

INVITED SURVEY PAPER

Survey of RFID and Its Application to International Ocean/Air Container Tracking

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SUMMARY “Internet of Things” (IoT) requires information to be collected from “anything”, “anytime”, and “anywhere”. In order to achieve this, wireless devices are required that have (1) automatic data acquisition capability, (2) small size, (3) long life, and (4) long range communication capability. One way to meet these requirements is to adopt active Radio Frequency Identification (RFID) systems. Active RFID is more advantageous than passive RFID and enables higher data reading performance over longer distances. This paper surveys active RFID systems, the services they currently promise to provide, technical problems common to these services, and the direction in which research should head in the future. It also reports the results of EPCglobal (EPC: Electronic Product Code) pilot tests conducted on global logistics for tracking ocean/air container transportation using active RFID systems for which we developed several new types of active RFID tags. The test results confirm that our active RFID tags have sufficient capability and low power consumption to well support ocean/air transportation and logistics service.

key words: *RFID, ubiquitous, sensor, passive, active, positioning, container, tracking*

1. Introduction

“Internet of Things” (IoT) requires the collection of information from “anything”, “anytime”, and “anywhere” [1]. One of the technologies that meet this requirement is Radio Frequency Identification (RFID) [2]. The functions required of RFID tags depend on their role in the usage scenario. For example, if tags are attached to all objects within a scenario, as in the MIT Auto-ID center cases [3], [4] described later, cost is a more important issue than the functions provided by the tags.

Recently, much attention has been focused on active RFID tags, which use an internal power source to continuously power them and their RF communication circuitry. Active RFID tags have many advantages over passive ones; for example, long range communication. From these points of view, one of the most suitable fields for active RFID systems is managing or tracking large stacks objects (e.g., containers or pallets), where the stack is so large that objects in the middle are hidden from view. We have developed new types of active RFID tags with low power consumption that offer long-life battery operation; they overcome the key

problem of conventional devices. This paper details the results obtained by applying them in international pilot tests of ocean/air container transportation and logistics.

The rest of this paper is organized as follows. Section 2 describes the principle of passive RFID systems and Electronic Product Code (EPC) tags. In Sect.3, we introduce several types of active RFID systems. Section 4 reports present services that employ active RFID systems. In Sect.5, we describe standards for active RFID systems. Sect.6 introduces our new types of active RFID tags and the results of three international pilot tests of ocean/air container transportation and logistics in which our tags are used. In Sect.7, we conclude the paper with a summary of key points.

2. From Barcodes to RFID

Auto-ID discriminates objects automatically, and part of this service is already in use as barcodes or optical character recognition (OCR). The introduction of barcodes was a revolutionary step because it fundamentally changed physical distribution systems.

It is now exceptionally rare to find a product that has no barcode. In addition, optical barcode readers are popular and low in cost. However, barcodes have the following drawbacks:

- They can be read only in line of sight.
- They are easy to spoof.

Thus, barcodes are not suited for identifying individual products. On the other hand, RFID systems can overcome these drawbacks.

2.1 Passive RFID Tags

Wireless tags were originally designed to deter shoplifting rather than to manage products. A simple shoplifting protection system cannot discriminate each product as having a specific ID. However, tags for anti-theft [5]–[7] that can not only distinguish individual products but also transmit the unique data stored in themselves are available at very economical cost. Such tags, which have individual IDs, are called “basic RFID tags”. These tags are called “passive tags” because the power for their operation is supplied by an external interrogator to reduce tag cost.

Figure 1 shows the working principle behind high frequency (HF) passive tags. The power is supplied by a form of electromagnetic inductance between the tags and the in-

Manuscript received August 10, 2011.

Manuscript revised October 21, 2011.

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DOI: 10.1587/transcom.E95.B.773

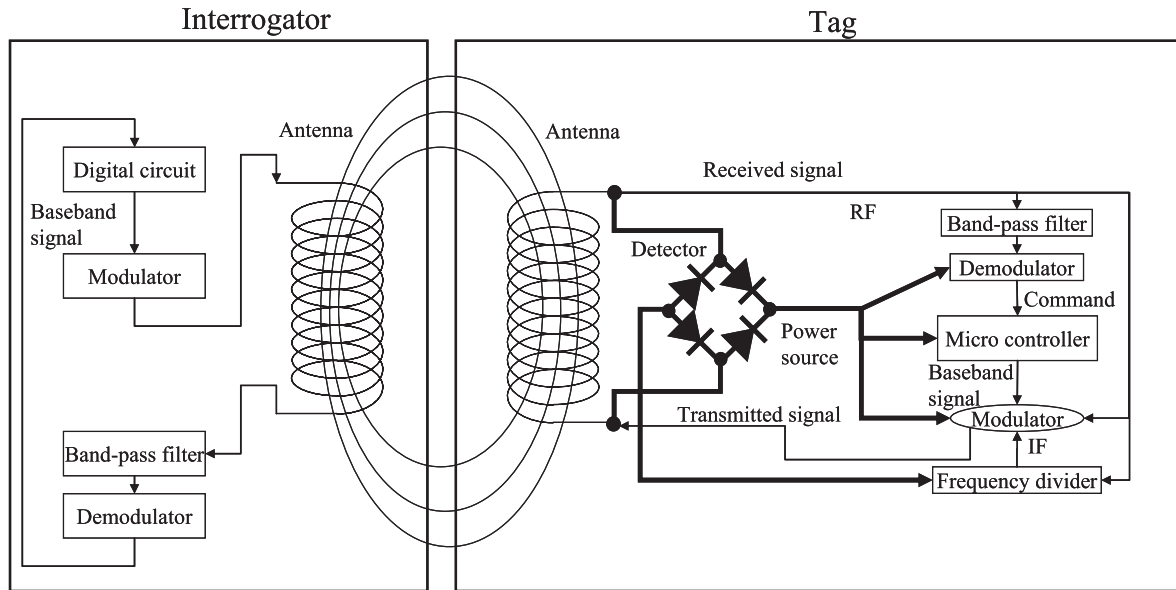


Fig. 1 Basic circuit diagram for passive tag and interrogator.

terrogator. Ultra high frequency (UHF) passive tag systems use higher frequencies than HF tag systems and the coupling between tags and interrogators becomes an electric connection as per the “Germanium Radio” principle.

Interrogators transmit RF modulated waves that combine power transfer with signaling. Tags receive and simultaneously detect the waves and use them for power. Depending on the system, typical tags can have a simple microprocessor and a divider. They recognize received commands and reply with their own assigned ID. Passive tags cannot drive an oscillator because they have no battery. However, the powerful carrier waves are sent by the interrogator and utilized instead of an oscillator. Electromagnetic inductance type tags can only transmit signals over one meter, but they can be used worldwide because the frequencies are standardized from 100–135 kHz (LF: low frequency) and 13.56 MHz (HF).

UHF passive tags offer extended communication distances (e.g., 10 m) using the 915 MHz 4 W system employed in the US.

For passive RFID systems, the European Union (EU) is currently using an 869 MHz 2 W system and Japan is using a 953 MHz 4 W system. However, it is impossible to achieve long communication ranges at under these frequencies because the small antennas of the tags must be specially tuned to each frequency to obtain high gain. The European Telecommunications Standards Institute (ETSI) has tried to switch the frequency to address this issue [8]. For the same purpose, the Japanese government has started to switch the allocated frequency from 915 to 930 MHz. Through these efforts, a common new worldwide band from 915–921 MHz will be created in the near future.

The 2.45 GHz band can be used worldwide, but its maximum communication range is only a few centimeters due to the low commonly allowed transition power

(10 mW/MHz in Japan).

Since passive tags provide only simple functions, and the goal is extremely low cost, chip size is limited to less than a few hundred square micrometers [9], [10].

Many approaches to improving chip performance have been tried [11], [12]. Gains are limited however, since they do not work by themselves; a coil or an antenna is needed to receive the interrogator’s signal.

Each tag’s antenna must be tuned to offer high performance [13], [14]. In actual use cases, the tags are attached to the surfaces of things and tag’s antenna performance is degraded by the change in dielectric constant when it is mounted (especially on the boxes filled with bottles or cans). There are many studies on this issue [15]–[19].

Collision due to simultaneous tag responses is also one of the key problems in RFID systems that prevent identification delays from being reduced, especially when tag density is high. To minimize collision, the interrogators must use an anti-collision protocol. There are many studies on this issue [20]–[22].

2.2 EPC Tags

The Global Standard One (GS1) System (Originally referred to as the EAN.UCC System, with EAN referring to “European Article Numbering” and UCC referring to “Uniform Code Council”) is the most widely used supply chain standards system in the world. Its product barcodes have been used since the 1970s in the food industry, but nothing has restricted their use in non-food industries.

At first, EAN.UCC was willing to apply its own product barcodes scheme to RFID codes. However, their minimum length of RFID codes was determined to be 96 bits because it was necessary to apply them up to the item level.

