2-6 Toward Smart Factory using Wireless Communication Technologies

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Currently wired communications are main usages in the manufacturing field, because they have a potential to realize high reliability for controlling of process machines. In recent days, however, wireless communications receive a lot of attentions based on product life cycle acceleration [1]. In a collaborative effort between private and public sectors, the National Institute of Information and Communications Technology (NICT) and member companies of Flexible Factory Project teamed up to carry out a series of tests and evaluations for wireless communications technology in several currently-operating factory sites, for the purpose of promoting the integration of IoT on the factory floor. Within a factory, there are potential instability issues in wireless communications when several different wireless systems running at the same time and location [2]-[7]. In order to tackle these issues, the project began in June 2015 and has been ongoing since. This paper shows situations of wireless environment and requirements for stable operation of manufacturing systems using wireless communication technologies.

1 Introduction

The specifications of production lines—such as system layout, process line length, and equipment used—in factories need to be updated frequently to accommodate frequent change in product life cycle, production volume, product specifications and manufacturing processes. These changes are usually made gradually to minimize expenses. To maintain the productivity of these factories it is necessary to develop flexible production lines capable of facilitating these changes.

Wireless communication is vital in developing flexible production lines. Factories are generally equipped with machines of various ages acquired from various manufacturers. Diverse interfaces and protocols are available for wireless communications, although they are not compatible with each other. For example, sensors are attached to legacy machines to collect data about quality, management, control and safety during their operation. If we use wired communication, these systems are difficult to set up, manage and operate and may be costly.

As the popularity of wireless communication use in factories increased, however, some issues were identified [7]. For example, Wi-Fi control of Automatic Guided Vehicle (AGV) may cause transfer delay of materials to the next process, if interruption or delay of control data should occur.

Fig. 1 A scene from the Flexible Factory Project experiment

Should such problems occur, the causes must be identified and resolved to recover the production line as quickly as possible to maintain the productivity of the system. For more than two years, NICT has undertaken various experiments to evaluate the performance of wireless communication systems installed and operating in factories (Fig.1). The objective of the evaluation is identification and realization of optimized wireless control methods that are most suited to each particular use in a

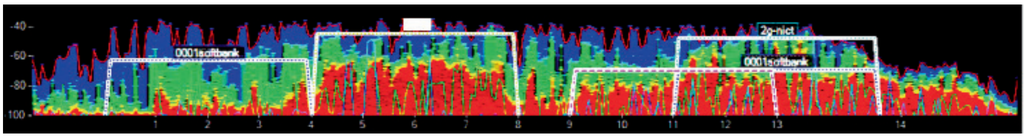

Fig. 2 Effect of residential Wi-Fi access points measured in small and medium-sized factories adjacent to residential areas

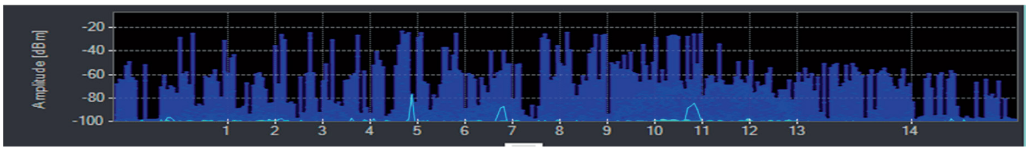

Fig. 3 Effect of manufacturing equipment noise measured in isolated large factories

manufacturing environment [2]–[7]. The research activities reported here (called the "Flexible Factory Project") is an effort carried out under interdisciplinary cooperation between industrial sectors and enterprises [8].

There are two aspects of the challenges discussed: the current status and future challenge of wireless communication in factories, and the requirement specifications for introducing safe and reliable wireless-controlled manufacturing equipment.

2 Challenges of wireless communication technology used in the factory

Through various experiments and reviews, we have come to know that there are three major challenges to use wireless communication technology in the factory.

