# Asset Tracking System Using Long-life Active RFID Tags

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**Abstract**

We have developed an asset tracking system using long-life active RFID (radio frequency identification) tags that reports the position of an asset when required. To determine the location of a tag attached to an asset indoors, such as in stores, warehouses, and offices, we use a high-precision location system that is not greatly affected by environmental factors. Experimental results show that the root-mean-square error between the estimated and actual tag positions measured at 77 points is 2.9 m, indicating that this locating system is applicable not only to asset tracking but also to other ubiquitous services that utilize the position of an item or a person indoors.

## 1. Introduction

RFID (radio frequency identification) tags are used in various fields. For example, the tag system schematically illustrated in **Fig. 1** is actually working in many stores. This system comprises gates and RFID tags attached to items or merchandise. Items a and b have tags a and b, respectively. If either item passes through the gate before the tag has been disabled by the cashier, the system generates an alarm. This system uses passive RFID tags [1]. A passive RFID tag receives radio waves generated from the

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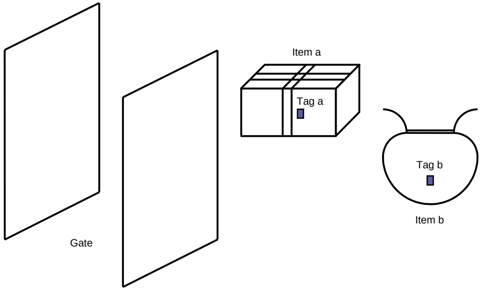



Fig. 1. Passive RFID tag system using gates.

gate, modulates them, and emits return signals. If the gate receives the return signals transmitted from the tag, it sounds an alarm because the presence of the tagged item at that location is unauthorized. The passive RFID tag system in combination with a gate is a low-maintenance system because the tag (or transmitting station) does not require a power source. However, the communication range is limited to a few tens of centimeters, so it is unsuitable for longer-range applications.

In contrast, the active RFID tag system (**Fig. 2**) is known as a long-range tag system [2], [3]. Here, a power source is provided to each of the tags 1–6 to extend the communication range. In general, the active RFID tag system uses a frequency band assigned to a specific low power, and can communicating in a range up to several tens of meters. However, this active RFID tag system only has a function for determining the presence or absence of tags 1 through 6 in the communication areas a and b of the receiving stations a and b, respectively. If the conventional active RFID tag system is used to estimate the position of each tag, the position estimation error exceeds the communication range. In order to improve the positioning accuracy, the transmission power of the tag must be lowered or the sensitivity of the receiving station must be reduced, while increasing the number of receiving stations, to narrow the area covered by each receiving station. Thus, this is not applicable to an asset tracking system, which reports the position of the asset only when required, to reduce the cost.

To overcome the above problems of the active RFID tag system, locating systems of the type illustrated in **Fig. 3(a)** have been proposed; the most well known example of this is the Global Positioning System (GPS) [4], [5]. The system shown in Fig. 3(a) includes a transmitting station $T_1$, three or more receiving stations $A_1$-$A_3$, and a center station communicating with the receiving stations. The transmitting station transmits a signal containing its identification code and the current time (i.e., transmission time) at a predetermined time interval using radio waves. Every time a receiving station receives the signal from the transmitting station, it transmits the received signal together with the reception time and its identification code to the center station. The center station calculates the distance between the transmitting station and each receiving station based on the information provided by the receiving stations, and estimates the position of the transmitting station. More precisely, the center station determines the signal propagation time from the transmission time to the reception time and calculates the distance between the transmitting station and each receiving station by multiplying the propagation time by the propagation speed of radio waves. Then, the center station estimates the position of the transmitting station by triangulation relative to the receiving stations.