The MIT Auto-ID Center was initially founded in 1999

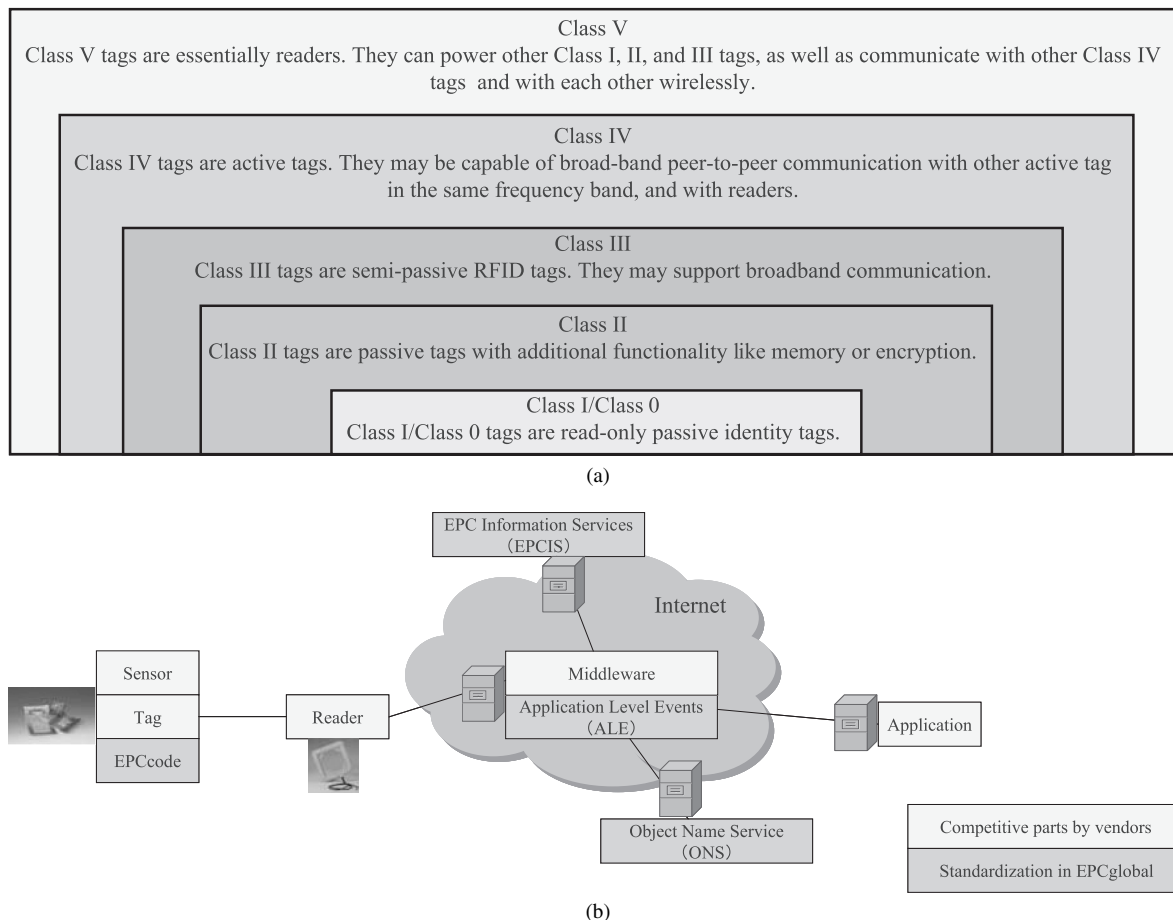


Fig. 2 (a) Classes in RFID. (b) Standardization of EPCglobal architecture framework.

to develop an open standard architecture for creating a seamless global network of physical objects. The center thought that an important factor in tag popularity up to item level was low cost. In 2001, the center proposed the “Class-1” passive RFID tag concept with a write-once function [23].

The Class-1 tag concept was a “five-cent tag”, which sacrificed security and rewritability. This five-cent price is now becoming realistic with mass production. Furthermore, it adopts UHF tags, which can reach longer distances than HF tags. The plan was that after the benefits of RFID systems had been recognized, enhanced tags could be created to allow various new services to be introduced. This is shown in Fig. 2(a) as follows.

- Class 2: Secured passive RFID tags with read-write function
- Class 3: Semi-passive RFID tags
- Class 4: Active RFID tags, and
- Class 5: Active RFID tags with multi-hop (multiple hopping) function

After EPCglobal took over EPC standardization activities from MIT Auto-ID center in 2003, work has advanced rapidly. EPCglobal was founded by EAN.UCC [24].

In 2006, through a tie-up between EPCglobal and the International Organization for Standardization (ISO), the

air-interface protocol for “Class-1 Generation-2” passive RFID tag was authorized as the ISO standard (ISO/IEC 18000-6 Type C) [25]–[27].

The unique ID of an EPC tag is known as an EPC code. It is up to 202 bits in length (GIAI: Global Individual Asset Identifier). EPCglobal defines the EPCglobal Architecture Framework (Fig. 2(b)). Each module has been standardized. For example, object name service (ONS) [28] is a service that makes detailed information accessible through networks based on the ID and offers the information to locations that require it after rapid certification via the network. EPC Information Services (EPCIS) [29] allows various clients to capture and access EPC-related data and the business transactions with which that data is associated. Many studies related with EPCIS, such as improving performance [30], [31], extending functions [32]–[34], and usages [35]–[40] have been carried out. The role of the Application Level Events (ALE) interface [41], [42] within the EPCglobal Network Architecture is to provide independence between the infrastructure components that acquire the raw EPC data, the architectural component(s) that filter and log that data, and the applications that use the data. ALE extension [43]–[47] and usages [48]–[50] have been studied.

In 2005, Wal-Mart Stores Inc. asked top suppliers

to use case-level or pallet-level RFID tagging to prevent shoplifting [51]. This was the first case of using EPC tags for large usage models.

Since then, many types of RFID systems have appeared. In particular, the power consumption of tags has been substantially improved. EPC tags have evolved to the “Class-1, Generation-2” category that has long reading range and improved reading rate.

Wal-Mart began to release EPC tags to track individual pairs of jeans and underwear in 2010 [52]. These tags enable Wal-Mart employees to quickly learn, for instance, the sizes of jeans that are missing, with the aim of ensuring that shelves are optimally stocked and that inventory is tightly watched. It is predicted that Wal-Mart’s “tipping point” will drive RFID prices lower if it is successful.

Boeing, Fujitsu and Alaska Airlines are working together to develop a service to enable greater efficiency in aircraft maintenance operations in 2011 [53]–[55]. Part information — such as serial numbers, manufacturing date, and maintenance history, contained on tags — significantly reduces airlines’ operating costs.

The Ubiquitous ID center, the standardization organization for RFID in Japan, also has plans to simplify tag functions to decrease cost. It has proposed its own 128-bit ID (UCODE) [56], [57], and its plans for data distribution are along the same lines as those of the Auto-ID center.

2.3 Problem of Privacy

Stores that sell small, expensive goods that are easy to shoplift such as CDs, videotapes, and DVDs already use wireless tags to deter shoplifting. However, the tag functions are disabled or the tags are removed from the goods when the goods are purchased. Below, we explain the two main reasons for disabling the tag functions upon purchase [58], [59].

First, if the tags are affixed to all goods and their functions continue to work outside the store, then anyone with a reader can obtain information about those goods. The retailers had to treat this not as a simple technical issue, but as a social issue with significant ramifications regarding customer satisfaction. Currently, the focus of introducing RFID is on increasing the efficiency for retailers or manufacturers. The main obstacle to this system is expected to be the issue of the invasion of customers’ privacy. If this system does not readily provide significant advantages to the customers, they are unlikely to accept it.

Several proposals to ensure privacy protection have been put into use. One of them is to use the “Kill” command feature proposed by the MIT Auto-ID Center. Each tag has a unique password, and when it receives the password, the tag erases itself. This function is useful in protecting customer privacy, but it raises some further problems. On the other hand, the “encryption” function described previously will give tags and readers a certain degree of security. While several encryption schemes have been proposed, none is a complete solution. Some of them allow tag output to include

relatively constant information, need data to be rewritten to the tag memory to avoid tracking, or require users to make conscious decisions.

For active tags, these restrictions are not as strict as for passive tags. For example, the active tags in car keys used for wirelessly locking and unlocking the doors from a short distance use the code hopping technique. Anyhow, the privacy issue is not simply technical but has a human side. Solving it completely will take a considerable amount of time.

3. Active RFID Systems

As we discussed in Sect. 2, passive tags must be put on all products. They must have a short range and simple functions to keep the cost low. The cost of a passive tag is currently under \$1. Now, let us assume that a tag is affixed to each delivered or stocked carton, rather than to each individual product. In this case, a tag cost of several hundred dollars would be acceptable if one carton held a hundred items and the tag were reused ten or more times. Of course, in this case, it would not be possible to trace each product and detect it as having been shoplifted. However, a tag cost of several hundred dollars would allow an active RFID tag to be used. It would then be possible for the tag to contain a sensor, function as a reader, or record data in itself. Moreover, the range could be extended to approximately one kilometer if a license were obtained. This would not involve privacy problems because the tags would never fall into the hands of other persons.

3.1 Simple Active RFID Tags

The simplest active tags only transmit IDs periodically and do not have a receiver. Simple active tags normally have minimal functions to extend the battery life as much as possible. For example, they ensure that IDs are only transmitted for asset management or for pallet recognition. Therefore, their use yields inexpensive sensors that consume very little power, such as vibration sensors and thermal sensors, to be integrated into simple, active RFID tags. In such cases, these sensors transmit only single bits of information. The effect of sensor inclusion on battery life is very slight if they are integrated into simple active tags. Figure 3 shows an example of a simple active tag whose only function is to transmit its ID [60]–[62]. The battery will last approximately five years if it transmits its ID once every ten seconds based on the regulations for low-power radio ($500 \mu\text{V/m}$ at 3 m). This power level, called “bijaku”, does not require any license or certification in Japan.

3.2 Semi-Passive RFID Tags

Simple active tags do not have a receiver function. To implement this function, one proposal uses an unpowered receiver and waits until it receives a signal, in the same way that a passive tag does, and then uses onboard battery power

to transmit its ID and data. This type of tag can be used to track containers or monitor the air pressure of car tires.

Generally speaking, the communication range between a passive tag and an interrogator is defined by the power transfer efficiency. On the other hand, semi-passive tags have a battery to provide power but do not have an oscillator [63], [64]. Consequently, the communication range can be extended. Semi-passive tag components are low power digital parts and battery life is estimated as about 10 years. In spite of these benefits, there are very few semi-passive systems in actual use.



Fig. 3 Simple active RFID tag and reader [60], [61].

We estimate that the cost, range, and size of semi-passive systems lie somewhere between those of passive and fully active systems.

3.3 Sensor-Equipped RFID Tags

Sensor-equipped RFID tags have the same functions as simple active RFID tags. In addition, they have several sensors and a large memory for recording sensor data [65]. Tags have been proposed for monitoring air pressure, temperature, vibration, and other factors. In order to measure these values, analog-to-digital (AD) conversion is required. Though there is little difference between these tags and simple active RFID tags, they decrease battery life and their cost is slightly high.

These tags have been used for the following purposes:

- 1) Temperature monitoring of food [66],
- 2) Door status, acceleration, and temperature for valuable cargo such as very expensive and sensitive parts [67], and
- 3) Health data for elderly people for healthcare shown in Fig. 4 [68]–[70]. A number of RFID-based healthcare systems have been studied [71]–[73].

