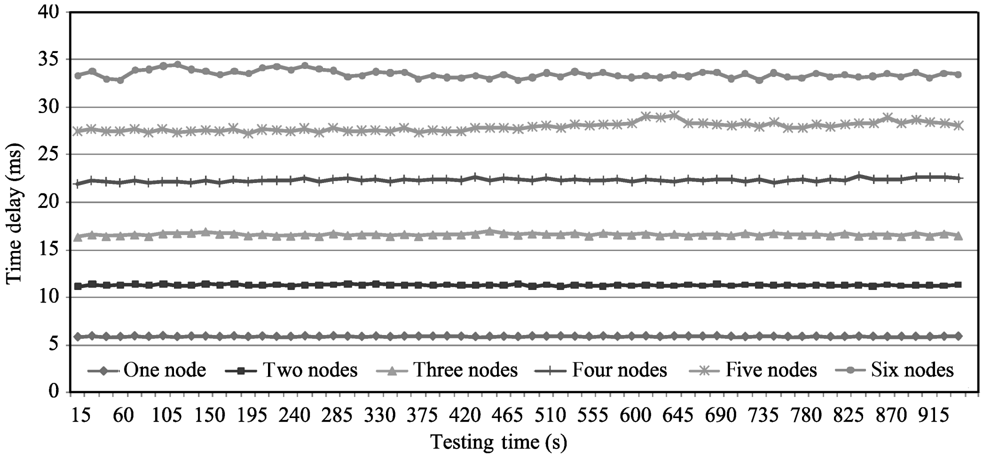

Fig. 8 Effects of upper-layer protocol

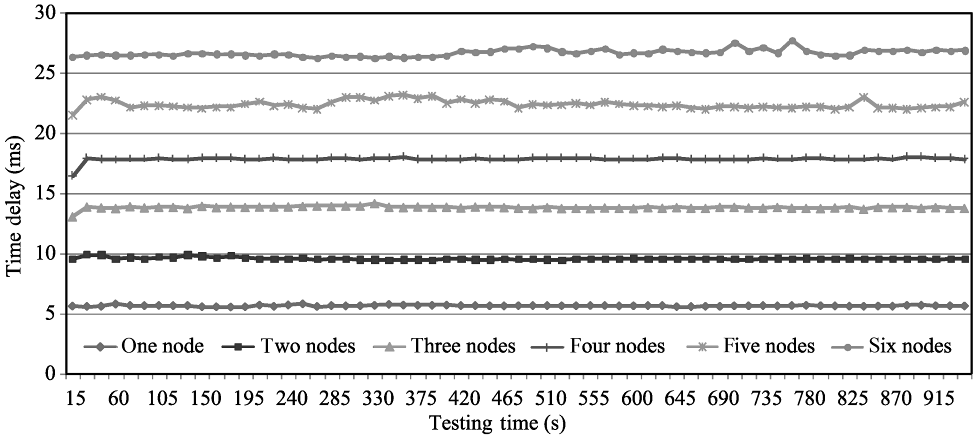

Fig. 9 Effects of physical distance between nodes and coordinator

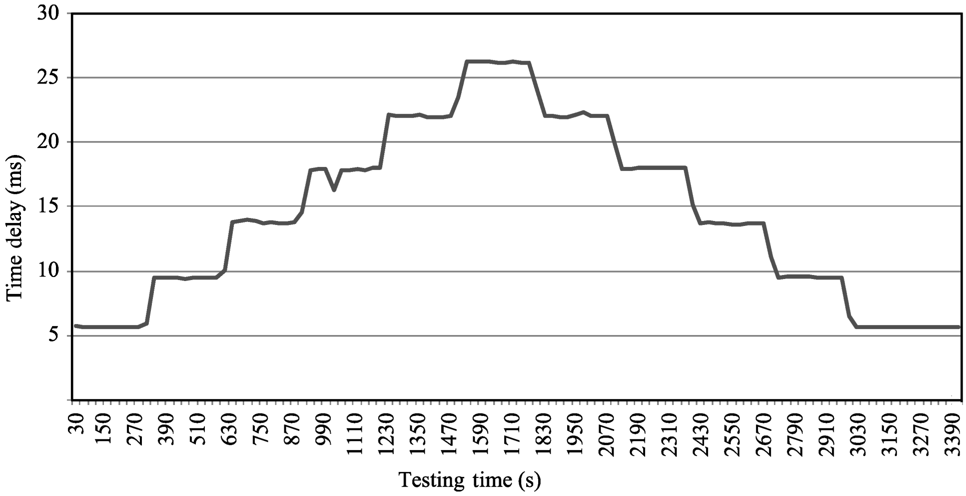

Fig. 10 The steady of wireless network when adding or reducing wireless nodes

4.4 Effects of physical distance between nodes and coordinator

This experiment is used to test the effect of physical distance between devices and coordinator. In order to obtain experimental measurements, the topology in Fig. 4 has been considered, but this time, the distance is 5 m between the devices and coordinator. Since there were few electromagnetic interferences in the laboratory environment, the impact of physical distance is very little, as can be seen in Fig. 9.

4.5 Steadiness of wireless network

This experiment is used to test the steadiness of wireless network when the number of wireless nodes changed. The topology in Fig. 4 is used and some wireless nodes are turned on/off when the network is running. The steadiness of the wireless network can be seen in Fig. 10.

5 Conclusions

This paper has presented a preliminary performance study of the IEEE 802.15.4a wireless standard in industrial applications via practical experiments, including 1) numeral wireless nodes, 2) numeral data packets, 3) data transmissions with different high-layer protocols, 4) physical distance between nodes, and 5) adding and reducing the number of wireless nodes. Experimental results show the following:

1) Time-delay becomes big if the wireless nodes increase.
2) Efficient high-layer protocol can reduce the time-delay.
3) The time-delay depends on the number of packets being sent.
4) The physical distance between devices and coordinator has little impact unless there are large electromagnetic interferences.
5) The wireless network based on IEEE 802.15.4a is steady when adding or reducing the nodes in a wireless network.

It is clear that the IEEE 802.15.4a standard is suitable for some industrial applications with more relaxed throughput requirements and time-delay. These wireless networks can also be integrated into wired networks that are already existed, i.e., hybrid networks. However, the compatibility between the IEEE 802.15.4a and existing wired networks is a key for successful integrations. It is thus necessary that the performance analysis of hybrid wired/wireless networks should be conducted in the future work.

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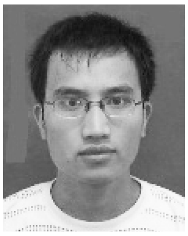

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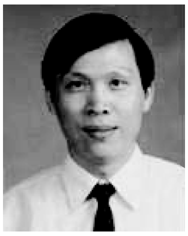

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