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Distributed Computing Approach for Wireless Sensor Network Design in a Wire Harness Testing System

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In this paper, we propose the design of the wire harness testing system of Fujian Creation Electronics Co., Ltd. (FCE). To reduce the installation cost, wireless sensor network technology was introduced to eliminate the wiring task. The wireless sensor network contains numerous sensors and each of them uploads a large amount of detection results to the server. This lengthens the collection time of detection results and customers cannot accept the long system refresh time. A method of addressing the time constraint is required. In this study, we propose a wireless sensor network system that addresses the time constraint. The proposed system distributes the computing tasks from the server to the sensors to reduce the amount of uploaded data. By this method, we then propose novel network protocols for the proposed system and formally present them in this paper. The performance estimation showed that the proposed system addresses the time constraint while it reduces the labor cost and improves the operation efficiency.

1. Introduction

In this study, we aim to reduce the cost of installing the wire harness testing system of Fujian Creation Electronics Co., Ltd. (FCE). The existing wire harness system employs a traditional Ethernet/IP network. A customer has suggested replacing existing sensors in wired communication lines with wireless sensors to further reduce installation costs. Previous attempts used various Zigbee communication modules, but owing to the high density of sensors and the large number of detection results uploaded by these sensors, none of these prototypes were able to meet the time constraint proposed by the customer.

Many researchers addressed this problem,[(1–3)] but their targets were wireless sensor networks with a complex network topology. A patent applied WIFI technology to reduce the cost of correcting error in wiring testing systems.[(4)] This invention does not consider the problem of data collision caused by a large number of sensing devices simultaneously transmitting a large

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amount of sensing results. This problem significantly lengthens the system refresh time, which is the main challenge and innovation of this study.

In this study, we first address the problem of wireless sensing networks containing only one cluster.[5] Although the network topology considered in this paper is simple, the traffic congestion caused by a large amount of uploaded data exceeds the carrying capacity of the 802.15.4 communication module.

Distributing the computation load is a method of reducing the time delay caused by a large amount of transmitted data.[6–9] This method extends the computation from the server to the sensors and provides the sensors with the ability to directly process and analyze data locally.[6–9]

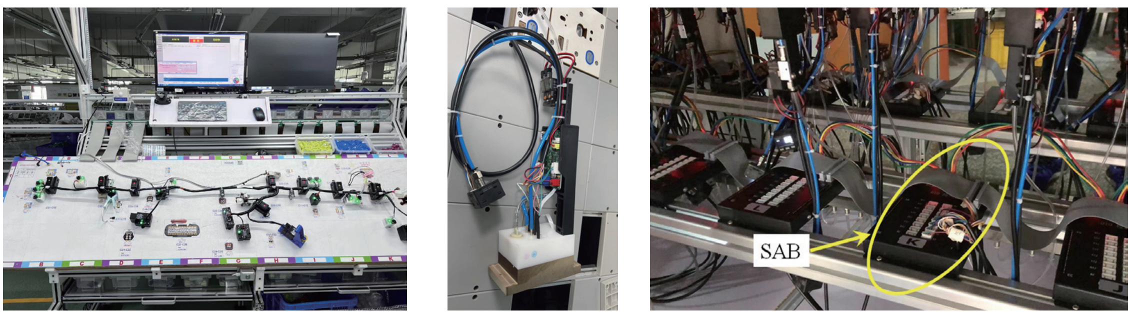
We adopted the above method to reduce the amount of uploaded data. On the basis of this method, we proposed crucial network protocols for the proposed system and formally present them in this paper.

The remainder of this paper is structured as follows. In Sect. 2, we present the system architecture and the functions and challenges of the existing system. In Sect. 3, we briefly discuss the methodology to solve the problems mentioned in Sect. 2. The proposed system architecture is presented in Sect. 4. To complete the system architecture, necessary network protocols and corresponding algorithms were also proposed in Sect. 4. In Sect. 5, we discuss some problems regarding this study. The conclusions and some ideas for future works are then presented in Sect. 6.

2. Problem Description

The black cable in Fig. 1(a) is a wire harness being tested. This system comprises numerous wire harness connectors (WHCs), several signal acquisition boards (SABs), and a server. The sockets on the table are WHCs.

The pins in a plug of each wire harness may connect to some other pins through electronic circuits. If there are no breakpoints or wrong wiring in the internal circuit, supplying electricity to a pin will increase the voltage in the corresponding pins.



(a) (b) (c)

Fig. 1. (Color online) Existing wire harness testing system and its main components. (a) The overview of the existing wire harness testing system. (b) WHC. (c) SAB.

Therefore, if any of the following is true, then the testing system concludes that there exist some errors in the circuit. This is the method for testing a wire harness.

1. Some SABs did not detect an increase in voltage in the corresponding pin.
2. Some SABs detected an increase in voltage in non-corresponding pins.