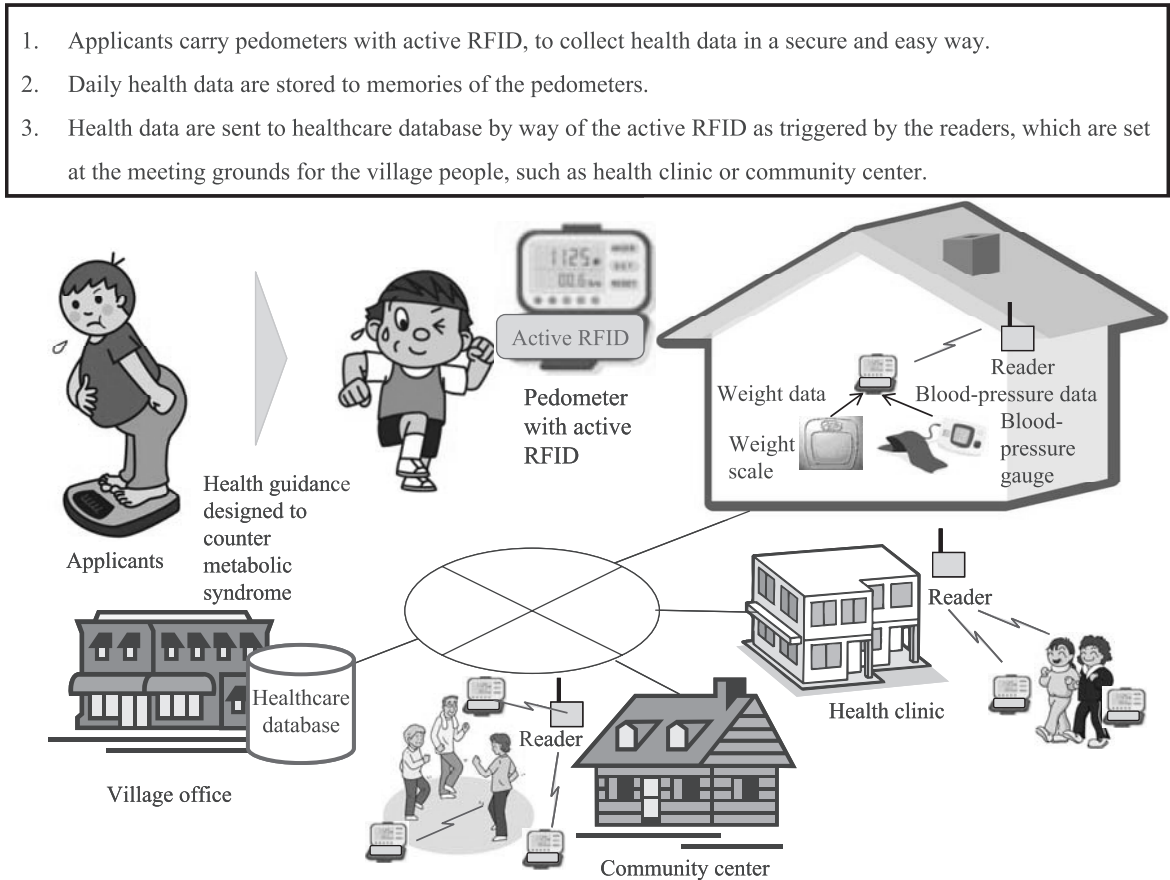


Fig. 4 Health care experiment using active RFID tags [68]–[70].

3.4 Multi-Hop RFID Tags

The most widely used wireless communications standard for wireless LANs is IEEE802.11; it allows communication over a few hundred meters when there are no obstacles between the terminals [74]. However, this standard has some drawbacks if it is used for RFID. These drawbacks are as follows:

- (i) High power consumption caused mainly by using high frequencies; the aim is high data rates rather than long range.
- (ii) High probability of interference because many users already use such frequencies.
- (iii) High cost, which will be hard to decrease, because an expensive microprocessor is required by the complex communication methods.
- (iv) Long link connection establishment time necessitated by the advanced OS used.

It is of course possible to use a wireless LAN for RFID tags despite the short life or expense. For these reasons, a number of ideas have been proposed to simplify IEEE 802.11 standards. Bluetooth [75], [76] was initially planned to be a very simple protocol. However, as it was changed to accommodate general-purpose use, many functions were added to it. Its power consumption is becoming much higher than originally planned because of its complex signal processing. The IEEE802.15 standard has been developed to address problems such as systems whose power and data rates are lower than those of wireless LAN systems [77]. The “Zigbee” standard, one of the solutions given in IEEE802.15.4, was developed for very small sensor networks [78], [79] and used for RFID reader networks [80], [81]. It can support multi-hop functions with lower power than that given in IEEE802.11. The IEEE802.11 standard

mentions many chips that include the Media Access Control (MAC) function.

Recently, smart grids have become one of the most widely discussed topics in this field [82], [83]. They appear to be suitable for Zigbee applications. The Zigbee standard may be applied to connectors among outdoor power meters, but the IEEE802.15 Smart Utility Networks (SUN) standard [84] is starting to be applied with focus on smart grids [85].

Several protocols for multi-hop RFID have been proposed in order to extend the coverage [86]–[88].

4. Present Services Using Active RFID

As mentioned above, appropriate functions must be selected for each application. Figure 5 shows present RFID services [89]. It is necessary for all services to know “when”, “what”, “where”, and “result”. The equipment should consume low power. Since readers are connected to networks, the application can determine “when” by checking the time tags are read. We can easily handle “what” by assigning a unique ID to each tag. The difficult issues pertain to “where” and “result”.

4.1 Tracking Systems

The most simple and important demand of RFID logistics is tracking cargo. Systems that supervise cargo tracking can be achieved by combining multiple cells.

Active tags transmit beacon signals; the existence of a tag within a cell is checked via its beacon. If the cargo with tag enters another cell, the moving history can be recorded.

Martinez-Sala et al. proposed a tracking system for returnable packaging such as cases, boxes, pallets and containers in the supply chain [90]. Their requirements for active RFID tags were long range reading capability, temper-

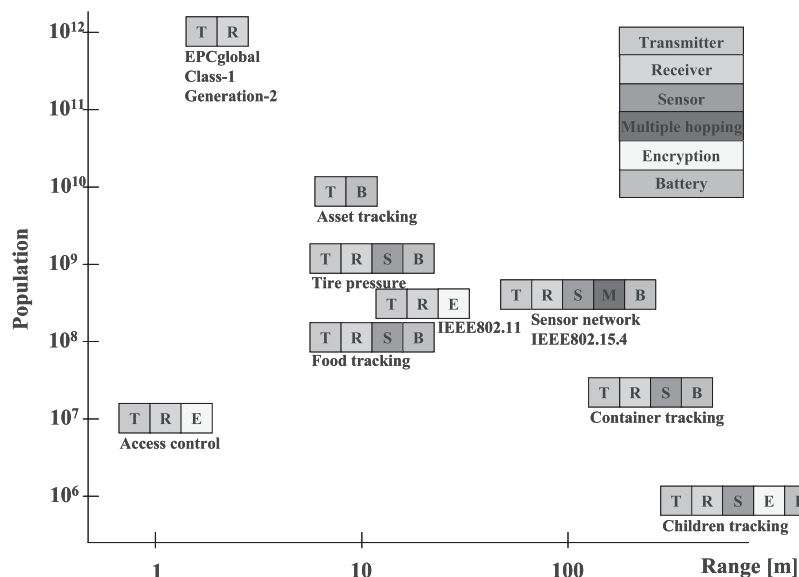


Fig. 5 Functions of various RFID systems.

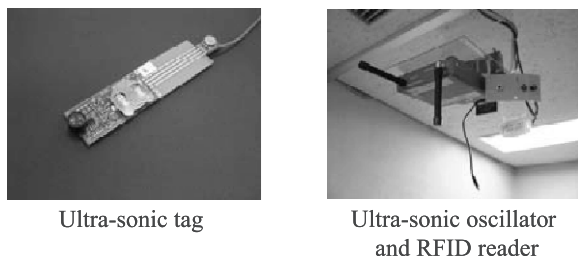


Fig. 6 Ultra-sonic tag, oscillator, and RFID reader.

ature monitoring, and nearly 100% success reading capability. They focused their attention on active RFID system cost, but not to lifetime.

Yoon et al. proposed implementing an active RFID system for harbor logistics (Container tracking) [91]. Their requirements for active RFID tags were long range reading capability and E-seal function (monitoring the opening and closing of containers). They also focused their attention on active RFID system cost, but not on lifetime.

Bhanage et al. proposed an asset tracking system. Since their requirements for active RFID tags were low cost and long life, they used simple active RFID tags [92].

4.2 Position Estimation/Real-Time Location System (RTLS)

Global positioning system (GPS) is widely used outdoors as a position estimation tool. It estimates the position from the arrival times of radio signals transmitted from satellites. Its accuracy inherently decreases significantly indoors because the radio signals from the satellites are attenuated and reflections from walls or floors have a detrimental effect. Thus, indoor RTLS is one of the popular demands of users.

There are some positioning approaches based on triangulation (angle-of-arrival (AOA), received signal strength (RSS), time-of-arrival (TOA), and time-difference-of-arrival (TDOA), etc.). More detailed information is given in [93]–[97].

As an example of indoor positioning based on the TOA technique, Ultra Wide Band Impulse Radio (UWB-IR) can be used due to its high resolution in the time domain [98], [99].

Furthermore, if ultrasonic waves are used instead of using radio waves, propagation speed goes down and we can readily utilize Micro-Processing Units (MPUs) with low clock speed. MIT's Cricket [100], [101] and UCLA's iBadge [102], [103] estimate indoor position by using the difference in the transmission rate of ultrasonic waves compared to that of radio waves.

Furthermore, MSU's LANDMARC improves the overall accuracy of locating objects or persons by utilizing the concept of reference RFID tags [104].

