Applications of Fast-Moving RFID Tags in High-speed Railway Systems

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Abstract: *RFID technology has been widely utilized for the tracking and identification of numerous stationary and moving objects. One of the most challenging RFID applications has to do with the improvement in reliability, scheduling and efficiency of large-scale transportation infrastructure. As an example, Radio Frequency Identification (RFID) technology in Ultra High Friency（UHF）frequencies (840-845MHz and 920-925MHz) is one of several technologies currently being utilized in China to monitor and regulate the railway system. Despite the very successful performance of ATIS RFID-based system for conventional trains with speeds up to 150kph, numerous challenges have to be resolved for the extension of this technology to modern high-speed and ultra high-speed railway systems with speeds up to 500kph. This paper identifies these issues, such as collision and insufficient reading time, and proposes various ways to alleviate their effect in UHF-RFID enabled railway systems*

Keywords: *RFID, fast moving, train,tracking systems*

1. Introduction

Radio Frequency Identification (RFID) technology has been widely used in supply chain management, objection location, vehicle control, electronic toll collection (ETC) and so on. In China, the RFID technology is one of several industries that the central government significantly supports with the aim being to improve this industry's reliability and performance in the country's railway system, being included in China's Eleventh Five-Year Plan and National 863 Plan. In April 2007, the Ministry of Information Industry of China officially released the Trial Regulation on 800/900MHz RFID Technology Application, which stipulates the specific application bands of 840-845MHz and 920-925MHz. This regulation has removed legislative barriers and permits the official, commercial use of RFID technology, indicating that the RFID market has fully initiated.

Now-a-days there is an even higher need for RFID's functioning effectively with fast-moving objects, especially considering the proliferation of ultra-high/high-speed railways under construction in the world, as well as ETC systems in highways. For example, China plans to spend more than $1 trillion on expanding its railway network from 86,000 km at the end of 2009 to 110,000 km in 2012 and 120,000 km in 2020. Perhaps the most ambitious rail investment is its goal to invest in 13,000 km of high-speed rail by 2020. Two major track types are being investigated: very high-speed rail, for trains traveling at 350 kph (220 mph); and typical high-

speed rail, for trains traveling at 200-250 kph (125-155 mph). In United States, President Obama has announced his ambition for the development of high-speed passenger rail lines in at least 10 regions, expressing confidence in the future of train travel (Avoine, G. & Oechslin, P., 2005). The government has identified 10 corridors, each from 100 to 600 miles long, suitable for high-speed development. Many high-speed railway systems have also been brought into operation in Japan and European countries. As we can see that we should focus on the RFID technology used by the fast moving objects, especially for the railway system, high speed cars and ETC system.

In this paper, problems and challenges in the operation of RFID tags in high-velocity environments are analyzed and a number of solutions are proposed. This paper is organized as follows: section 2 gives an overview of an existing railway-related RFID application, Section 3 discusses about the challenges of fast-moving RFID tags in a single-tag scenario and a multiple-tag scenario, Section 4 briefly describes some solutions to the fast moving RFID tags, Section 5 points out the future work.

2. Overview of an Exsisting RFID Application for Normal-Speed Railway Systems

Automatic Train Identification System (ATIS) is designed to identify railway cars arriving at or departing from railway stations, and it has been widely used in all railway bureaus in China (Knowlton, B., 2009), and RFID

tags have been attached to more than 15,000 locomotives and 550,000 carriages. Almost 2000 sets of Automatic Equipment Identification (AEI) were installed at each station and 523 stations were installed the Center Process System (CPS). Each tag was written with 128bits data including the car's ID and other related information. When those cars pass by the readers, their RFID's ID information are recorded and sent to CPS for further process.

The ATIS is mainly used to identify the cargo trains whose speed is less than 100kph. It reports the identities of the vehicles/wagons and trains to the railway information center for various applications, such as TMIS (Transportation Management Information System), scheduling System, etc. The location can be effectively tracked and the tracking information of trains is recorded and shared with other systems. The ATIS includes 6 parts (Knowlton, B., 2009), as shown in Fig.1. The first part is the UHF band, passive RFID tag for vehicles a reading distance close to 1.4m; the second part is the AEI module, which is composed by the RFID reader, magnetic steel which are used to startup or shutdown the RFID reader, computers and lighting protection device equipment, as showed in Fig.2 and Fig.3; the third part is CPS, which was interconnected to the AEI, is used to process, store, and share the RFID information with other railway information systems; the fourth part is the faults detecting information system, which is used to identify the malfunction of trains through the information from CPS; the fifth part is the information terminal; the sixth part is the RFID-tags writing equipment, which is used to write the vehicle identity information, that is allocated by the management department, onto RFID tags.