**Figure 3(b)** illustrates another known locating system [6]. This system includes a transmitting station $T_1$ and three or more receiving stations $A_1$-$A_3$. The transmitting station generates and transmits radio signals during the positioning operation. Each receiving station reports the measured intensity of the received signal to the center station. The center station calculates the distance between the transmitting station and each receiving station from the signal intensity, and estimates the position of the transmitting station

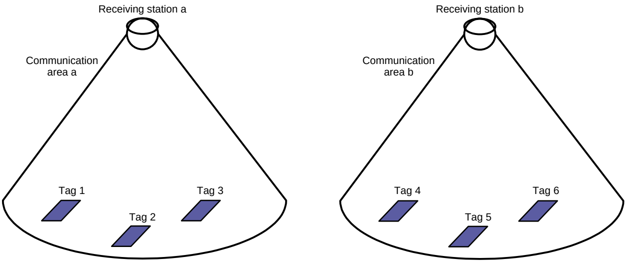
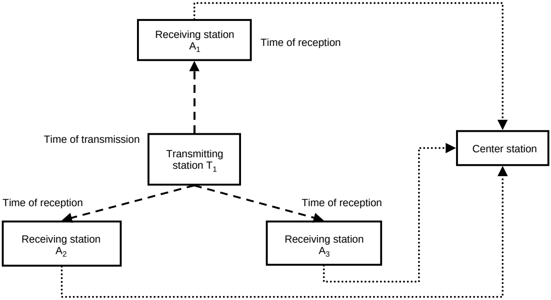
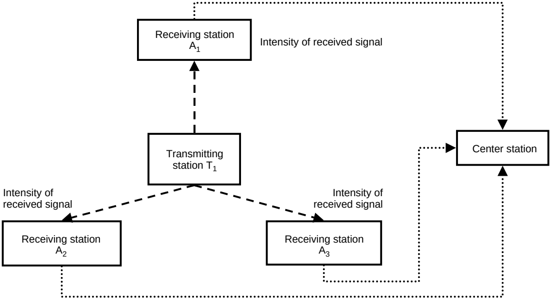



Fig. 2. Conventional active RFID tag system.




(a) System using transmission time.




(b) System using signal strength.

Fig. 3. Previously proposed locating systems.

based on its relative position to each receiving station.

Although positioning based on GPS may be effective outdoors, it is unsuitable indoors. Even if a position is estimated using amplitude information, in many cases the relationship between the distance and intensity of the received signal does not obey Friis' formula, which is expressed by

$$L = 20 \times \log_{10}\left(\frac{4\pi d}{\lambda}\right), \qquad (1)$$

where $L$ denotes the propagation loss, $d$ the distance, and $\lambda$ the wavelength.

The reason Friis' formula does not work for indoor propagation is that the receiving station may be blocked from line-of-sight transmission, or local fluctuations in intensity of the received signal may occur due to the influence of reflected waves.

This paper presents an asset tracking system using long-life active RFID tags. In this system, we used a locating system for determining the location of a transmitting station attached to an item or a person, and more particularly a locating system for efficiently determining the positions of a number of transmitting stations indoors, such as in stores, warehouses, and offices, with high precision without being subjected to much influence from environmental factors. This locating system is applicable not only to asset tracking but also to other ubiquitous services that utilize the position of an item or a person indoors.

## 2. Our locating system

**Figure 4** schematically illustrates an example of our locating system, and **Fig. 5** illustrates its transmitting and receiving stations. The locating system includes transmitting stations ($T_1$-$T_8$), receiving stations ($R_1$-$R_4$), a server connected to the receiving stations and functioning as a data management unit, and a positioning computer connected to the server. The server and positioning computer function as the center station in Fig. 3. The locating system also includes

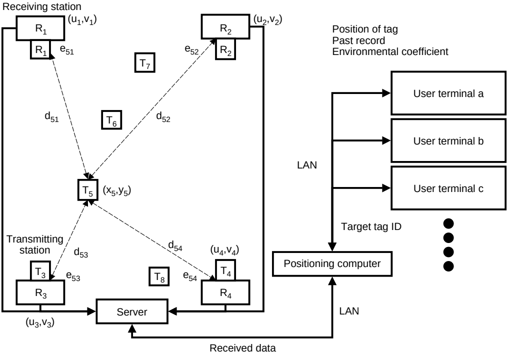



Fig. 4. Our locating system.