The SABs and the server compose a LAN. The server controls the pins through the help of the SABs. Each SAB pin has a unique identification number in the system. If pin A in the wire harness is plugged into pin B in WHC, and the other end of pin B is plugged into pin C in SAB, then pins A, B, and C have the same identification number. The server can send the instructions to the specified pins by indicating the identification number of the receivers. Figure 2 concludes the method above.

The testing procedure is composed of three stages: the system setup stage, the system installation stage, and the wire harness testing stage. In this paper, we formally present the three stages as follows.

2.1 System setup stage

Whenever a customer provides a new type of wire harness, a test plan for this is required. A test plan for a type of wire harness consists of the parameters below.

1. Required WHCs: For each plug in the wire harness, the corresponding WHC type and installation position should be clearly recorded in the test plan. We assume that this type of wire harness needs w WHCs, and $TID = <TID_1, TID_2, \ldots, TID_w>$ forms the sequence of type IDs of the w WHCs. $\forall TID_i \in TID$; we define the following notations:
   - $NoP(i)$ denotes the number of pins in the corresponding WHC of TID_i.
   - $TIDPinSeq(i) = <P_{i,1}, P_{i,2}, \ldots, P_{i,NoP(i)}>$ denotes the sequence of identification numbers of the pins in the corresponding WHC of TID_i.
2. Relationships between the WHC and SAB pins: For the convenience of subsequent expression, we make the following assumptions and notation definitions:
   - $AllPinSeq = <P_1, P_2, \ldots, P_n>$ is denoted as the sequence of identification numbers of the SAB pins satisfying the following:
     - $\forall P_i \in AllPinSeq, \exists TID_j \in TID$ and $\exists P_{j,k} \in TIDPinSeq(j)$ satisfying $P_i = P_{j,k}$.
     - $\forall TID_j \in TID$ and $\forall P_{j,k} \in TIDPinSeq(j), \exists P_i \in AllPinSeq$ satisfying $P_i = P_{j,k}$.

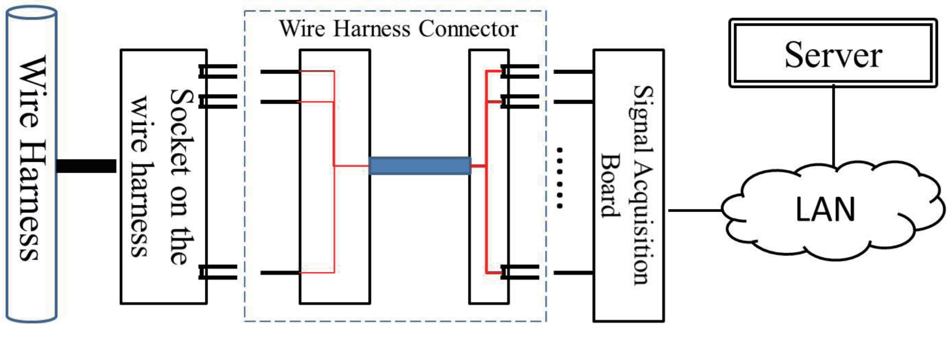


Fig. 2. (Color online) Existing wire harness testing system architecture.

- $\forall TID_i \in TID$ and $\forall P_{j,k} \in TIDPinSeq(j)$; define $Map(j, k) = i$ if $P_i = P_{j,k}$.
- $\forall TID_i \in TID$; the number of prior pins of TID_i is defined as $Map(i,0) = \sum_{j-1}^{i-1} NoP(j)$.

3. Correct pin map: For each pair of pins P_i and P_j, the correct pin map specifies whether P_i connects to P_j. According to this previous description, the correct pin map of a wire harness containing n pins is defined to be an $n \times n$ matrix $A = <A_{i,j}>$. $\forall P_i \in AllPinSeq$ and $\forall P_j \in AllPinSeq$; $A_{i,j}$ is defined as follows.
   - If $i \neq j$, then $A_{i,j} = 1$ if and only if pin P_i connects to pin P_j.
   - If $i = j$, then $A_{i,j} = 0$.

2.2 System installation stage

In this stage, the system installation engineers follow the procedure below.

Step 1. Install the WHCs at the correct position in accordance with the specifications of the test plan.

Step 2. According to the specifications of the test plan, plug the WHC pins into the corresponding SAB pins.

Step 3. Check if the WHC pins are correctly plugged into the corresponding SAB pins. If not, correct the errors.

Step 4. Perform the self-testing procedure. If the testing system passes the self-testing procedure, terminate this procedure and then move to the wire harness testing stage. Otherwise, go to Step 3.

The existing wire harness testing system contains at least 20 SABs, and each SAB has 128 pins. Owing to the lack of clear identification marks on the pins, the above procedure is gingerly and prone to errors. The testing system will not perform correctly if a pin is plugged incorrectly. Therefore, the above procedure should be performed by proficient engineers. This significantly increases the cost of labor and lengthens the installation time.