We have also developed an indoor position estimation system in which the objects incorporate the RSS technique [105] or ultra-sonic tags shown in Fig. 6 [66]. Experiments showed that the positioning error of the RSS system was

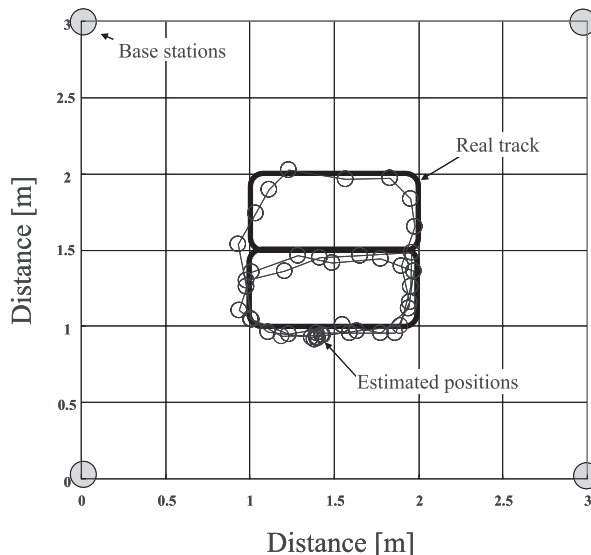


Fig. 7 Position estimation using ultra-sonic RFID tags.

about 2.9 m in an 8 m \times 12 m office room. On the other hand, the positioning error of an ultra-sonic system was estimated as being only a few cm in the 3 m \times 3 m area shown in Fig. 7. The use of CR2032 batteries yields a tag lifetime longer than one year.

5. Standards and Regulations for Active RFID

Many standardization approaches for RFID systems have been considered. GS1 prepares space for serial ID numbers. However, it cannot easily resolve protocol issues, especially for active RFID systems.

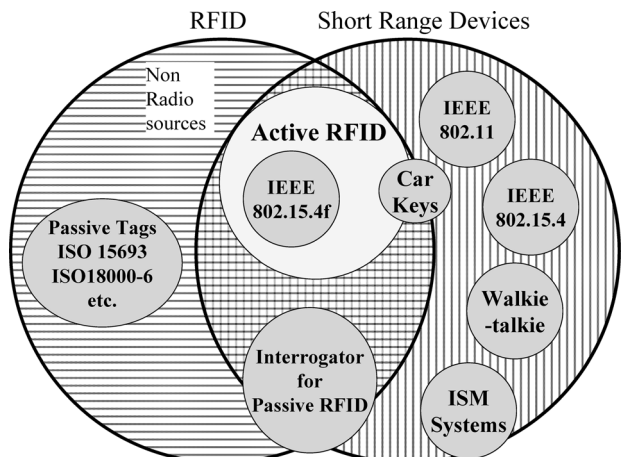
Figure 8 shows functional RFID categories for short range devices. The short range device category is defined as that in which common use is achieved by low power radio systems, which depends on national regulations. In this category, an official license is not usually required; instead, mere certification suffices.

Assuming typical logistics services based on RFID, tags are attached to cargo to report their status (i.e., where and what they are).

It is easy to understand that tags must be attached to particular cargos. This means the tags travel with the cargos around the world. Fortunately, if passive tags are used we do not need to be concerned about Radio Regulations (RR). This is because passive tags are defined as “non radio sources” since they cannot transmit without the use of an interrogator.

Only the interrogators are regulated by RR. If the cargos move from Japan to the US, a 953 MHz interrogator certified by Japanese RR is used in Japan and the other 915 MHz interrogator certified by Federal Communications Commission (FCC) is used in the US to read tags.

On the other hand, if simplest beacon active tags are attached to the cargos, the operation frequency must be chosen carefully because the active tags transmit periodic beacons



ISM: Industrial, Scientific, and Medical

Fig. 8 RFID categories for short range devices.

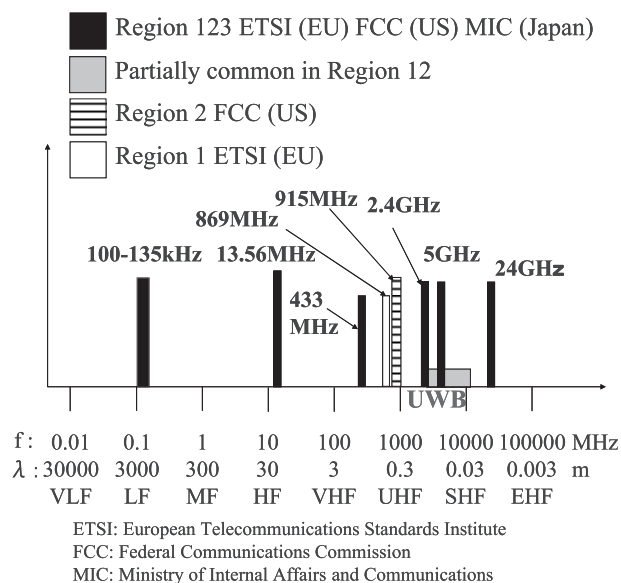


Fig. 9 Frequency allocation map.

anywhere without commands. This means active tags must have licenses for all countries that they pass through.

Figure 9 maps frequency from the viewpoint of locality. Here, UWB is defined as 3–10 GHz. Permitted conditions (channel mask, radiation power, usage, mandated data rate, etc.) differ among regions. In particular, Japanese RR prohibits outdoor usage in this case.

There are six bands for worldwide use. Active tags are expected to be small in size and to have long communication range. These demands limit the frequency. LF (100–135 kHz) and HF (13.56 MHz) applications require huge TX antennas and millimeter wave (24 GHz) applications require clear line of site propagation conditions. Active tags’ frequencies should be selected from among 433 MHz, 2.4 GHz, or 5 GHz to meet worldwide usage demands.

EPCglobal has been trying to establish recommenda-

tions for active tags. As a first step, they collected requirements from all users who were interested in using active RFID. Among these users, container carriers, air cargo carriers, aircraft makers, and chemical companies were particularly helpful in providing their requirements.

EPCglobal defined a baseline functional requirement as a foundation for active tags. It also identified particular functional groups for specific user scenarios. These groups form additional requirements that are an extension of the baseline capability. Active tags are not limited to any one of these functional groups and can be inclusive of some or all of them. These groups and their definitions are listed below.

- A) Sensor Tags: These require sensor integration and additional data capacity for data storage.
- B) Data Rich Tags: These require extended memory for user data.
- C) Location Tags (Types 1, 2, and 3): These require real time location capability and Types 1, 2, and 3 are identified by the spatial resolution offered. Types 1, 2, and 3 have <1 m, <3 m, and <10 m location resolution, respectively.
- D) Multi-Communication Tags: These support multiple communication protocols.

The so-called “almighty tags” must have all these functions. There is only one way in which the four types of tags can be merged in one body; it can be described as 1 W TX power, 1 GHz bandwidth with 1 GB memory, and 100 sensor types. But in this case, it is too expensive and the battery life is too short.

In the process of making EPC recommendations, it is difficult to satisfy user demands. The final recommendations will be issued within 2011.

The IEEE802.15.4f standard was written in 2009 to focus only on the simple functions of active RFID systems [106]. The people who wrote the standard were very familiar with the EPC discussions but decided to ignore the high functional capability of the EPCglobal system. The 433 MHz and UWB formats were discussed. The final draft was completed in Nov. 2010 and a sponsor ballot is now being prepared.

Table 1 shows the applicable existing standards for active RFID. The 2.4 GHz, 5 GHz, and 433 MHz bands are worldwide bands, but there is no common UWB channel. The 2.4 GHz and 5 GHz bands are already being used as worldwide bands. The dominant usage case is high speed WiFi. The IEEE802.15.4 standard shows another use case of the 2.4 GHz band, which is low speed applications within small areas (i.e., personal area networks), known as “Zig-bee”. This is defined as 868 MHz for the EU, 915 MHz for the US, and 950 MHz for Japan. These three frequency bands are regional bands. The IEEE802.15.4 standard stipulates 2.4 GHz for worldwide usage. The IEEE802.15.4a chirp spread spectrum (CSS) and ISO24730-2 standards both define RTLS frequency as 2.4 GHz [107], [108]. Under these standards, precise tag position can be calculated by detecting the phase differential between the base stations. These two systems require wide bandwidth (20 MHz)

Table 1 Existing standards applicable to active RFID systems being discussed in EPCglobal.

Air Interface Protocol	Frequency	Data rate	FCC (US)	ETSI (EU)	MIC (Japan)	Purpose	Power Consumption	One way
IEEE 802.11.g	2.4GHz	Up to 54Mbps	Yes	Yes	Yes	Rich data exchange	Largest	X
IEEE 802.15.4	(1) 2.4GHz	Typically 250Kbps	Yes	Yes	Yes	Sensor network	Small	X
	(2) 868MHz		No	Yes	No		Small	X
	(3) 915MHz		Yes	No	No		Small	X
	(4) 950MHz		No	No	Yes		Small	X
IEEE 802.15.4a CSS	2.4GHz with 20MHz Bandwidth	1Mbps	Yes	Yes	Yes	Real time location	Small	X
ISO 24730-2	2.4GHz with 20MHz Bandwidth	60Kbps	Yes	Yes	Yes	Real time location	Very small	O
ISO 18000-7	433.92MHz	27.7Kbps	Yes	Yes	Yes for international transport	Simple active RFID	Small	X
IEEE 802.15.4a UWB	3-10GHz	At least 1Mbps	Yes for some channels	Yes for some channels	No	Real time location	Smallest	O
IEEE 802.15.4f	(1) 433MHz	31.25Kbps/250Kbps	Yes	Yes	Yes for international transport	Simple active RFID	Very small	O
	(2) 6-10.6GHz	1Mbps	Yes for some channels	Yes for some channels	No		Smallest	O

to maintain accurate position in spite of the small packet size. Both IEEE802.15.4 UWB and IEEE802.15.4f UWB specify that very short pulses should be transmitted to measure the trip time of signals. A 500 MHz bandwidth is needed to measure position precisely. The UWB data rates must be faster than the 50 Mbps data rate in Japan. These low speed RTLS UWB systems can not be used in Japan. ISO18000-7 and IEEE802.15.4f use 433 MHz. ISO18000-7 defines a two-way system [109]. Interrogators transmit periodic wakeup signals and if tags detect these commands, they send signals back to the interrogators. IEEE802.15.4f specifies the simplest beacon tag. It does not define the communication sequence in detail. 433 MHz must be used for international logistics purposes in Japan.