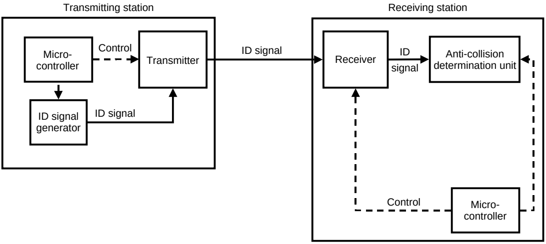



Fig. 5. Structures of the transmitting and receiving stations used in the locating system.

user terminals a-c connected to the positioning computer. These components are connected to one another via a local area network (LAN). In the example shown in Fig. 4 the receiving stations ($R_1$-$R_4$) are fixed, and their positions are known. $T_1$-$T_4$ are attached to $R_1$-$R_4$, respectively, so they can be regarded as having the same positions as them. The positions of $T_5$-$T_8$ are unknown. The transmitting station has a microcontroller, a transmitter, and an ID signal generator. The ID signal generator periodically generates an ID signal containing a unique ID of that transmitting station.

The receiving station has a microcontroller, a receiver, and an anti-collision determination unit. The receiver receives signals and measures their intensities. The receiver then passes the received signals onto the anti-collision determination unit which reads (or extracts) the identifiers from the received signals. The receiving station reports the received signal intensities and the corresponding identifiers together with time stamps to the server. The server records and stores each of the intensities in association with the corresponding identifier and time stamp. Time stamps may be created by the server when the server receives signal information from the receiving station.

The positioning computer estimates the position of transmitting station $T_5$ (in the example shown in Fig. 4) using information about this transmitting station stored in the server. The estimate is also stored in the server. The user can obtain the position of the transmitting station $T_5$ by inputting the identifier of this transmitting station through the user terminal to be retrieved in the server. The positioning computer determines a correcting formula defining a relationship between signal intensity and distance to accurately estimate the position of either a transmitting or receiving station indoors. The first correcting formula is a corrected Friis' formula using correcting coefficients including environmental coefficients. Since the distance and hence the positional coordinates of a transmitting station are estimated based on the actually measured value taking into account the correcting factors, the positioning accuracy is improved even indoors.

The algorithm using a corrected Friis' formula (that is, the first correcting formula) is explained in detail below. For simplicity, the explanation below uses two-dimensional coordinates, but the positioning computer actually estimates positions using three-dimensional (spatial) coordinates.

### 2.1 Algorithm of corrected Friis' formula

If the known position of the $j^{th}$ receiving station is ($u_j$, $v_j$) and the unknown position of the $i^{th}$ transmitting station is ($x_i$, $y_i$), then the distance between the stations is expressed:

$$d_{ij} = \sqrt{(x_i - u_j)^2 + (y_i - v_j)^2} \,. \quad (2)$$

First, we correct Friis' formula using correcting coefficients $S_1$ and $S_2$ on the assumption that signal intensity decreases logarithmically with distance. The corrected formula considering interference from environmental factors is expressed as

$$e_{ij} = S_1 \times \log_{10}(d_{ij}) + S_2 \,, \quad (3)$$

where $e_{ij}$ denotes the intensity of the signal transmitted from i received by j.

The solutions for two unknowns ($S_1$ and $S_2$) that minimize the error can be obtained by minimizing estimation function "q" given by Eq. (4).

$$q = \sum_{j=1}^{rn} \sum_{i=1}^{tn} (e_{ij} - \widehat{S}_1 \log_{10}(d_{ij}) - \widehat{S}_2)^2 \,, \quad (4)$$

where rn denotes the number of receiving stations at known positions and tn denotes the number of transmitting stations at known positions. In the example in Fig. 4, both rn and tn are 4, so there are 16 ($4 \times 4$) terms in the equation. Consequently, two unknowns ($S_1$ and $S_2$) can be determined. To clarify the explanation, the unknowns are marked with an arc above the symbols in Eq. (4).

Next, the estimated distance $k_{ij}$ derived from the measured intensity $e_{ij}$ is expressed as

$$k_{ij} = 10^{(e_{ij} - S_2)/S_1} \,. \quad (5)$$

Now, the position of the target (unknown) transmitting station "i" is determined by minimizing estimation function hi expressed by

$$h_i = \sum_{j=1}^{rn} \left( 10^{(e_{ij} - S_2)/S_1} - \sqrt{(\widehat{x}_i - u_j)^2 + (\widehat{y}_i - v_j)^2} \right)^2 . \quad (6)$$

The unknowns in Eq. (6) are also marked with an arc above the symbols for clarification. Using this method, the position of an unknown transmitting station can be estimated accurately even if the number of fixed-position receiving stations is not so large.