2.3 Wire harness testing stage

The existing system adopts the system procedure shown in Fig. 3 to periodically examine the wire harnesses mounted on it. Once the procedure starts, the testing system continuously displays “Error” until all the sockets of the tested wire harness have been plugged into the WHCs correctly. In the meantime, the testing system displays “Pass” to the tester if the wire harness passes the test, or still displays “Error” otherwise. This procedure performs continuously until the testing system is shut down.

2.4 Demands and challenges

On the basis of previous descriptions, the labor cost and installation time in the system installation stage can be further reduced if the wiring task can be performed automatically. Therefore, FCE desires to introduce wireless network technologies to improve the testing system.

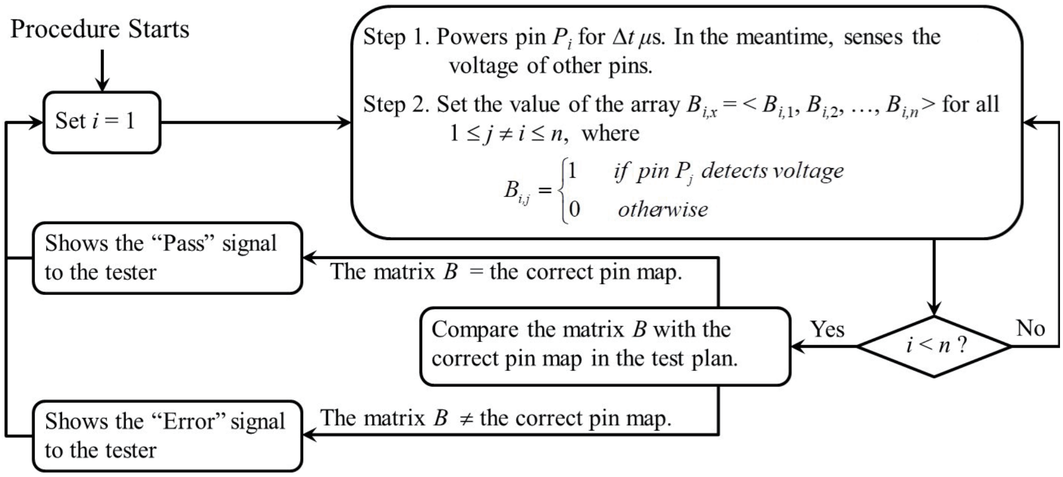


Fig. 3. System procedure in wire harness testing stage.

Directly introducing wireless communication modules such as Zigbee cannot satisfy the time constraint. The time constraint stems from the bonus model for the tester. The bonus for the tester increases with the number of wiring harnesses it has tested. The testers receive fewer bonuses if the system tests the wire harnesses slowly. The testing system that does not satisfy the time constraint from the customers not only significantly increases the operating costs, but also angers the testers. The customers stated that testing a wire harness must be done in 2 s.

In the rest of this paper, the device fused by the SAB and WHC is called a sensor. Numerous types of tested wire harness contain more than 1000 pins. This indicates that the sensing results that must be uploaded to the server exceed 1 M bits in the existing system. On the basis of the IEEE 802.15.4 specification,[10] the solutions that directly adopt the communication module of 802.15.4 cannot upload 1 M bits of sensing results to the server within 2 s.

The first strategy for solving the above problem is to increase the data rates. This may be performed by adopting the communication modules with high enough bit rates. This can also be achieved by adopting communication modules with multiple channels and then designing the appropriate channel assignment algorithm for the wireless sensor network. The second strategy is to reduce the amount of uploaded data.

If the first strategy is adopted, it is expected that the cost of the sensor would be increased significantly. If the system employs customized communication modules, the reliability is under-evaluated and the corresponding R&D cost is appreciable. Given this reason, we attempt the second strategy.

3. Methodology

On the basis of the descriptions in Sect. 2, the server maintains the correct pin map and compares the correct pin map with the sensing results. Therefore, the testing system requires the sensors to upload their results to the server. If the testing system asks the sensors to make the comparison and then reports the comparison results only, the traffic in the wireless sensor network would be significantly reduced. The server requires only to collect and analyze the comparison results from the sensors and then show the judgement to the tester.

Assume that the testing system proposed in this study adopts the polling approach to collect the data uploaded by sensors. The server first sends an instruction to a sensor and then the sensor uploads its comparison result. According to the system parameter definitions below and the packet format in Fig. 4,[10–12] the testing system takes only 42 bytes to collect the comparison result of one sensor.

- The source and destination address are both 4 bytes.
- The payload of a request packet contains only 1 byte. The payload presents only the request instruction from the server to a sensor.
- The payload for the uploading packets contains only 3 bytes. The payload presents 1 byte for instruction and 2 bytes for the comparison results.

If the testing system contains n sensors and all the packets are successfully transmitted without retransmission, then its network transmits $42 \times 8 \times n = 336n$ bits when collecting the comparison results. Thus far, there have been no tests on wire harnesses with more than 200 sockets according to the experiences from FCE. If the system adopts the 802.15.4 communication modules, it is expected that collecting the sensing results of 200 sensors would require less than 0.3 s if no retransmission is required.