6. Application to International Ocean/Air Container Tracking

We are focusing on the development of an active RFID system that can be applied to international ocean/air container tracking.

Figure 10 shows the container traffic at the world's busiest container seaports [110]. In 2008, the world's total container traffic was around 500 million TEU, and the top five container seaports were all located in Asia. "TEU" stands for "Twenty-foot Equivalent Unit," i.e. a 20-foot (about 6.1 m) long shipping container.

RFID technology has attracted attention as a means of ensuring security and transparency in cargo transportation.

This technology was developed in the wake of some very unfortunate incidents (e.g., the "gyoza" dumpling tampering scandal that rocked Japan as a whole in 2008) [111].

To address this problem, we have developed several types of 433 MHz active RFID tags and performed many experiments on them under actual environments. This section describes the results we obtained in using these tags to conduct international pilot tests on ocean/air container transportation and logistics. The pilot project comprised the following three phases and active RFID tags were applied to each of them:

- Phase 1 (Jan-Feb. 2007): Ocean container tracking from Hong Kong to Japan.
- Phase 2 (Jan. 2008): Air cargo tracking and air pallet management from China to the US via Japan.
- Phase 3 (Dec. 2008–Feb. 2009): Fifty ocean containers and 3,000 pallets (fully automatic reading in real logistics environment) from Japan to the Netherlands.

These pilot tests used active tags licensed in Regions 1, 2, and 3 (i.e., Europe, America, and Asia) as defined by ITU-R. The test results confirmed that the 433 MHz standard could be used around the world.

Each phase was operated using actual international logistics lines, and the authors supplied several types of active RFID tags for attachment to containers or pallets. We also provided readers and other tag control equipment. From the viewpoint of active RFID tags, the pilot results confirmed that our active RFID tags have sufficient capability to han-

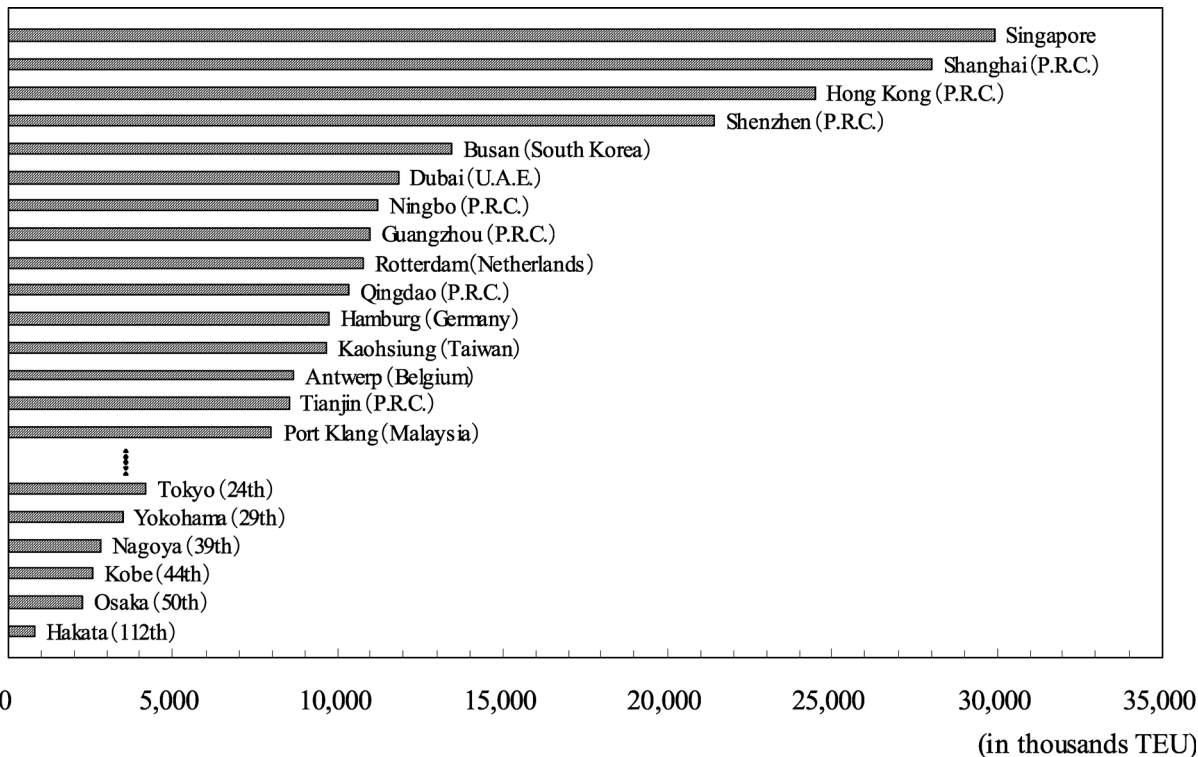


Fig. 10 Container traffic at the world's busiest container seaports (Year: 2008).

dle ocean/air transportation and logistics service.

6.1 Pilot Phase Outlines

These pilot tests were sponsored by the Industry Action Group of EPCglobal's Transportation and Logistics Services Division. The objective of the pilot tests was to verify the interoperability among different vendors' equipment, such as RFID tags, readers, and software used in experimental systems on actual logistics lines [112]–[115]. In terms of effectiveness, the results should appeal to everyone for whom international logistics is a topic of concern (e.g., consignees, shippers, and customs agents).

The pilot phases are outlined below.

6.1.1 Phase 1: Ocean Container Tracking

The first pilot test phase demonstrated how RFID can be applied to transportation and logistics from a terminal port in Hong Kong to a port in Japan [116]. This phase evaluated the use of both active and passive RFID tags for the sea shipment of cartons and containers between the two regions.

Goals of this phase included:

- Demonstrating interoperability among multiple trading partners and service providers in a global supply chain,

- Utilizing EPCIS and standards-based RFID technology components,

- Enabling visibility at critical events across the supply chain,

- Testing and developing requirements for active RFID

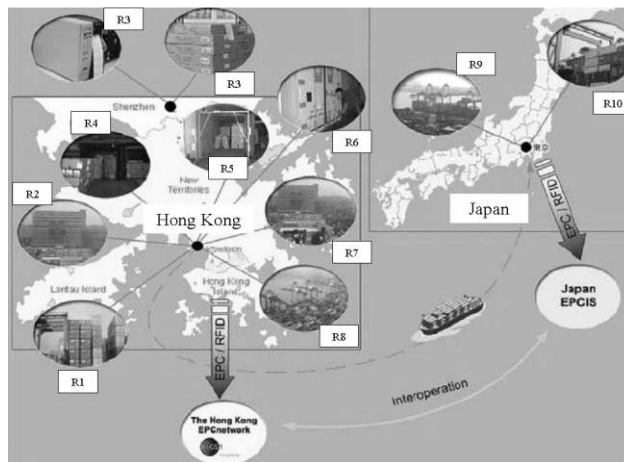


Fig. 11 Phase 1 pilot route map.

and integration with associated technology,

- Identifying standards opportunities for transportation and logistics providers, and

- Creating an environment of open results and information sharing for the EPCglobal member community.

Figure 11 shows the route map of the Phase 1 pilot. We targeted transportation from Hong Kong to Ohgishima (Kawasaki City) near Tokyo port during January and February 2007.

The logistics flow in the pilot test was from the shipper's warehouse in Hong Kong to the consignee's warehouse in Kawasaki, with the products being loaded into an ocean

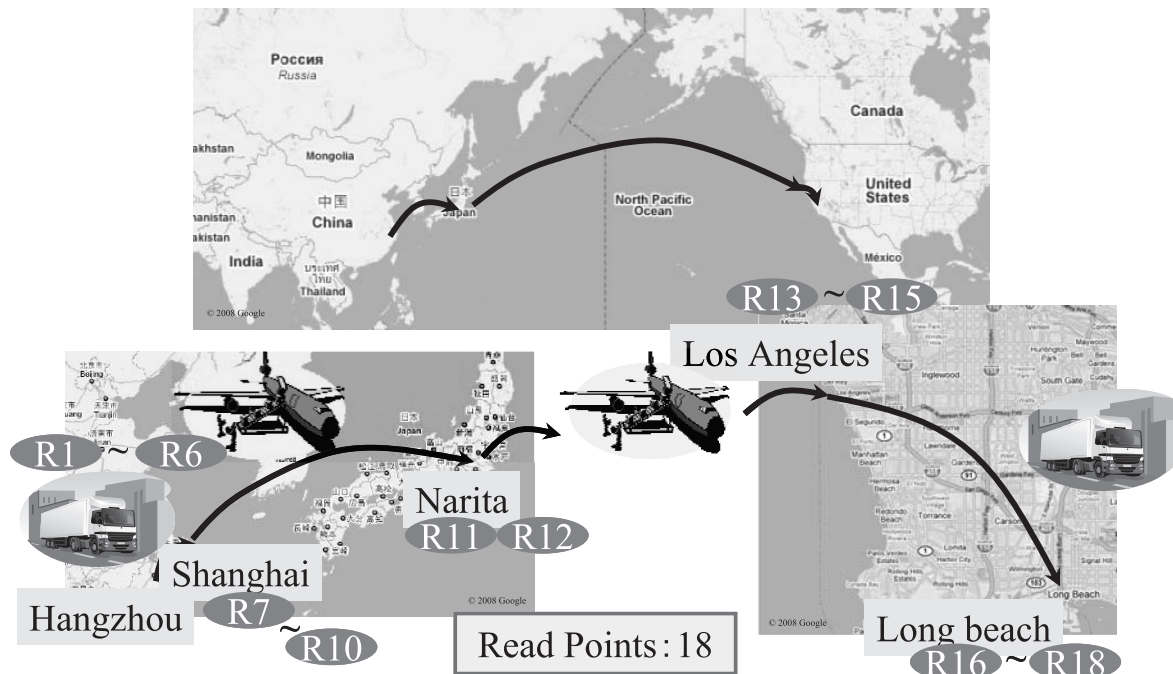


Fig. 12 Phase 2 pilot experiment map.

container at a Hong Kong warehouse. Active RFID tags were attached to empty ocean containers at the container pool beforehand. All products were labeled with passive RFID tags before loading them into the container. In Fig. 11, “Rx” indicates the “read points” where active and/or passive RFID read operations were performed. The term “read operations” refers to such things as transferring data from tags to readers, controlling access to active tags, uploading data to the system via a network, and aggregating or disaggregating active and passive tags. The network in this phase was constructed by a wireless LAN and mobile phones.