(1) Dynamic fluctuations in wireless environment

There are many metallic bodies that shield electromagnetic waves in the factory as well as frequent traffic of personnel and vehicles. Such conditions in closed space can easily become a nest of a multipath environment where ephemeral (several milliseconds to several seconds) blind zones appear, disappears and move around. The manufacturing environment is commonly associated with dynamic and unpredictable changes that make operations of a fixed wireless system with a predetermined strategy difficult. Such changes include: set-up changes in processes, on and off of system power, layout changes and introduction of a new production line that takes place in short and random periods (in several hours to several days). All these changes can make the wireless environment transform into a significantly different entity in several months or in several years.

(2) Diversity of wireless environment

Depending on the location of the factory, the wireless environment inside a factory is subject to electromagnetic waves from outside (foreign wave) and necessitates measures against it. Figure 2 shows a screen capture of a 2.4 GHz range spectrum analyzer operated in a factory located near a residential area. The measurement was a part of a frequency usage survey in the 2.4 GHz range. The horizontal axis represents the level of received signal strength and the horizontal axis represents the used channel: the display color becomes redder as the time of radio wave reception becomes longer. The identification name (ESSID) of a Wi-Fi hot spot installed by a telecommunica-

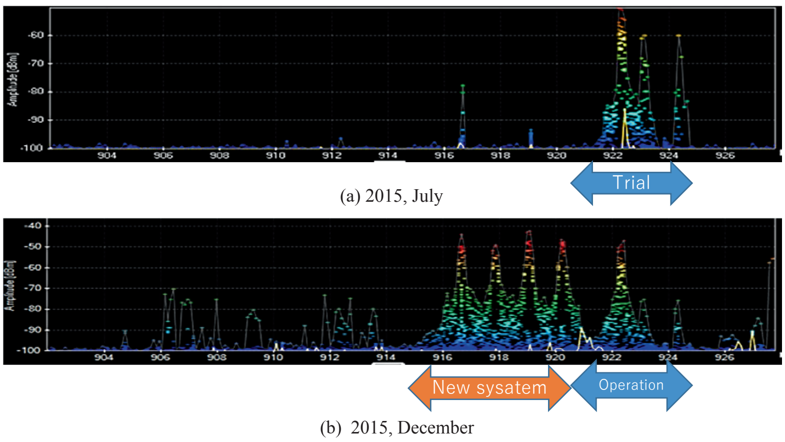

Fig. 4 Temporal change in 920 MHz band usage

tions carrier can be seen on both ends of Fig.2, indicating that the spectrum analyzer received signals stronger than those from the factory's RFID tag system for a wider frequency range. This finding leads to the conclusion that the knowledge of the in-house system does not suffice to evaluate the wireless communication environment correctly, especially if the factory is located adjacent to a residential area.

Productions systems can also be a noise source that disrupts communications. Figure 3 shows a screen capture of a high temporal resolution spectrum analyzer operated in a large factory remote from residential areas. Because the spectrum analyzer was operated in the vicinity of a large processing machine, the screen is filled with strong noise.

As is apparent from these examples, the wireless communication environment in the factory is affected by variety of reasons such as: category of industry, scale of factory, existence of radio shielding objects, location (radio wave incident from outside), and noise from in-house equipment. Such complexity poses a challenge to effective utilization of radio waves in the factory.

(3) Mixed existence of dissimilar systems

It is very rare for all the systems in the factory to be replaced at once. Rather, individually optimized facilities in a system are updated/replaced in a staggered fashion, and each process undergoes stepwise revamping, often resulting in the introduction of dissimilar wireless systems in incremental steps. This situation makes system-wide optimization difficult. It is a general observation that the 2.4 GHz range, thanks to its generic applicability and ease of use, is the first to become congested.

3 Current status of wireless communication in the factory

This section describes some of the actual situations found in the factory. Figure 4 shows two screen captures taken on two separate days ((a) July 2015, (b) Dec. 2015) from a 920 MHz-band spectrum analyzer operated in a large factory located remote from residential areas. The horizontal axis represents the observed signal strength.