The probability of retransmission would be sufficiently low in a controlled environment. Under this condition, it is promising to reduce the system refresh time to within 1 s for the wire harnesses requiring less than 200 sensors.

Time synchronization is critical since the testing system requires the sensors to start the Step 1 procedure in Fig. 3 at the same time. On the basis of this requirement, the system architecture is proposed as Fig. 5.

In comparison with Fig. 2, a SAB and a WHC are fused into a sensor and the LAN is replaced with a wireless sensor network. Moreover, a power line with time synchronization function is added.

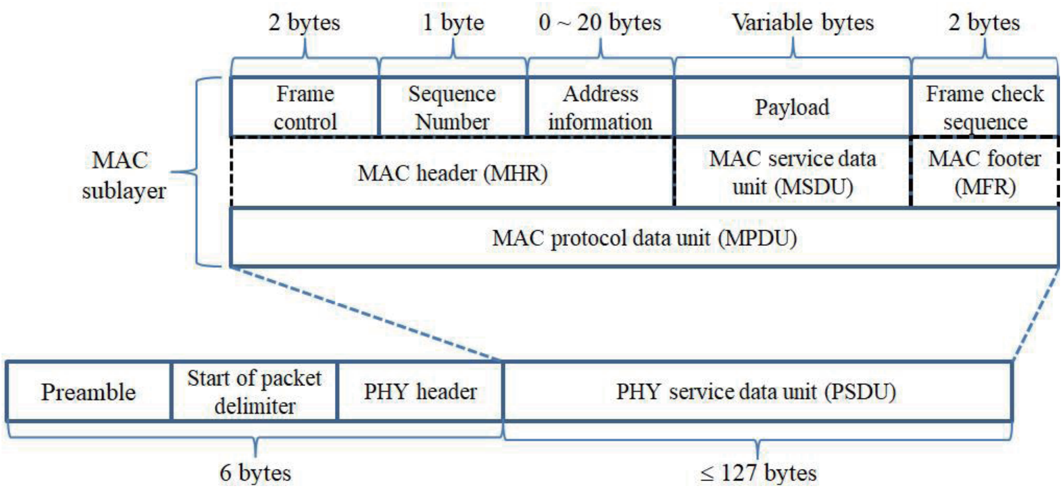


Fig. 4. (Color online) Physical and MAC layers of IEEE 802.15.4 packets.[10]

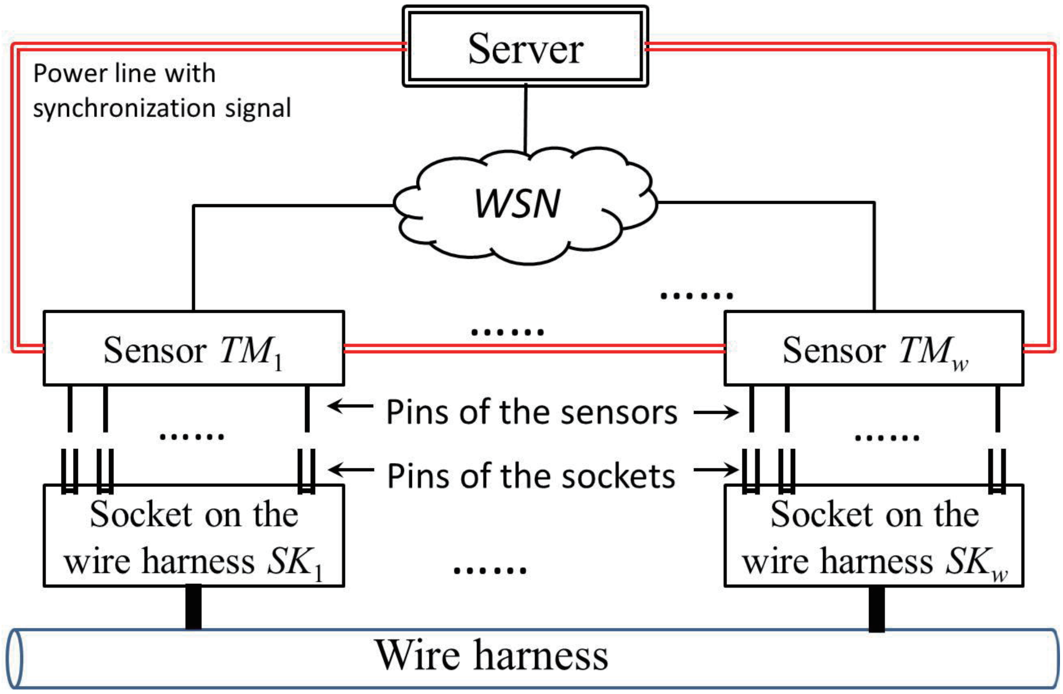


Fig. 5. (Color online) Proposed system architecture.