Our active RFID tags reported container door status and information when the container passed each gate, and stored temperature and vibration data in the tag memory was read out at the end point of the experiment.

6.1.2 Phase 2: Air Cargo Tracking and Air Pallet Management

The second phase of the pilot tests demonstrated interoperability among multiple trading partners and service providers in a global supply chain. This phase was completed in January 2008. From the factory in Hangzhou, China to the distribution center in Long Beach, California laptop computers were transported via air. The products were transported to Shanghai by truck. From Shanghai to Los Angeles, they were transferred by air, with transshipment in Tokyo. Finally, they were delivered from the Los Angeles airport to the consignee’s warehouse in nearby Long Beach by truck as shown in Fig. 12.

Figure 12 shows the route map. The key point of the experiment is that whilst in the plane no radio signals of

any kind could be emitted. Our active RFID tags can halt all emission upon receiving control signals. More detailed information is given in [117].

6.1.3 Phase 3: Ocean Container and Pallet Tracking

The Phase 3 pilot test was executed from December 2008 to February 2009 for transportation via an ocean container line from Tokyo in Japan to Amsterdam in the Netherlands. There were several notable points in this phase as compared with the first two phases, i.e., (1) automatic reading operations were performed at all read points during transfer, (2) all read points were networked during the pilot, (3) total time spent in transport exceeded one month, and (4) the number of items transported was very large, i.e., 39 containers carrying 1900 pallets.

Figure 13 shows the outline and system configuration of the Phase 3 pilot. Two types of active RFID tags were used in this pilot, i.e., pallet tags and container tags. The pilot started at an empty container pool near Tokyo port where container tags were attached to empty containers. Next, the containers were transported to the shipper’s warehouse located about 30 km from the empty container pool. The products were loaded onto pallets at the warehouse, and a pallet tag was attached to each pallet. The pallet and container tags were aggregated when loaded into the containers. The containers were then transported by truck to Tokyo port and loaded onto the vessel.

After a 25-day voyage, the vessel arrived at Amsterdam port. The containers were then transported by truck to the consignee’s warehouse, where the products were unloaded and the pallet and container tags were disaggregated.

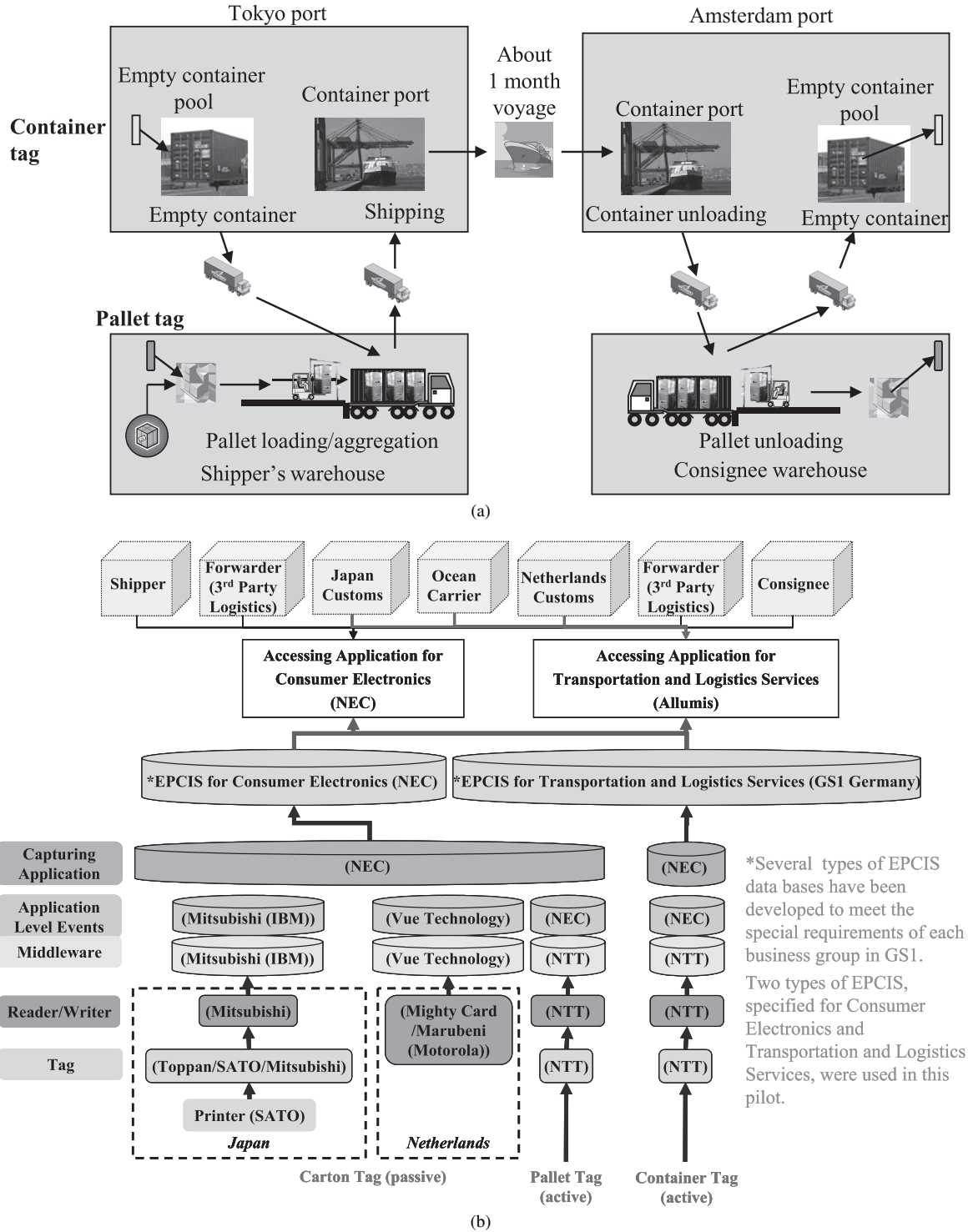


Fig. 13 (a) Phase 3 pilot transportation outline. (b) Phase 3 pilot system configuration [115].

Finally, the empty containers were transferred to an empty container pool near Amsterdam port.

There were six tracking points, four in Japan and two in Holland. The four points in Japan were the empty container pool at Ohi, a warehouse in Funabashi, an NYTT (Nippon Yusen Tokyo Terminal) gate, and an NYTT yard. The two points in Holland were the Amsterdam port and a warehouse

in Amstelveen.

6.2 Active RFID Tags for Each Pilot Test

This section describes the actual active RFID systems used in each pilot.

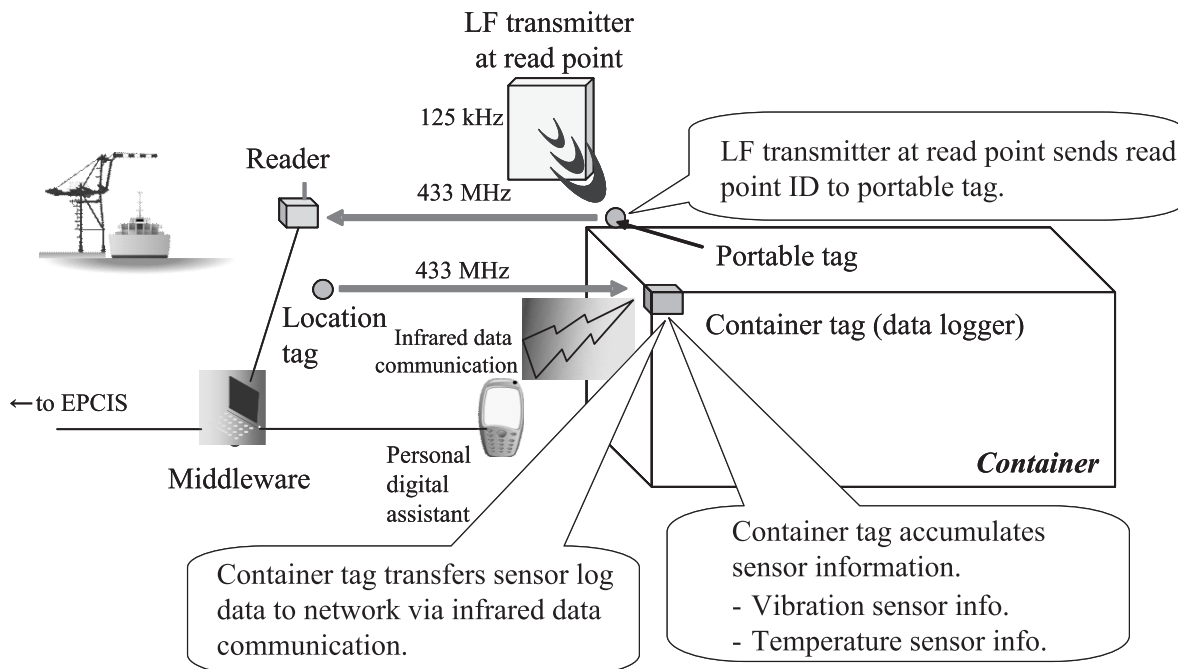


Fig. 14 Phase 1 system configuration overview.

6.2.1 Frequency Selection

It was very important that all pilot phases joined two or more countries that had different radio regulations. We chose 433 MHz for the main radiating frequency from the tags to the readers. This frequency has already been accepted for active RFID use in many countries such as the EU and the US. In Japan, the 433 MHz frequency was permitted only for international transportation in 2006.

There exists another frequency that can be used internationally, i.e., 2.4 GHz. However, for purposes of avoiding interference, we chose not to use this frequency since 2.4 GHz radio is already being widely used for wireless LANs.