The capture taken in Dec. 2015 shows much higher signal strength than in the capture taken in July 2015, indicating significant growth in the usage of the 920 MHz range. Similarly, usage in the 2.4 GHz range and the 5 GHz range also shows a general increase. Note, however, that these two ranges still have space for additional traffic, and no significant change in the rate of packet loss was observed. As is apparent from this example, the radio wave environment undergoes changes with the growth of wireless uses.

Adoption of wireless communication is considered to follow similar steps as did the urban infrastructure with city growth. Therefore, the following discussions will be based on the four-stage model of urban development: (1) Initial stage, (2) Growing stage, (3) Mature stage, and (4) Reconfiguration/Total management stage.

(1) Initial Stage: the scope of wireless communication is limited to exchange of small lumps of data (usually ≦50 bytes) under relatively relaxed punctuality requirements. Typical example includes the data exchange between remote controllers and OK/Not-OK signaling for better visualization of the process status. Stable system operation can be achieved relatively easily by introducing modern manufacturing equipment with wireless communication capability and a suitable wireless communication scheme.

(2) Growing Stage: wireless communication is applied to those devices that exchange data at higher frequency, e.g. sending data and RFID. Allowed time delay ranges

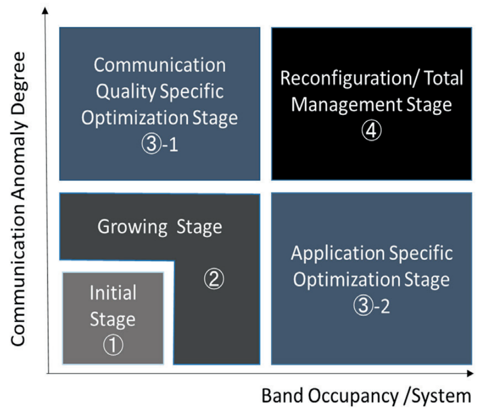

Fig. 5 Four unwire stages

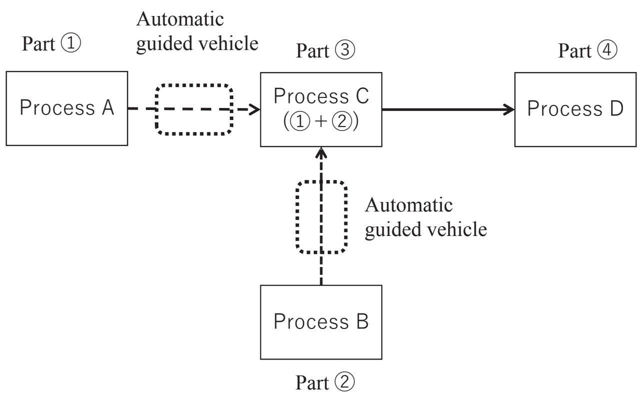

Fig. 6 Typical production line configuration

from several seconds to several minutes.

(3) Mature stage: wireless communication is further applied to much faster control purposes (allowed time delay window: from several hundred milliseconds to several seconds). Such applications include in-line inspection and control of moving vehicles in the factory. In this stage, optimization of wireless communication is considered to progress in two different directions.

(4) Reconfiguration/Total management stage: leading-edge applications are introduced into the factory including: wireless in-house network, in-house IP telephone, regular data exchange for remote control, and real-time image data traffic.

Summarizing the descriptions above, the process toward widespread use of wireless communication can be conceived to advance in the following four stages ("Unwire" stages), which are classified using two parameters: band occupation rate per system, and communication anomaly degree of the communication (See Fig.5).

(1) Initial Stage
(2) Growing Stage
(3) Mature Stage
  (3) -1 Communication Quality Specific Optimization Stage
  (3) -2 Application Specific Optimization Stage
(4) Reconfiguration/Total Management Stage

Machines in the factory are designed individually rather than systematically. The wireless communication function is selected and implemented accordingly.