4. Proposed Protocols and Algorithms

Because the comparisons are performed in the sensors, the testing system must be redesigned. The proposed system also separates the testing procedure in three stages: the system setup stage, the system installation stage, and the wire harness testing stage.

4.1 System setup stage

In addition to the information that must be maintained in the test plan described in Sect. 2, the test plan must also maintain the following information for all the sensors:

1. Correct pin map: The correct pin map defined in Sect. 2 shows the circuit connectivity of each pair of pins in the corresponding type of wire harness. Owing to the poor computational resources and memory space of the sensors, requiring the sensors to maintain the whole correct pin map is inappropriate. Each sensor should maintain only the necessary part of the correct pin map. Applying the definitions in Sect. 2, we formally define the correct pin map for each sensor as follows.
   - $\forall TID_i \in TID$; the correct pin map for TID_i is an $n \times NoP(i)$ matrix $B_i = <B_{x,y}>$, where $\forall P_x \in AllPinSeq$ and $\forall P_{i,y} \in TIDPinSeq(i)$, $B_{x,y} = A_x, Map_{(i,\, y)}$.
2. Electrical test sequence: The electrical test sequence is helpful in canceling the instruction from the server to a sensor, which requests the sensor to power the specific pin. This significantly reduces the traffic load of the wireless sensor network.

Assuming all the sensors know the electrical test sequence of their pins, whenever the server asks all its sensors to perform the electrical test simultaneously, the server broadcasts the corresponding instruction to all its sensors. Once the sensors receive that instruction, they reset the time to 0. The sensors then perform the corresponding procedure according to the electrical test sequences of their pins. Specifically, at the time $k \times \Delta t$, the sensor that owns the pin whose electrical test sequence is $k + 1$ powers this pin and all the sensors sense the voltage of the other pins.

According to the definitions in Sect. 2, the sensor TID_i must learn the value of $Map(i, 0)$ from the server. $\forall P_{i,j} \in TIDPinSeq(i)$, $Map(i, 0) + j$ is the electrical test sequence of $P_{i,j}$.

Although the identification number of the sensors in the wireless sensor network must be unique, numerous sensors may exhibit the same type of WHC. To distinguish between these sensors of the same type, each sensor has two identification numbers in the proposed system. The first identification number is its object ID. The second identification number is its type ID, which indicates the type of WHC it belongs to.

TID_i in the test plan is the type ID of the sensor in the proposed system. Since $TID_i = TID_j$ may happen, a new sequence $OID = \langle OID_1, OID_2, \ldots, OID_w \rangle$ is employed to specify the object ID for the sensors in the wireless sensor network. In this stage, the values in the sequence *TID* can be determined, whereas the values in the sequence *OID* can only be determined in the next stage.

4.2 System installation stage for the proposed solution

After the sensor $TID_i \in TID$ has been installed in the correct position, the testing system must determine the value of OID_i. One method to complete this task is as follows: first, create a QR code for each sensor and paste it in a prominent position of that sensor. This QR code contains the object ID of that sensor. Secondly, after entering this stage, pairing operations can be performed by scanning the QR code and selecting it on the server side.

After a sensor has been installed correctly and has been powered on, the sensor collaborates with the server to complete the tasks below.

- Add this sensor to the wireless sensor network of this system.
- Select the necessary information in the test plan and then send it to this sensor.

In this study, we proposed the auto-configuration protocols below for the two tasks above.

Auto-configuration protocol for the sensors whose ID is OID_i

Step 1. The sensor whose ID is OID_i continuously receives packets until it receives one whose receiver is OID_i. The sensor OID_i then records the sender's ID as the ID of the server and then returns an acknowledgement to the server.

Step 2. The information below is received. Go to the next step once the sensor OID_i receives the instruction "*GoToNextStage*" from the server.

- Number of pins
- Value of $Map(i, 0)$
- Correct pin map for the sensor OID_i

Step 3. The sensor OID_i sets the electrical test sequences for all its pins. Then, the sensor OID_i sends a response for the instruction "*GoToNextStage*" to the server and then terminates this procedure.

Auto-configuration protocol for the server

Step 1. Query the test plan to learn the information below.
- Sequence $OID = <OID_1, OID_2,\ldots, OID_w>$
- $\forall OID_i \in OID$, the correct pin map for the sensor OID_i
- $\forall OID_i \in OID$, the value of $Map(i, 0)$

Set $DisConnectedOID = OID$

Step 2. Continuously and periodically send packets whose instruction is "*Hello*" to the sensors whose object ID belongs to the set *DisConnectedOID*. As long as the server receives an acknowledgement from the sensors in the set *DisConnectedOID*, go to step 3.

Step 3. Assume that an acknowledgement is sent from the sensor whose object ID is $oid \in DisConnectedOID$, and send the information below to the sensor *oid*. Go to step 4 if the sensor *oid* receives the information successfully; otherwise, go to step 2.
- Number of pins of the wire harness
- Value of $Map(i, 0)$
- Correct pin map for the sensor *oid*

Step 4. Transmit the packet whose instruction is "*GoToNextStage*" to the sensor *oid*.

