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A Combinatorial Methodology for RFID Benchmarking

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ABSTRACT

With recent advances in wireless technologies, RFID (Radio Frequency Identification) becomes an important enabling technology for logistics and supply chain management systems and beyond. Effective deployment of these systems requires careful selection and seamless integration of RFID components such as tags, readers, middleware and standards. The frequent releases of new RFID components obsolete past experiences quickly and thus impose great challenges to the selection and integration process. Systematic classification and accurate comparison of their features and relative performance are desirable. To serve these purposes, benchmarking is a promising measure. Nevertheless, how can RFID components be reliably benchmarked? RFID benchmarking should address at least two technical challenges. First, the performance of RFID components are rarely determined by a single factor. Second, the measurements are subject to natural environmental noises. In this paper, we propose a combinatorial benchmarking methodology to help address these two challenges.

Keywords

RFID, benchmarking, combinatorial testing, methodology

1 INTRODUCTION

As the global trade's volume increases and its pace accelerates, computerized systems of logistics and supply chain management are increasingly important. This trend is further fueled by global offshoring, such as the transference of manufacturing processes, customer service centers and professional work from one geographical location to the others. For example, the total freight shipment volumes within the United States alone are expected to increase by 70% between 1998 and 2020, and its foreign import amount would double within the same period [7]. To grow strongly with the above opportunity, logistics and supply chain companies should streamline their business processes. They should provide timely and accurate information of stock flows to their clients.

With the recent advancements of wireless and integrated circuit technologies, RFID *(Radio Frequency Identification)* emerges to be one of the most promising enabling technologies to facilitate such business processes. The use of RFID resolves common limitations encountered in existing barcode technologies. Examples of limitations include: (*a*) barcode scanners can only scan one barcode each time, and (*b*) barcode systems generally do not support item-level tagging [12]. In many cases, items should attach with barcode, and manual taking of the barcode readings are needed. Since manual processes are slow and error-prone, they are unreliable, even if the technologies are mature. The automatic nature of RFID technology to read data should reduce the error due to manual mistakes. Moreover, RFID readers support much higher read rates, which is the number of times the reader can read/write data from/to a tag per second, than their barcode counterparts do. Because of various RFID advantages over the barcode technologies, Gartner [4] predicts that the worldwide RFID spending will surpass three billion US dollars by year 2010.

However, unplanned adoption of RFID does not necessarily warrant business successes. Effective deployment of RFID systems requires careful selection of RFID components and their seamless integration into the target supply chain processes. These components include tags, readers, middleware and domain-specific applications on top of middleware. Even a component developed by a company is unlikely to have the same characteristics as the

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component developed by another company, the frequent releases of new RFID components by countless manufacturers make the selection decision and integration process challenging.

The problem can be much alleviated if benchmarks of these components are available. RFID benchmarks provide a comparative measurement of RFID components, thus offering a useful means for managers and engineers to evaluate various potential solutions, no matter they are developed in-house or by vendors. Traditionally, benchmarking is a technique used extensively by the industry to facilitate management decision by systematically classifying features of interesting entities (both software and hardware) and comparing their relative performance. However, how can RFID components be reliably benchmarked? We need to address at least two technical challenges. First, the performance of RFID components are rarely determined by a single factor. Second, the measurements are subject to natural environmental noises.

In this paper, we propose a combinatorial benchmarking technique to help address these two challenges. Figure 1 shows the experimental setup at the Hong Kong University of Science and Technology to help study the problem of RFID benchmarking.

This paper is organized as follows. Section 2 overviews the background of RFID benchmarking. Section 3 presents our benchmarking methodology, which is followed by the explanation of a novel combinatorial benchmarking method in Section 4. Finally, we conclude our work in Section 5.

Figure 1: From upper-left and then clockwise: a conveyor belt system; a simulation system of supply chain; benchmark measurement in anechoic chamber; and a scene with multiple tags and multiple readers.

2 BACKGROUND

2.1 RFID Tags and Readers

RFID devices are mainly grouped into readers and tags. An RFID reader is a device equipped with antennae to read data from and write data to an RFID tag via radio waves. Four frequency ranges are used in practice, and they are: 135 KHz, 13.56 MHz, UHF (860 to 960MHz), and 2.45GHz. Both active and passive RFID tags are common.