When the train approaches the station, it crosses the startup magnetic steel first, which is fixed 40-50m ahead of the corresponding AEI/RFID reader, and a pulse signal is generated, which is transmitted to the CPS. Then, the CPS sends a "startup" command to turn on the RF reader. The identity of each vehicle is transmitted by a passive RFID Tag mounted underneath the vehicle, and received by the RFID Readers mounted along the railway tracks. During the operation, the Reader is connected to the railway system through a wired network. Once the Reader has received the identity sent from tags, the reader will report the vehicle arrival or departure to the CPS unit. The CPS unit collects all the information from readers in the network and reports the vehicle arrival/departure to the railway system for different application.

When the train departs from the RF reader, it crosses the "shutdown" magnetic steel and a pulse signal is generated. The CPS, then, receives this signal and transmits a command to shutdown the reader. This process is an efficient way to control the RF reader and has proven to be a successful method for conventional-speed trains.

Considering the "rugged" metal-proximity and moving-metal environment, the number of missing tags is very low, especially for speeds below 100kph, with values below 5 percent. There are numerous reasons for even such a low number of missed tags, that should be addressed in future RFID railroad-related applications: interference from more than one tags transmitting signals simultaneously, interference from surrounding magnetic waves from other railway applications, problematic performance of tags which are stained, rusted or non-effectively shielded.
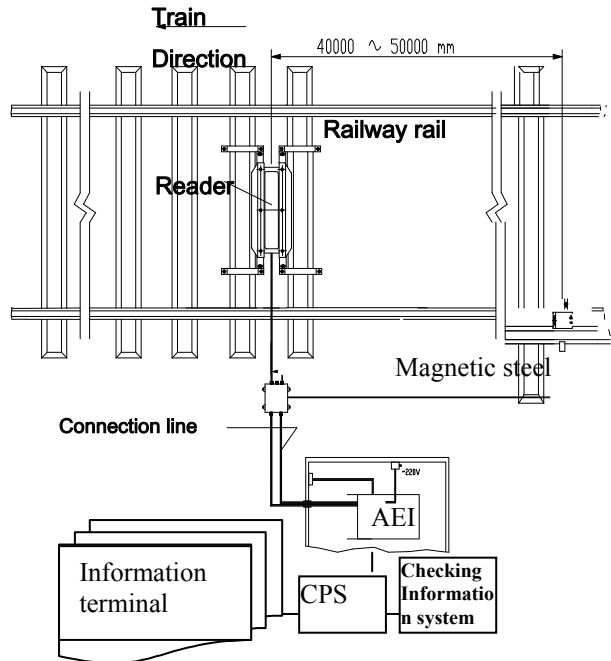

Fig. 1. Components of ATIS

Fig. 2. RF Reader fixed between two railroad ties

Fig. 3. Magnetic steel fixed next to the railway rail

3. Challenges for Fast-Moving ("High-Speed") RFID Tag

Through an investigation conducted in cooperation with the Chengdu Railway and Nanchang Railway Bureaus, the following issues related to the ATIS operation have been pointed out:

A. The ATIS system can be easily RF disrupted

Since ATIS system makes use of the electromagnetic spectrum, it is relatively easy for it to be jammed in the presence of third-party high-energy interferer in the same frequency band. If the RFID readers of two or more different solutions operating in the same electromagnetic spectrum are set in the same environment, the rate of identification declines dramatically.

B. Failure to identify the tags attached on vehicles due to RFID reader-initiated or Tag-initiated collisions

A common phenomenon is that the ATIS fail to identify the tags attached on the vehicles, especially when there are several trains passing by the readers with high speed. This problem mainly caused by the reader collision, tag collision or shifted-frequency/non-sufficient reading time.

C. Security Problems

Anyone with an RFID tag reader can read the tags, since the used RFID technology (no security protocol is utilized) eliminates the need of being swiped or obviously scanned, that is common in magnetic strips or barcodes.

In order to resolve this issue applying a security algorithm, more bits of information will be required to exchange between an RFID reader and a tag. Given that the bit rate transmitted by RFID tag is fixed, it will cost more time to complete the tag-reader communication.