Each wireless communication system is selected from the following two viewpoints. One of them is the stage

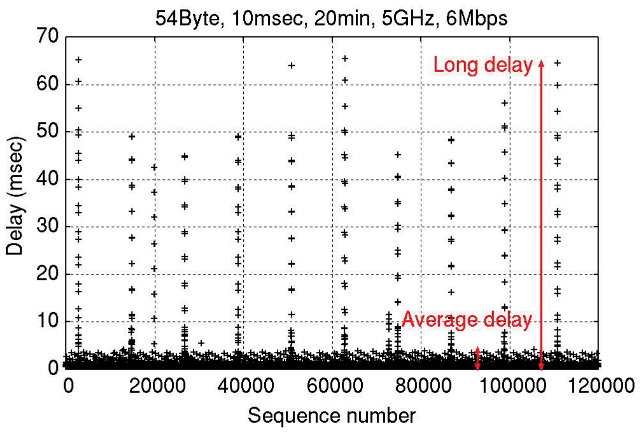

Fig. 7 Data delay observed in automatic conveying machine control channel

characterized by a communication quality-oriented system that places special focus on the avoidance of data loss in specific data packets (③ -1 Quality Specific Optimization Stage), and the other is characterized by the existence of a system that provides leading-edge additional value to manufacturing machines (③ -2 Application Specific Optimization Stage). The following are concrete examples:

③ -1 Communication Quality Specific Optimization Stage

This stage is characterized by the introduction of communication quality-oriented systems typically used to control AGV. They place special focus on loss in particular packets. Design strategy tends to be single-system centric and place focus on the avoidance of data loss and optimization of delay time. The techniques often employed to maintain communication quality include multiple generation and transmission of the same packet.

The following is a concrete example from an on-site experiment. Figure 6 shows the overall manufacturing flow in the factory where our experiment was carried out.

It is a typical "one-by-one production" line, where the line accepts a large part, processes it, and outputs it sequentially on a one-by-one basis. In the figure, two parts (part ① and part ②) are transferred from two separate previous processes into the line by means of automatic guided vehicles. When they are put into the line, they are first joined together into a larger part ③ for subsequent processing. In this particular example, part ② is a large semi-assembly, on which part ① is to be mounted. After undergoing subsequent assembly with other parts, the finished product (part ④) is transferred to the next process.

The devices (a pair of transmitter and receiver) used in the experiment were mounted on racks (height 150 cm) which were arranged in two different arrangements for comparison: line-of-sight (LOS) and non-line-of-sight (NLOS) arrangements. The communication distance for the LOS and NLOS arrangements were approximately 15 m and 25 m, respectively. Wi-Fi used in the experiment was an OpenWRT 4.1.1-based wireless mesh router RMR9000 [9] driven by an ath5 k-based Wi-Fi driver.

The experiment was carried out by sending limited-time broadcast communication from the transmitter to the receiver. The receiver returned the broadcast messages to the transmitter by way of LAN cable to evaluate delay time (both ends used a common terminal clock). The maximum round trip time (RTT) by way of LAN cable amounts to several hundreds of microseconds, which can be ignored in this experiment. Data to control AGVs was sent/received

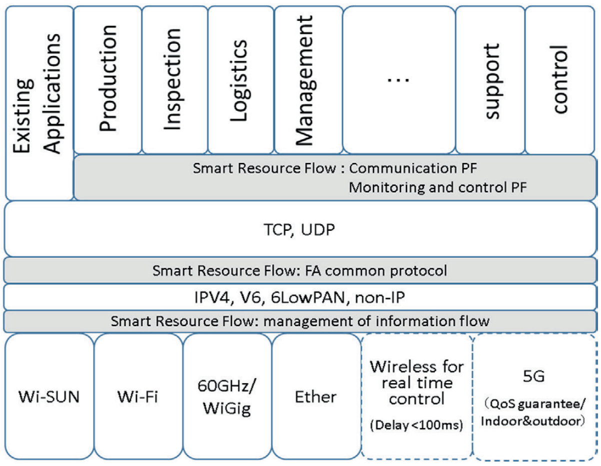

Fig. 8 Wireless platform protocol stack in the proposed Smart Resource Flow (SRF) scheme

using IEEE 802.11 a. The control channel occupation rate for this purpose was several percent at most.