Active tags generate signals actively using the power from their own batteries. Passive tags can only generate radio waves using the power from the readers in proximity. Hence, the effective ranges (or signal strengths) of active tags are generally larger than these of passive tags. However, passive tags are generally cheaper and smaller than their active counterparts.

An RFID reader demodulates the radio waves received from an RFID tag and converts the waves to data. It also uses certain error-masking mechanisms to filter out unreliably data, from the perspective of a particular reader.

2.2 A Three-Tiered RFID Architecture

Layer architecture is a general architecture to model a system at high level. As shown in Figure 2, the architecture of an RFID system can be modeled using the three-tier architecture: application, infrastructure, and device. The device tier has been introduced in Section 2.1.

The application tier consists of application-specific software components to provide value-added services to their users. Examples of RFID applications are enterprise resource management (ERP) and workflow management system (WMS).

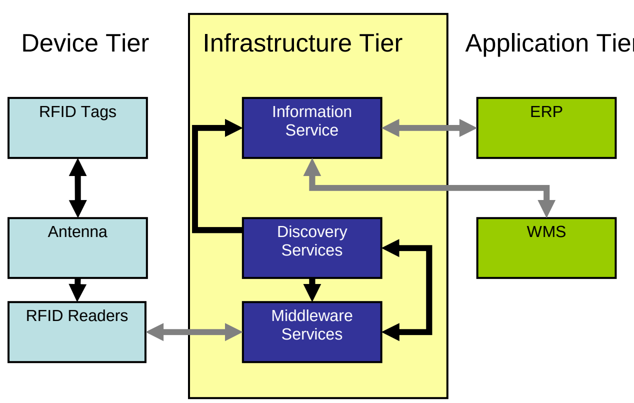

Figure 2: A three-tiered RFID architecture.

Unlike those in the application tier, software components in the infrastructure tier are mostly generic, in the sense of not tailoring towards a particular application. They frequently support a well-defined application programming interface (API) to the components at the application tier. The API provides a high-level abstraction of the RFID environments and relieves application programmers from the tedious manipulation of low-level device-specific codes. Components of the infrastructure tier can be further organized into those providing information services, middleware services and discovery services. A middleware service interacts with RFID readers at the device tier through serial ports or sockets at certain configured network addresses.

2.3 Related Work

As RFID emerges to be an enabling technology of the supply chain industry, many companies, including RFID vendors, has launched pilot projects. They focus on examining the quality of RFID tags, the operation profiles of specific setting, data quality, read rates of the RFID readers, and optimum tagging locations based on the product characteristics.

American Power Conversion (APC) [1] is a provider of global end-to-end infrastructure availability solutions for retailing. APC evaluates the variability of using different RFID components to meet their business goals of complying with the retail chain's requirements. For which, the IBM testing center helps APC to manage the impact on the variability of vendor hardware, including antennae, readers and tags.

Testing should also help reduce the technical risks for adopting new RFID components such as upgrading the existing system by the RFID-enabled solutions. For example, the Sun RFID Test Center [14] helps its customers to mitigate their risks through testing. However, their testing methodology is unclear to public at this stage.

Alien Technologies [2] tests the readability of RFID applications under a variety of conditions, including location of tagged cases, antenna types and positions, tag orientation, proximity of a tag to a reader, relative orientation of an antennae with respect to a tag, multiple tags scenarios, the movement speed through portal, the configuration variables of the RFID applications, and interference amongst radio frequency (RF). Their test results indicate that those poorly performing tags consume more than a double, in terms RF power, compared to the good ones. However, they do not release reproducible procedures. In view of the above, Avery Dennison amongst others has established their own production quality criteria to test the performance variations of tags [3]. This further demands the availability of RFID benchmarking.