Step 5. Once the server receives a response from the sensor *oid* before timeout, set $DisConnectedOID = DisConnectedOID - \{oid\}$ and then go to step 6 or 4.

Step 6. Go to the wire harness testing stage if $DisConnectedOID = \varphi$; otherwise, go to step 2.

4.3 Wire harness testing stage for the proposed solution

The testers are allowed to test the wire harness at this stage. For testers, the standard operating procedures for testing wiring harnesses are the same as those of existing systems.

Figure 6 shows the proposed testing procedures for the sensors and the server. Once the sensors enter this stage, they continuously sense the power line for the time synchronization signal. In the meantime, the server performs the following procedure:

Step 1. Broadcast a time synchronization signal to the sensors through the help of the power line.

Step 2. Wait for at least ($n \times \Delta t + \Delta t$) μs, where n is the number of pins in the wire harness, Δt is the time for supplying electricity to a pin, and ΔT is a system parameter.

Once the sensor has detected a time synchronization signal, the sensor performs the following procedure:

Step 1. Let $i = 1$.

Step 2. Power pin P_i for Δt μs if pin P_i belongs to this sensor. Sense and record the voltage of other pins in Δt μs. If $i < n$, set $i = i + 1$ and then go to step 2. Otherwise, go to step 3.

Step 3. Compare the sensing results and the correct pin map received in the second stage.

Step 4. Upload the comparison result to the server.

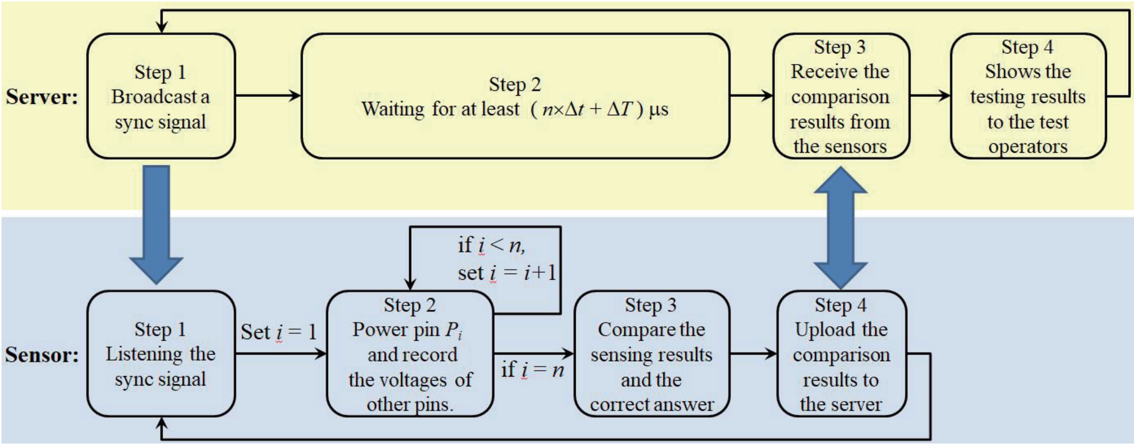


Fig. 6. (Color online) Testing procedures for the sensors and the server.

The assumptions below are used to illustrate how to calculate the comparison result between the correct pin map for the sensor and the sensing results of the sensor in step 3 of the sensor procedure.

1. The object ID is OID_y.
2. The matrix $D_y = <D_{y,i,j}>$ maintains the sensing results of the sensor OID_y.
3. The matrix $A_y = <A_{y,i,j}>$ is the correct pin map for the sensor OID_y.

If $P_{y,j} \in TIDPinSeq(y)$ and $Map(y, j) = i$, then the sensor OID_y supplies power to $P_{y,j}$ for Δt µs in step 2 of the sensor procedure. In the meantime, the sensor OID_y senses the voltage in all other pins. After that, $\forall P_{y,j} \in TIDPinSeq(y)$, the value of $D_{y,i,j}$ is determined according to the equation below.

$$D_{y,i,j} = \begin{cases} 1 & \text{if the } pin\ P_{y,j} \text{ detects voltage} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

After the sensor OID_y sets the value of $D_{y,i,j}$ for all its pins, the sensor compares the sensing result $<D_{y,i,j}>$ and the correct pin map $<A_{y,i,j}>$. The comparison result of the two matrices $<D_{y,i,j}>$ and $<A_{y,i,j}>$ is an integer calculated as

$$Comparison\ result\ for\ the\ sensor\ OID_y = \sum_{i=1}^{n}\sum_{j=1}^{n}\left|A_{y,i,j} - D_{y,i,j}\right|. \tag{2}$$

Because step 2 in the sensor procedure requires at least $n \times \Delta t$ µs, the server must wait for at least $n \times \Delta t$ µs in step 2 in the server procedure. In addition, the sensor requires some time for calculations and other work; so in step 2, we require the server to wait for $n \times \Delta t + \Delta T$ µs. This ΔT µs is not only used to reserve time for the sensor to deal with the extra works, but also considered an important system parameter to improve channel reusability and avoid mutual interference between adjacent wireless sensing networks. Some further discussions regarding the system parameter ΔT are given in the next section.