In addition to 433 MHz, we used other radio frequencies for tag control, i.e., 125 kHz for Phases 1 and 2 and 13.56 MHz for Phases 2 and 3.

6.2.2 Phase 1: Ocean Container Tracking

Figure 14 shows the system overview. We achieved pseudo-two way tags by using A) LF transmitters at read points, portable tags, and 433 MHz readers, and B) 433 MHz location tags and container tags in order to manage container location.

For example,

- 1) LF transmitters allow the container's passage through the read points to be recognized and the system to be alerted. The LF transmitter at the read point sends read point ID. Portable tags of the type shown in Fig. 15 receive read point ID from the LF



Fig. 15 Phase 1 portable tags.



Fig. 16 Phase 1 container tag (data logger).

transmitter and send a response (which includes the read point ID) that is captured by the reader on the ground. Readers on the ground receive 433 MHz portable tag beacons that also include the tag ID associated with the container ID for checking the

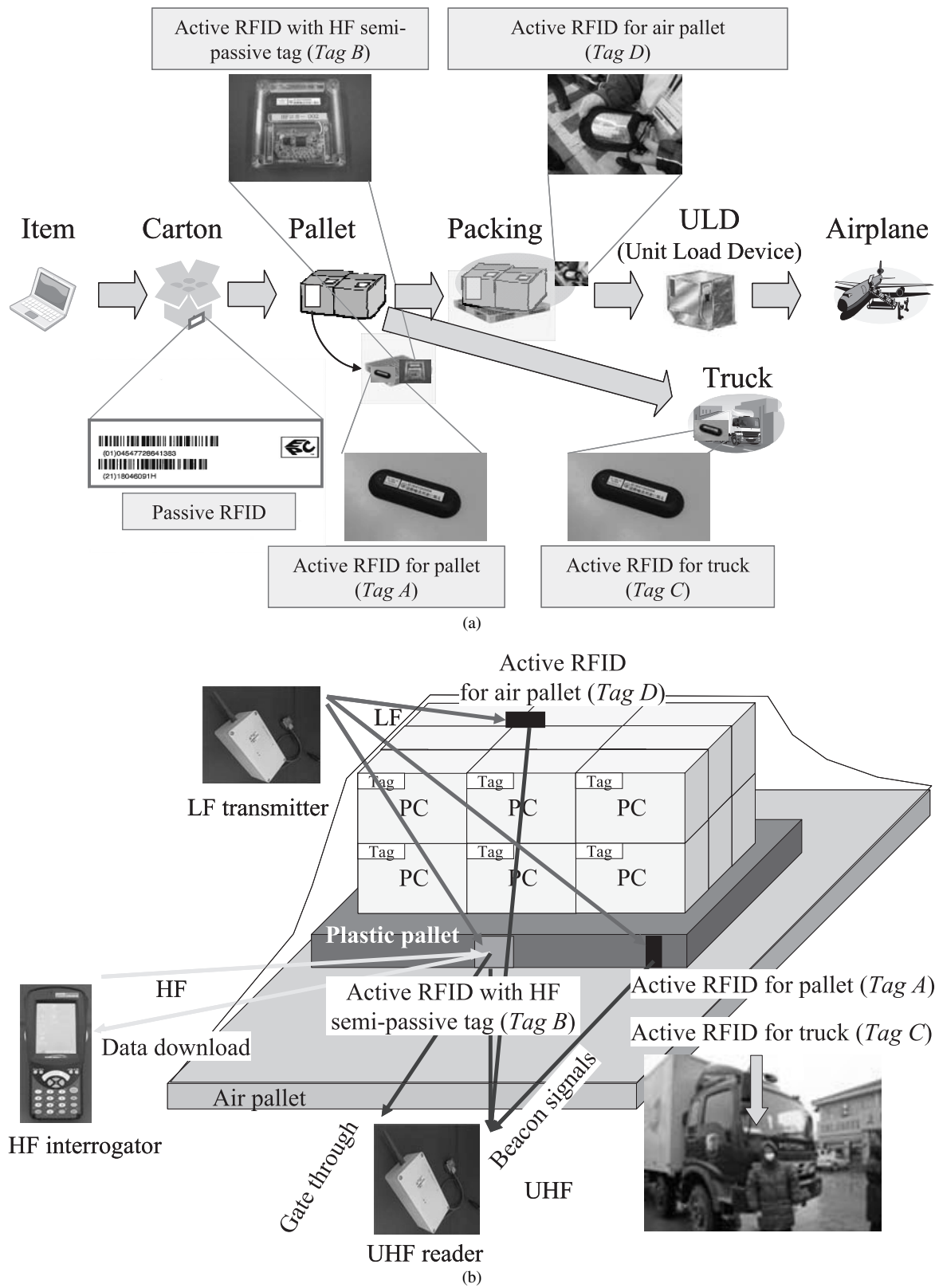


Fig. 17 (a) RFIDs and transportation modes in phase 2 pilot test. (b) Phase 2 air transfer arrangement.

arrival/departure of the container at/from the designated read point.

- 2) We can recognize the container's position using 433 MHz location tags set on the vessel, yard gate, etc. The container tag captures the periodic 433 MHz location beacon, which includes location tag ID. The role of container tags of the type shown in Fig. 16 is to log sensor data and location data; that is, the container tags also work as "moving readers". All logging data stored in the container tags (data loggers) were downloaded and manipulated by middleware via personal digital assistants (PDAs) using the infrared data association (IrDA) protocol.

6.2.3 Phase 2: Air Cargo Tracking and Air Pallet Management

The purposes of Phase 2 were air cargo tracking and air pallet management. In this Phase 2 pilot test, we used passive RFIDs and four kinds of active RFID.

(1) Passive RFID

Passive RFID was attached to the carton.

(2) Active RFID for pallets (Type A tags)

Cartons were loaded on plastic pallets at Hangzhou.

We attached active RFID tags (Tag A) to the plastic pallets. These tags contained a vibration sensor and sent beacons containing vibration event whenever they detected vibration if they were in active status.

(3) Active RFID for pallets with HF semi-passive tags (Type B tags)

This active RFID has a temperature-humidity sensor and a logger to store the sensor data.

(4) Active RFID for trucks (Type C tags)

This active RFID uses type A tags and were attached to trucks. At the Hangzhou and Shanghai gates, an active RFID reader read the Tag C beacon to ascertain the situation in which a truck approached the gate.

(5) Active RFID for air pallets (Type D1, D2 tags)

When the pallets were loaded onto a ULD (Unit Load Device), they were put on an air pallet (i.e., a metal board) and wrapped in a net. A Tag D was attached to this net. Tag D1 is used from Shanghai Pudong International Airport to Narita International Airport and Tag D2 is used from Narita to Los Angeles International Airport.

With this configuration, it is possible to determine the items packed on this pallet.

To build a normal tracking system, a simple UHF active tag was attached to each air pallet (Tag D) and each truck (Tag C), and UHF readers were fixed at each of the tracking points. The tracking points were a factory in Hangzhou,

Table 2 Active RFID tag specifications.

Item		
UHF part	Frequency	433.92 MHz
	Data rate	38.4 kbps
	Modulation	FSK
	Power	Less than 1 mW
LF part	Frequency	125 kHz
	Data rate	0.3 kbps
	Modulation	OOK
HF part	Frequency	13.56 MHz
	Data rate	26.48 kbps
	Modulation	PPM

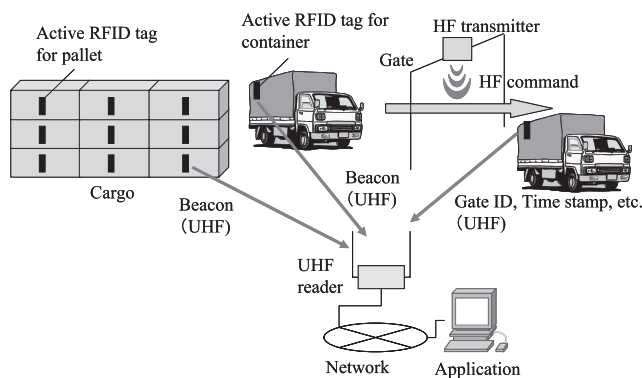


Fig. 18 Phase 3 system overview.

Shanghai Airport, Narita Airport, Los Angeles Airport, and a warehouse in Los Angeles.

Figures 17(a) and (b) show the transportation route in Phase 2. Table 2 shows active tag specifications.

6.2.4 Phase 3: Ocean Container and Pallet Tracking

In Phase 3, we used active RFID tags, UHF readers, and HF transmitters. Figure 18 shows the system overview for this phase. UHF readers were set at tracking area and HF transmitters were set at choke points such as gates.

Both container tags and pallet tags sent periodic beacons at intervals of 10 and 30 seconds, respectively.

Each HF transmitter sent gate ID and time stamp every 0.3 seconds.

When container tags and pallet tags receive HF commands (which include gate ID and time stamp) from HF transmitter at the gate, both tags send a response (which includes the HF command information) that is captured by the UHF reader so the time at which the cargo passed through the gate can be recorded.

UHF readers send the received data from tags to the application through the Internet to aggregate the tag ID and



Fig. 19 Phase 3 active RFID tag for pallets.

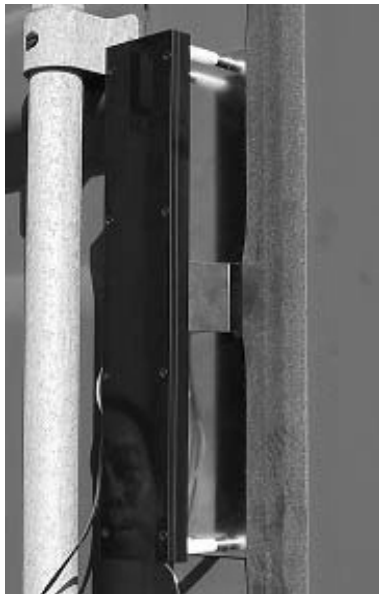


Fig. 20 Phase 3 active RFID tag for ocean containers.

the container ID or the cargo ID in the database.

Container tags were also able to report container door status.

Active RFID tags for pallets and ocean containers are shown in Figs. 19 and 20, respectively.

Table 3 shows the specifications of the active RFID tag and the HF transmitter.