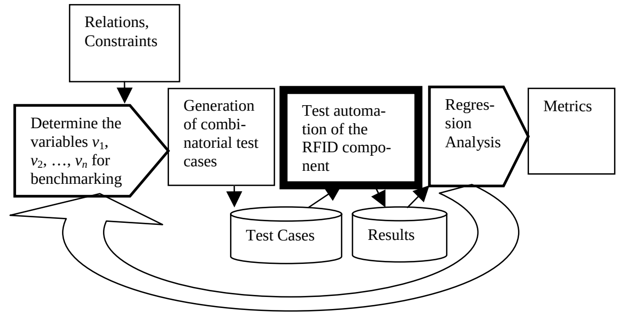

Figure 3: RFID benchmarking process

In some application scenarios, multiple RFID readers are deployed to provide adequate coverage. Their effective sensing zone are unavoidably overlapped. As such, multiple readers may detect a tag simultaneously. Their induced signals at the tag may collide and thus the superimposed signal is distorted [12]. There are wireless protocols to address the situations of multiple readers. To benchmark the device performance under such situations, RFID Alliance Lab [15] has conducted a comparison test, named conveyor testing. The test examined the performance of multiple RFID tags when they were attached to packaging boxes on a production conveyor system operating in a simulated distribution center.

Federal Aviation Administration (FAA), a testing laboratory, designs two experiments focusing on integrated operations and multiple product applications [10]. The first one aims to evaluate the technical and operational capabilities of an end-to-end system that tracks and matches baggage for passengers. The second one aims to evaluate the deployment of RFID to facilitate the check-in and baggage handling processes. However, whether their setting are applicable to other scenarios are unknown.

2.4 Performance Benchmark

Although the maximum data rate supported by an RFID tag is generally labeled on the tag by its manufacturer, it varies significantly from the actual read rate. Like others, our experiments show that it is affected by the distance and orientation between the tags and readers, to name two.

Read rate is by far the most commonly used performance benchmark of RFID tags. One can benchmark a tag in controlled environments under ideal conditions, such as anechoic chamber [6]. Controlled variables for those measurements include adjusting readers' emission power, the distance between tags and readers [12], or the physical orientation of tags.

In addition, a tag's performance is also tampered when its surrounding objects, such as metals or water, detune its radio waves. The performance measurement involves benchmarking of detuned frequencies of radio waves in the presence of surrounding objects. It is necessary to benchmark the tag's read rate when it is in isolation, as well as in the neighbourhood of other tags [15].

2.5 Combinatorial Testing

Combinatorial testing [16] is a strategy that alleviates the state explosion problem when there are many input parameters for the test object. It aims to select test suites, in which test cases represent different combining values of input parameters.

Previous research on software testing shows that it is inadequate to detect faults by varying one parameter or two. For example, Kuhn et al. [17] report that combinations of up to six parameters are required to detect over 90% of all faults. Test case generation strategies, such as AETG [19]or IPO [18] strategies, have been proposed and shown to be effective.

3 OUR BENCHMARKING METHODOLOGY

As we have discussed in Section 2, RFID architecture can be modeled as a three-tier architecture, which consists of components in the device, infrastructure and application tiers. In theory, each component at any tier could be benchmarked. We have discussed with the industry that they are more interested in benchmarking components at the device and infrastructure tiers, because the components are these tiers tend to be of commonality in nature, and hence benchmarking could be more meaningful.

Figure 3 depicts our methodological process to benchmark a component. We note that our process is generic to each of the three tiers. Our benchmarking process commences by first identifying the independent and dependent variables of the benchmarking component. Suppose the benchmarking component is a kind of tags. Examples of the independent variables could be its distance and orientation from the target readers, whereas dependent variables will be read rates, detuned frequencies, maximum effective distance and power consumption, to name a few. However, not all combinations of variable values are legitimate. For example, for RFID tags, they will be generally governed by the physical laws and environmental constraints. We shall use the published RFID models to serve as constraints amongst some of the variables. This allows our methodology to build on top of a sound theoretical foundation.

After identifying the variables and the associated constraints governing these variables, we propose to generate benchmarking test cases using a combinatorial approach. Details of the combinatorial approach will be given in the next section. The results will be a set of test cases.

We then proceed to execute the test cases. Our trial run has indicated that this part of the process is extremely tedious. As such, test automation for RFID components is necessary. Moreover, the relationships between an RFID components and RFID models are likely to be unclear. We thus initially have more variables (and hence more test cases) than that of applying a particular RFID model. This further makes the test execution process cumbering. However, we view it necessary to collect scientifically the experimental data with respect to the variables.