The server applies the polling approach in step 3 of the server procedure and in step 4 of the sensor procedure. After that, the sensor goes to step 1 to repeat the test procedure again. The server fuses the comparison results from all the sensors and then shows the testing result to the tester. After that, the server goes to step 1 to repeat the test procedure again.

4.4 Performance estimation

Figure 7 shows the time of each task in testing a wire harness. To estimate the time required to test a wire harness, we make the following notations and assumptions to the parameters in Figs. 6 and 7:

1. In the prototype of the proposed system, $\Delta t = 200$, $\Delta T = 20000$.
2. The probability of retransmitting a packet is denoted as P_{RTP}.
3. The collection time for the i-th sensor is $T_{CCR}(i)$.
4. In case of no retransmission, $T_{CCR}(i) = T_{CCR}$ for all i. T_{CCR} can be restricted in 2.5 ms for all i in the prototype of the proposed system.
5. The time required to test a wire harness is related to the parameters n, w, and P_{RTP}. We denote $T_{TWH}(n, w, P_{RTP})$ as the time required to test a wire harness.
6. The packet transmission events are mutually independent.

By applying the notations above, the time required to test a wire harness can be estimated as

$$T_{TWH}\left(n, w, P_{RTP}\right) = n \times \Delta t + \Delta T + \sum_{i=1}^{w} T_{CCR}\left(i\right). \quad (3)$$

According to the assumption that the packet transmission events are mutually independent, the expected value of the random variable $T_{CCR}(i)$ is $\sum_{j=1}^{\infty} j \times T_{CCR} \times \left(1 - P_{RTP}\right) P_{RTP}^{j-1}$ for all i; therefore, the expected value of $T_{TWH}(n, w, P_{RTP})$ can be estimated as

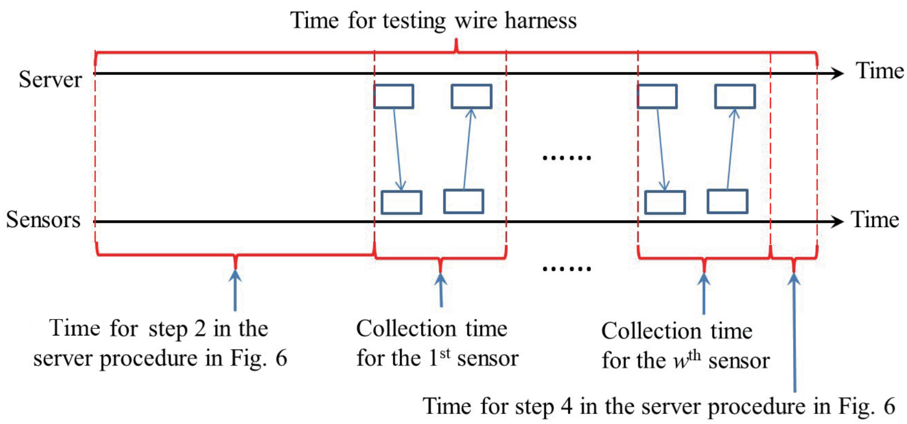


Fig. 7. (Color online) Communications between server and sensors in testing a wire harness.

$$E\left[T_{TWH}\left(n,w,P_{RTP}\right)\right]=n\times\Delta t+\Delta T+\frac{w\times T_{CCR}}{1-P_{RTP}}. \quad (4)$$

Figure 8 shows the distribution of the expected value of $T_{TWH}(1024, w, P_{RTP})$, where the unit of time is 1 s. The number of pins in most wire harnesses is less than 1024, and the number of sensors is between 30 and 80. Moreover, n can be restricted to be less than 2048 and w can be less than 256. According to Eq. (4), the expected value of $T_{TWH}(2048, w, P_{RTP}) - T_{TWH}(1024, w, P_{RTP})$ is 0.2 s. This shows that the proposed system satisfies the time constraint from the customer in most testing activities.

5. Discussion

The first problem of this study is which sensor network technology should be adopted. The first technology that we recommend to FCE is power line communication (PLC).[5,10,13] In the literature, the bit rate of PLC is sufficient to meet the needs of uploading a large amount of data from the sensors to the server, and it also has the ability to eliminate the wiring operations, without considering the problem of wireless signal interference from adjacent wire hardness testing systems. Owing to the fact that the PLC communication module is much more expensive than the 802.15.4 communication module, and PLC currently cannot find a solution with a voltage lower than 5 V, coupled with the R&D team being much familiar with the 802.15.4 communication technology solution, FCE ultimately adopted the 802.15.4 communication technology solution. If the 802.15.4 solution does not perform as expected and the customer is willing to bear the increased costs, then the PLC solution would be reconsidered.