6.3 EPCglobal Pilot Test Results

6.3.1 Phase 1: Ocean Container Tracking

Figure 21 shows the sensor data recorded in Phase 1. We found that temperature and vibration data were gathered throughout the entire transportation period. In addition, we found that using the LF transmitter made it possible to ascertain the time when a given container passed through a given gate.

6.3.2 Phase 2: Air Cargo Tracking and Air Pallet Management

Figure 22 shows the sensor data obtained in Phase 2 on January 22-25, 2008. We found that temperature, humidity, and vibration data were obtained throughout this period. Furthermore, we confirmed that all tags were quiescent while

Table 3 Active RFID tag and HF transmitter specifications.

Item	Active RFID Tag (UHF part)	HF Transmitter
Regulation standard	ARIB STD-92	ARIB STD-T82 ISO15693
Frequency	433.82 MHz	13.56 MHz
Antenna	Pattern Antenna	Loop
Modulation	FSK	PPM
Data rate	38.4 kbps	26.48 kbps
Power	Less than 1 mW	4 W
Battery life	5 years	-
Operating temperature	0 - 50 °C	0 - 50 °C
Operating humidity	Less than 90% Relative humidity	-

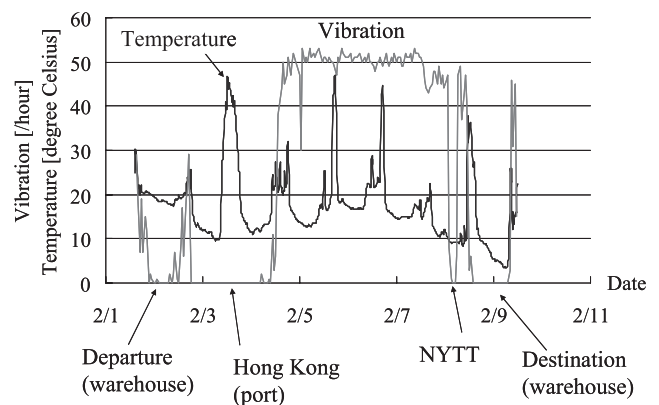


Fig. 21 Phase 1 sensor data.

on the plane.

6.3.3 Phase 3: Ocean Container and Pallet Tracking

The business location history of international logistics is strongly demanded by EPCglobal members. Figure 23 shows the container position history based on the results of automatically acquired beacons at the positions described in Sect. 6.2.4 in Phase 3 from December 8, 2008 to February 26, 2009. We found that our tags made it possible to track the containers automatically during this period. That is to say, our systems were able to obtain precise location histories and so meet EPCglobal requirements. In addition, we were able to visualize the container residence time, see Fig. 24. We found that logistical problems such as long-term stays in warehouses or yards could be readily identified.

6.3.4 Phase 3 Active RFID Tag Performance

Figure 25 shows the spatial attenuation of the UHF

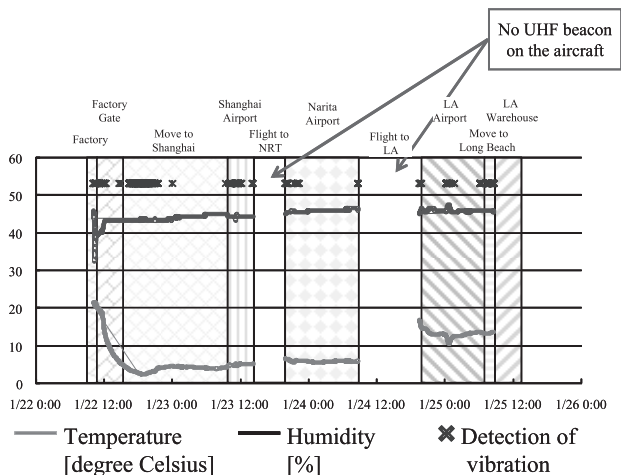


Fig. 22 Phase 2 sensor data.

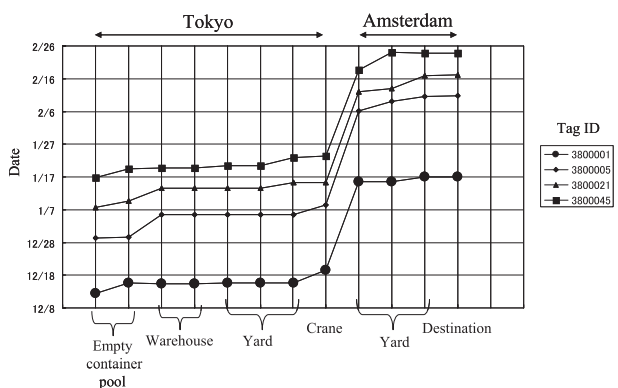


Fig. 23 Phase 3 beacon data of EPC pilot test.

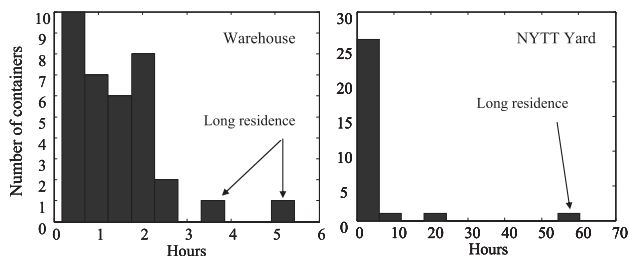


Fig. 24 Results of analyzing container residence time.

(900 MHz) and HF (13.56 MHz) bands under indoor conditions.

Loss in the UHF band is not a simple monotone decrease in which suppression increases with distance, because multiple paths exist. On the other hand, loss in the HF band is simple monotone decrease in which suppression increases with distance. The near field ranges of these bands are about 0.05 m and 3.2 m, respectively. In the near field, magnetic propagation is dominant.

We learned from the phase 1 and phase 2 pilot tests that ocean cargo carriers, owners, consignees, and yard managers of all pilot participants desired large cell coverage for

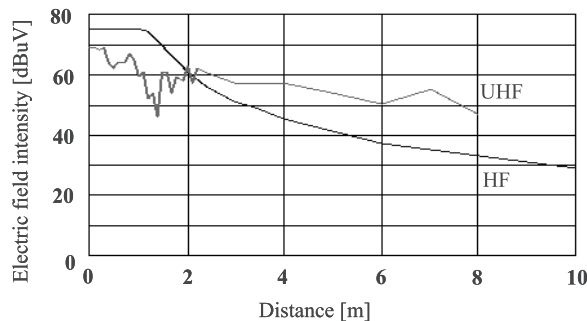


Fig. 25 Electric field intensity of HF and UHF.

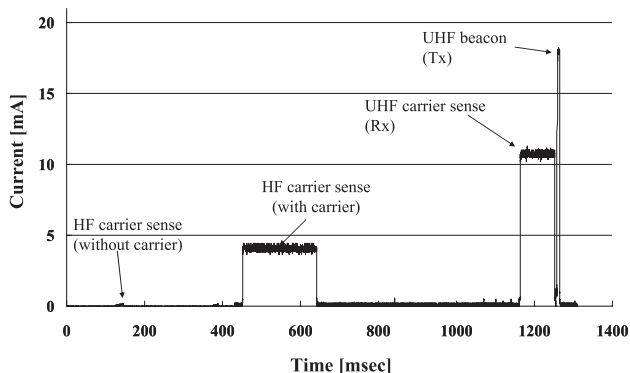


Fig. 26 Drain currents of phase 3 ocean container tags and pallet tags.

supervision with precise choke point resolution.

From the viewpoint of real-time monitoring, longer range (i.e. 500 m) is desired to reduce the necessary number of readers. On the other hand, from the viewpoint of gate operations, communication range should fit gate size (i.e. 2 to 3 m). In applying these principles, HF (13.56 MHz) was used for identifying the precise position at the choke points and UHF (433 MHz) was used for establishing large cells. Both frequencies can be used throughout the world.

Figure 26 shows the measured drain current of our phase 3 ocean container tags and pallet tags. HF carrier sense (without carrier), HF carrier sense (with carrier: receiving HF data), UHF carrier sense (Rx), and UHF beacon (Tx: sending UHF data) drain currents are about 150 μA, 4 mA, 11 mA, and 18 mA, respectively. We found that using a CR2450 battery as a power source gave our ocean container tags and pallet tags lifetimes of over three years and six years, respectively.

In this phase3 pilot test, UHF carrier sense time was set at 100 msec to avoid collisions with active wireless systems using the same frequency as that used at the warehouse. Carrier sense time should usually be 1 msec.

7. Discussion and Conclusion

There are various types of RFID tags and it is necessary to select the tag types that are best suited for a particular purpose. Our trials confirmed the successful application of our new types of active RFID tags that have high functionality.

We have developed and provided several types of 433 MHz active RFID systems for three EPCglobal pilot test phases. The results of these three phases are contributing to the improvement of freight visibility and the efficient use of logistics.

The 900 MHz band will soon be reallocated in Japan and the EU. The 916–930 MHz band will be allocated instead of 953 MHz. ETSI is also considering adopting a new 915–921 MHz band to replace the current 869 MHz band. The 902–928 MHz band is already being used as the ISM (Industrial, Scientific, and Medical) band in the US. This means that the 916–921 MHz will become the new UHF ISM band. These new worldwide unified frequencies will surely create major opportunities for many businesses and applications.

The multi-hop function to extend cell size is supported in IEEE802.15.4g [118], which defines smart meter protocol standards. However, it often increases power consumption if the communication range is high because it requires a high-performance receiver to relay the data coming from an adjacent node. Thus, it is difficult for battery-driven devices to achieve long life when using the multi-hop function. Our trials have demonstrated the possibility of developing useful systems that, without using the multi-hop technique, can cover actual container yards with a reader-tag communication distance of around 500 m by using active RFID tags with ultra-low power (less than 1 mW) and battery life of five years. This should prove to be a significant contribution to the study of the “Internet of Things (IoT)”.

Acknowledgments

We thank Messrs. Shuichi Yoshino, Kazuyasu Okada, Akihiko Nakajima, Akio Ikeda, Ryuji Kubozono, Yasuhito Hayashi, and Satoshi Hayama for their encouragement and fruitful discussions throughout the course of this work.

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