Regression analysis will be the step after the data collection to find out dominant factors for a particular effective RFID model. Dominant variables are distilled out and will be used for further refinement or application in subsequent benchmarking exercises. We then compare the results in an ideal situation (like in an anechoic chamber) and various business environments (like in a simulated distribution centre) to provide benchmarking metrics accordingly.

4 COMBINATORIAL BENCHMARKING APPROACH

Existing approaches mostly conduct benchmarking by adjusting one variable in each test, e.g., either tag orientation or distance. To save efforts, some benchmarking processes first select the tag whose performance lies in the median amongst a collection of tags in a benchmarking test and then use that as a one-size-fit-all value to perform other tests. This, however, is likely to produce biased benchmarking results.

As revealed by our initial real-life experimentation, a tag that exhibits a median performance in one test may not do so in other tests. An approach, which different combinations of variables take different combination of values even for the same test, is necessary. This motivates us to propose a combinatorial approach to benchmarking RFID components.

On the other hand, a full combinatorial approach is impractical. For example, if there are 100 variables and each takes 10 values, there will be 10^{100} distinct combinations. Indeed, as indicated in [19], full combinatorial approach is unnecessary to cover a vast majority of scenarios. The *t*-way approach, which varies *t* number of variables instead of all variables each time and up to *t* to be six, is viable and effective to realize a combinatorial approach.

Even we have degenerated the combinatorial approach to the pair-wise approach, in which the strategy only aims to cover every combination of any two variables, the size of a test is still forbiddingly large. Consider that we want to benchmark a tag based on tag model. For the ease of presentation, suppose that there are three independent variables: horizontal angle, vertical angle and the distance between the tag and a reader. Consider the following values:

Horizontal angle	Span 120º with 10º interval (i.e., 12 settings)
Vertical angle	Span 120º with 10º interval (i.e., 12 settings)
Distance	0.4 to 3 meters with 0.02m interval (i.e., 125 settings)

Without other factors, there will be 144 combinations. Since readers can read data in a high rate, the number of read can easily reach 100 in a few minutes. For statistic purpose, benchmarking engineers should repeat the experiment a number of, say 20, times. This compounds the total number of measurements to be 2880 with 100 readings each. Intuitively, the incurred complexity seems exceeding the single medium value as provided by existing benchmarking report available on market. Advanced methodological approach should be derived to realize effectively the combinatorial approach to tackling the state explosion problem in RFID benchmarking.

We propose to use a hierarchical strategy. At high level, clusters of variables are used instead of concrete variables. We partition the value space of a cluster and treat each partition as a value of the cluster. Combinations of clusters' values are used to produce high-level test cases. We then benchmark the RFID components using these high-level test cases, with sensitivity analysis. Highly sensitive combinations of clusters' values are then progressively refined into smaller clusters, and finally the original forming sets of variables, to produce more elaborated test cases. In this way, intuitively, those insensitive high-level clusters may only need to be measured by a small number of tests. This reduces the benchmarking efforts.

For example, we may consider the above three example variables as a cluster. We then partition the cluster into 3 partitions representing "close (< 1m) and small changes (<60º) in angle in either direction)", "near (< 2m but > 1m) and small changes (<60º) in angle in either direction)" and so on. We then apply test. Initially, there will be six measurements with 100 readings each. Suppose that three of them need further refinements. The "close (< 1m) and small changes (<60º) in angle in either direction)" can be refined into a series of clusters covering different distance ranges with interval 0.1m. In other words, the partition has been divided into 10 smaller partitions. We can then iteratively apply the procedure. We are conducting an initial experimentation (but the test automation takes time). We should report our findings soon.

5 CONCLUSION

With fast adoption of RFID technology in real-life logistics applications, it is important for the management to make decision of the selection and the deployment of this technology. However, such decision is difficult due to the relatively short product cycles of RFID components. Experience is quickly obsolete. As such, managers and engineers deploying RFID solutions rely on reliable benchmark to facilitate their decision processes. We have presented in this paper a benchmarking process of RFID components based on the combinatorial approach. The approach addresses the problem that some RFID benchmark indices are simultaneously affected by on more than one variable. The process can be adopted for the benchmarking of components in different tiers of the RFID architecture.

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