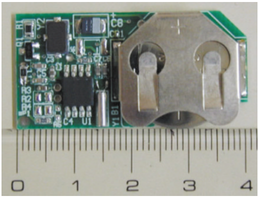
The estimated position of the transmitting station is stored in the server. As has been explained, to check the position of a target transmitting station, the user (or the manager) simply asks the server via the LAN by inputting the identifier of the target transmitting station through the user terminal. The positioning computer repeatedly estimates and updates the positions of transmitting stations using update information.

## 3. Application for asset management

Our prototype asset management application using long-life active RFID tags (shown in **Fig. 6**) is based on commercially available equipment. We chose the 300-MHz frequency band to avoid interference from wireless LANs. We use on-off keying (OOK) as the modulation method. Each tag is 4 cm × 2 cm × 0.5 cm and weighs 6 grams. An ID is sent out every seven seconds; this interval gives a battery life of about three years. The readers have an anti-collision function, which can handle signals from about 400 tags at a time.

In the prototype system we adapted commercially available readers to increase their sensitivity, and we developed software to handle the position and location information by linking to a database. The communication range is about 20 m (line of sight) or about 10 m indoors. **Figure 7(a)** shows the layout of the experimental laboratory and position estimation results. Receivers are fixed at positions P1-P5. The positions of tags set at each lattice point are estimated using the information supplied from these receivers. Each square in the graph is a unit area on the floor with a length of 1.0 m. In **Fig. 7(b)**, the root-mean-square (RMS) error between estimated and actual tag positions measured at 77 (11 × 7) lattice points is 2.9 m. By executing the positioning computer operation flow shown in Fig. 4, we could estimate the positions of multiple tags with high accuracy taking into account the environmental factors.

**Figure 8** shows an example of asset tracking. We can access this database directly from the Web, and we can search for individual assets: the room they are in, their positions in that room, and the movement history of each asset. Including image data in the




4 cm × 2 cm × 0.5 cm

Fig. 6. Photograph of long-life active RFID tag.

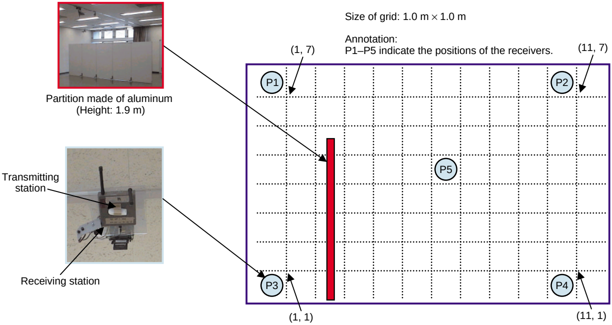



Fig. 7(a). Layout of experimental laboratory.

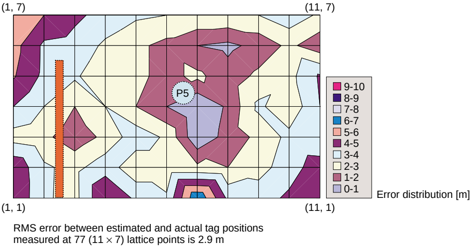



Fig. 7(b). Results of estimating tag positions.

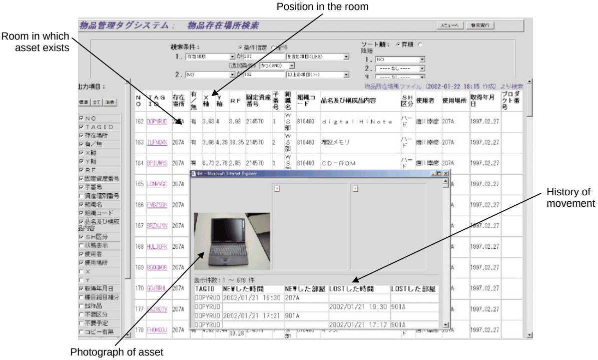



Fig. 8. Example of tracking of assets.

database lets us find the assets more easily. Furthermore, this system can email the owner to inform him/her when assets are moved from room to room or when none of the readers can receive signals from the tag, or it can email the administrator to inform him/her when the network experiences trouble.

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