Figure 7 shows the plot of delay time observed while the broadcast data (54 bytes) was sent repeatedly for 20 minutes (transmission rate 6 Mbps, interval 10 ms) using the common channel with AGV control communication.

The broadcast data was successfully sent within 5 ms on average. It is to be noted, however, that lumps of longer than average delays appeared in a cyclic fashion. Analysis of the data revealed that the long delays are synchronized with the signal transmission to control the two AGVs. The occurrence of the delay can be ascribed to the fact that the system sends the start control packet multiple times. This strategy is adopted to make the system more robust against accidental stoppage of AGV, which may cause entire halt of the line. If the number of AGVs increases that share a common frequency band, communication may be disrupted even if the frequency band still has plenty of space as a whole. The same is true for the introduction of a new system adjacent to the existing ones, if it shares the same frequency band.

③ -2 Application Specific Optimization Stage

In this stage, wireless communication is introduced mainly for such purposes as: transition of manual data gathering into an automated system, utilization of hitherto untapped information for new perspectives, improvement of process control and preventive maintenance. This stage generally requires technologies for long-term, large-scale data gathering and analysis. Momentum is gathering for the use of the 920 MHz range (e.g. Wi-SUN [10]) in the factory in line with the accelerated development of small and low-cost sensor devices. However, careful validation in advance is needed before introducing these applications because they may share the same frequency band with existing systems. Shared use of common frequencies may hinder proper operation of existing production systems, and the newly introduced system itself may suffer interference from the other systems, resulting in failure to make the most of its capability.

4 Reliable implementation of wireless communication system in the factory

When a new wireless communication system is introduced into a factory, users regard the following four aspects of the system as important. First, they generally do not favor the system if the internal mechanism is incomprehensible to them, and if it attempts full automation. A part of the reasons for this attitude can be ascribed to the fact that the users are themselves engineers: it is important for them to understand how the system works and locate and identify problems if it steps out of normal operation, at least the system configuration should be transparent enough for them to easily guess what is going on. Second, the system should allow gradual updates rather than complete replacement of the systems in the factory because heavy investment in factories and equipment directly affects product prices. Introduction of a new technology can generally progress only very slowly if it needs total system revamping in the factory. Third, guarantee of continued factory operation is essential. This involves transparency of system internals for the on-site engineers to understand what is going on, and what will take place next, enabling them to recover the system quickly at the time of production line failure.

In view of these considerations, construction of a platform is needed that allows the user to select and fit together the functions in need. The platform should also facilitate partial addition/modification of the existing system. Above all, in the factory, the establishment of an information sharing system is needed to allow the engineers on site to correctly grasp the current situation and assist their decision to update the system without sacrificing continued performance of the production line. NICT has proposed a framework to be implemented in the factory, Smart Resource Flow (SRF), to streamline the flow of all resources (material, power, manufacturing machinery, radio waves, and human resources), and is conducting research and development of a wireless communication-oriented variant, the SRF wireless platform, to make full use of radio wave resources in the factory. Figure 8 shows an overview of the configuration of its protocol stack.

To maintain compatibility with existing applications, the functions are arranged separately in the higher-level and lower-level layer of TCP/IP. The following criteria are also generally understood to constitute an important factor for decision making: ability to sustain stable operation as a whole system and safety of mutual connection (authentication, security).

5 Toward realization of smart factories with the full advantage of wireless communication

This report described the challenges that lay ahead in the passage toward full-fledged utilization of wireless communication technologies in the factory. Based on the results from demonstrative on-site experiments, this report stressed the importance to understand the nature of the communication needs and to select accordingly an optimum communication system that should be determined in consideration of two factors: the environment in which the machinery to be controlled is located, and the functions to be realized by them. To clarify the current situation of the factory, the author identified parameters that characterized various situations in the factory, and used these parameters to define four development stages of wireless communication usage. In line with these definitions, the author is planning to continue research and development of an SRF wireless communication platform and decision support technology, which will help enable even non-specialists in this area to design manufacturing equipment.

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Industrial wireless communication, Ad-hoc network, Sensor network