Fast-moving objects, such as high-speed trains, ground-moving airplanes, vehicles, need to be tracked more frequently. ATIS has proved to be a satisfactory system so far and has greatly elevated the information standard of railway systems. However, problems, as the aforementioned ones, require further investigation. Even so, as the speed goes to above 300kmp, one of the major challenges has to do with the very limited time that a tag remains in the reader range, incurring additional problems.

There are two fundamental factors determining the RFID performance in high-speed applications: the fraction of time in which a tag responds, and the speed in which it responds. The former metric is estimated by the ratio of tag responses per request, and the second is estimated by the number of responses per second (Barclay, L., 2002). There are a number of parameters that impact those values. Examples include the distance between the tag and reader antenna, especially for metal-mounted configurations, how much background noise exists in the environment, and the orientation of the tag (Barclay, L., 2002).

There are two scenarios, which involve the identification of a single tag or multiple tags simultaneously located within the reader range, respectively.

1) Single tag scenario within the range of a single RFID reader: For a single tag, laboratory experiments with stationary test sets quantify that the length of the read area (read distance) is 0.8m with 18ms of read latency, with 128 bits of ID and 64kbit/s transmit speed of tag. The above result allows us to calculate the maximum fast-moving RFID speed that can be effectively read, by requiring the time period that the fast moving object remains within the RFID reader's read range to be larger than the read latency. In particular, the maximum speed at which a vehicle's RFID data can be successfully read (EPC Grobal Inc., 2008) is 0.8084m/0.018s=167.7kph.

The data bit-rate of RFID tags is not the only contributor to the required RFID communication time. In fact, if the data rate was the sole factor in the experiment, then it would have been just 3cm for a reading transaction. As it turned out, however, it took nine times longer (EPC Grobal Inc. 2008). This means that if we were to improve the communication speed, we need to focus on other hardware and modulation-related factors, such as capacitor charging time rather than the data rate.

Rob, P (Rob, P., 2008) has experimented with readers from various manufacturers featuring similar trends. It was found that the read latency was heavily dependent on the tag-reader system. They also found that different tag models use different integrated circuits. Class 0 tags were comparable to "slow" Class 1 tags despite the fact that they show very similar response times.

For the single tag scenario, we can estimate that the existing reader can identify the tags with a maximum speed of about 167.7kph. This depends on two aspects, namely are the read distance and tag's respond latency.

Since the RFID tag is an emitting source that is moving relative to a fixed RFID reader, which is the observer, the Doppler shift or Doppler effect (Vogt, H., 2002) has to be investigated. This effect involves a change in observed frequency (f) by the reader of emitted waves produced by motion of the RFID tag (f_0). In particular, the received frequency is higher compared to the emitted frequency during the approach, it is identical at the time instant of passing by, and it is lower during the departure. For a typical railway system setup, where the source is either

directly approaching or receding from the observer (not in an angle) the formula that calculates the aforementioned frequency shift is the following:

$$\left| \left[(u + u_r)/(u + u_s) \right] \times f0 - f0 \right| \qquad (1)$$

where u is the velocity of waves in the medium, u_r is the velocity of the receiver relative to the medium (positive if the receiver is approaching the source) and us is the velocity of the source relative to the medium (positive if the source is moving away from the receiver).

As an example, this shift is expected to be 126 Hz for an approaching tag with 150km/h toward a fixed reader and 375 Hz for a speed of 450km/h. These values are negligible given the fact that the bandwidth of a typical RFID communications channel is 200 kHz and, therefore, the Doppler effect can be ignored for the examined types of applications.

2) Multiple Tag or Multiple Readers Scenario: Regarding the scenario with multiple tags existing within the RF range of a single RFID reader or a single or multiple tags existing within the range of multiple RFID readers, the situation becomes worse due to signal collisions.

An example of the former case is when two trains come across at the point where an RFID reader is set and each car of each train has at least one RFID tag attached on it, as shown in Fig. 4.

Collision among RFID tags also occur when signals from transmitted by two or more readers overlap, for example, a check point with two or more railway lanes with each lane installed a reader. A single tag is unable to respond to simultaneous overlapping queries.

In order to avoid the tag-initiated overlapping, many systems use anti-collision protocols. Anti-collision protocols enable the tags to take turns in transmitting to a reader. The reader-initiated overlapping can be solved by choose proper locations for different readers.

The reader needs to process the RF tag one by one under the control of the anti-collision algorithm. The UHF Class 1 Gen 2 Standard (Zhang, Y., 2001), which was developed by EPCglobal, recommends an anti-collision algorithm, based on the dynamic framed slotted ALOHA (Eberhardt, N., 2002). Nevertheless, the anti-collision algorithm needs further investigation, since the dynamic framed slotted ALOHA has not been designed for fast moving objects.