The second problem is what network protocol should be adopted when collecting the comparison results from the sensors. We initially intended to adopt or design appropriate

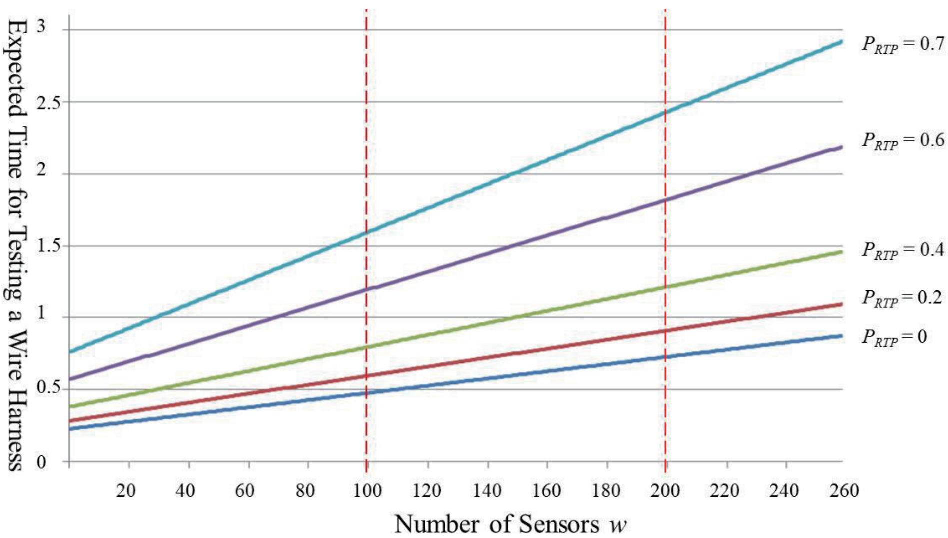


Fig. 8. (Color online) Estimated time required to test a wire harness

channel scheduling algorithms.[13,14] Specifically, the server first determines the order in which each sensor uploads comparison results and notifies all sensors of this order during the system installation stage. Afterwards, the server requests all sensors to upload the comparison results in this order. In comparison with the proposed approach, this method can further reduce the collection time of comparison results. However, this method has insufficient reliability and flexibility.

In practical applications, there are many testing systems in the same workspace, and the wireless signals between these testing systems can interfere with each other. Therefore, it is necessary to introduce a channel resource management server to avoid signal interference. For this channel resource management server, optimizing the channel resource allocation while avoiding interference is an important research topic. Although scheduling approaches can effectively increase the channel reusability, they make the channel resource coordination inflexible. Moreover, there may be other wireless devices using the same frequency bands. The wireless devices vying for the wireless sensor networks may still suddenly appear. Therefore, the system must also have sufficient resilience to cope with those unexpected events. Although the polling approach currently adopted in this study has sufficient reliability and flexibility, we are still looking for better channel resource management solutions.

Note that the parameter ΔT in Fig. 6 is helpful for adjusting the channel reusability. Increasing ΔT helps to increase the number of shared channels of adjacent wireless sensing networks. Nevertheless, this also increases the system refresh time in testing the wire harnesses, which will reduce customer satisfaction. Therefore, finding appropriate values for the system parameter ΔT is an important problem in the next study.

6. Conclusion and Future Works

In this study, we used distributed computing methods to design an appropriate wireless sensing network system for the wire hardness testing system. The proposed solution significantly reduces the system installation costs. Preliminary estimation shows that the proposed solution can reduce the system installation time by 27 to 34%. In the meantime, the time for testing a wire harness that has 80 sensors and 1024 pins is about 0.62 s. This is much lower than the customer's time constraint (2 s). This gives customers full of expectations for the proposed solution.

Although the proposed solution is satisfactory to customers, there may be other wireless devices using the same frequency bands in the actual working space. This means that we should design appropriate tools to detect or even avoid this problem. In addition, the problem of channel interference between the wire harness testing systems must also be addressed.

The preliminary idea in solving the channel interference problem is to introduce the FDMA technology. During the system installation stage, the server uses a public channel to build the wireless sensor network. After the wireless sensing network is constructed, the server assigns other channels as the working channels to its sensors. The server and sensors then apply the working channels in the subsequent tasks.

The proposed solution should introduce a channel resource management server to determine the working channels of each cluster. The channel resource management server assigns appropriate working channels to the clusters to avoid the frequency interference among them. The channel assignment problem is always a challenge for wireless sensor network design.[15] The channel assignment algorithm should be sufficiently flexible for the sudden appearance of vying wireless devices. Therefore, modeling the channel assignment problem for the wire harness testing system and then designing appropriate channel assignment algorithms to solve it will be the main challenge for the next study.

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