4. Solutions Proposed towards Enabling the Detection of Fast Moving Tags

As shown in previous section, for 900MHz passive tags and a read range of 0.83m, the speed limitation is 167.7kph. For the single tag scenario, this limitation is determined by the read distance and response latency of RFID tags. In addition to these factors, the limitation for multiple tags is further decreased by collisions among tags.

A. Single tag scenario within the range of a single RFID reader

1) Using Semi-passive RFID tags: It has been reported that active UHF beaconing RFID tag sends data to a mobile (handheld) or fixed reader (interrogator) at distances of up to 300 feet (100 meters) (Capetanakis, J., 1979). Its ultra-low power consumption and configurable ping rate enables it to work effectively for many years without maintenance (Capetanakis, J., 1979). By using this long range RFID reader-tag system, the communication time between tags and reader will be greatly enlarged, thus significantly increasing the previously maximum velocity of the moving RFID tag.

2) Fast responding chip sets: With fast responding RFID tags, the latency required for a RFID reader's request to be answered can be shortened. As a result, the round-trip communication time between the reader and the tag is decreased and it is possible for RFID reader to identify fast moving RFID tags even within a limited time period.
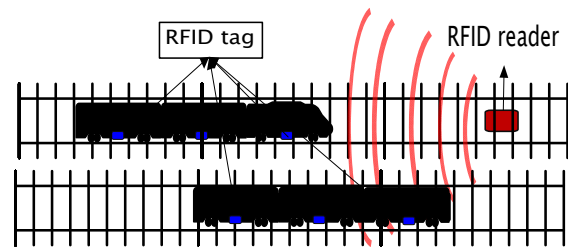

Fig. 4. Multiple Tags scenario

B. Multiple Tag or Multiple Readers Scenario

1) Anti-collision algorithm: The anti-collision algorithms are classified into two categories: deterministic and probabilistic (Chon, H. et al., 2004). Deterministic protocols are based on binary trees where each root-to-leaf path represents a unique tag id. Several such protocols have been proposed for Class 0 Generation 1 tags. Probabilistic protocols are based on the slotted ALOHA framework, where the channel time is split into frames. A single frame in turn is divided into several time slots. During a frame, each tag randomly chooses a time slot and transmits its identifier to the reader in that slot. These protocols have been proposed for Class 1 Generation 2 tags.

In tree-based protocols, which are based on the collision resolution algorithm studied in (Lee, E. &Yoo, Y., 2009), tags transmit at the same time, form a set. When a set causes collision, the mechanisms split it into two subsets and attempt to recognize two subsets in turn.

The binary tree protocol, which uses random numbers for splitting, is adopted as the standard for RFID anti-collision in ISO/IEC 18000 Part 6. The query tree protocol splits a set of tags by the reader's queries. Although tree-based protocols do not cause tag starvation, they have relatively long identification delay due to the splitting procedure starting from one set including all tags.

Probabilistic tag reading protocols can achieve smaller identification delays provided the amount of time wasted due to collisions and idle time slots is reduced

(Ramakrishnan, K., 2005). Collisions occur when more than one tag transmits in the same slot, in which case all their identifiers are lost. Idle time slots occur when none of the tags in the reader's vicinity choose a particular slot for transmitting their identifier.

For the use of anti-collision algorithms in high speed moving vehicles, the class 1 generation 2 needs to be improved. A kind of new method of combining the advantage of binary tree and ALOHA is an interesting direction.

2) Directional Antennas: Using highly directional antennas with narrow horizontal half-power beamwidth can prove very useful not only in reducing radio interference among readers or collision among RFID tags but also in increasing the RFID reader's read range.

3) More powerful RFID hardware Design: With the requirement of robustness and privacy, more processing powerful hardware is needed to perform the complicated algorithms described in previous subsections. The anti-collision algorithm is performed mostly in the RFID reader, which should decide which tag can talk first with the reader, whereas the encryption method requires the RFID tag itself to make a decision on whether the RFID reader can be trusted.

5. Future Work

As discussed above, the future work needs should involve all system aspects, ranging from the hardware up to the software protocol. Of extreme significance toward this target is expected to be the real world experimentation with typical passive RFID tags, other novel structures, such as Intel's WISP (Daniel, J. et al., 2008), as well as a programmable RFID reader based on, for instance, the USRP software radio platform, so that potential changes to the RFID protocol, including, among others, timeout parameters, can be performed.

6. Acknowledgments

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