Wireless Corrosion Monitoring for Reinforced Concrete Structures and Concrete Repair

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Table of Contents

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Chapter 1: Introduction

Reinforced concrete has been extensively used as a building material since the early 20th century and has gained some significant attention in the current field of preservation. The Solomon R. Guggenheim Museum (Frank Lloyd Wright), Curran O'toole building (Albert C. Ledner) and Silver tower (I. M. Pei) are just a few examples of the large number of reinforced concrete buildings found in New York City and around the country. The large number of buildings constructed with reinforced concrete throughout the world reflects the versatility of the material, and it is indeed one of the most successful man made construction materials. It is not only economic, fire-proof and robust, but also "can be engineered to satisfy a wide range of performance specifications, unlike other building materials, such as natural stone or steel, which generally have to be used as they are." (Meyer 2007, 1)

As the name indicates, reinforced concrete consists of reinforcement and concrete. Concrete is made of cement and sand, which creates a binding matrix as a paste form, and aggregates, which provide a desirable compressive strength. Because concrete itself lacks tensile strength, reinforcing steel is used to provide the tensile properties that are needed for concrete structures. Although steel is known to corrode when air and water are present, when sufficient cover is provided by the concrete mix, it is protected from these elements and thus in a non-corroding condition due to the high alkaline environment of the concrete (pH 12 - 13). Therefore, in most cases reinforced concrete is a durable and strong material. However, like other building materials, reinforced concrete deteriorates over time. The failure of reinforced concrete is caused by corrosion of the reinforcing steel and degradation of the concrete. These differing modes of failure can occur independently, but mutually influence one another. (Figure 1.1)

The corrosion of reinforcing steel is the most common mode of failure for reinforced concrete. Corrosion of steel in concrete is usually inhibited by a passive layer formed on the surface of the steel in the high alkaline environment. However, the protective environment is disturbed by carbonation and chloride attacks. Carbonation is the reaction between carbon dioxide (CO_2) and

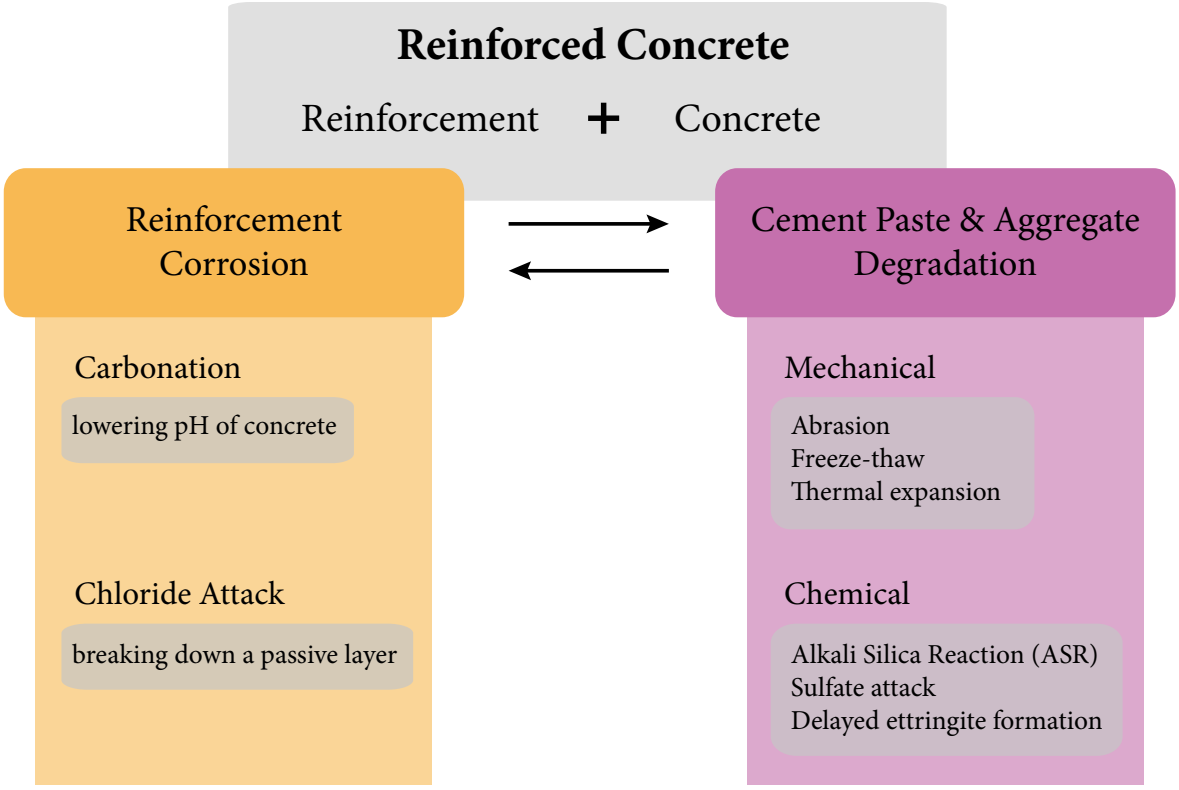

Figure 1.1 The modes of reinforced concrete failure

calcium hydroxide ($Ca(OH)_2$) within cement paste. When concrete carbonates to the depth of the reinforcement, the high alkaline environment becomes more neutral (pH 9) and the reinforcement is no longer protected from corrosion. Another factor in reinforcement corrosion is chloride ion, which can be present from sea water or deicing salts. When chloride ions reach the reinforcement, it accelerates the corrosion by breaking down the passive layer inhibiting corrosion.

The durability of concrete is also compromised by mechanical damages caused by abrasion, freeze-thaw cycles, thermal expansion, and chemical effects, such as alkali-silica reaction (ASR), delayed ettringite formation and sulfate attack. Such damages not only result hazardous situations such as of falling debris, but also make it easier for carbon dioxide and chloride ions to infiltrate to where the reinforcement exists. Therefore, the damaged concrete is much more vulnerable to carbonation and chloride attack. At the same time, cracking and spalling of concrete, which occur as a result of the rebar corrosion, accelerate the degradation of concrete by allowing more areas to be exposed to the mechanical and chemical damages.

Although both modes of failure are equally important issues, this research focuses on monitoring of the deterioration caused by corrosion of the reinforcing steel because it is the most common and serious problem for the reinforced concrete structures. Cracks and spalls on the surfaces of reinforced concrete structures are indicative of significant corrosion of reinforcing bars, which can eventually cause structural problems if left unrepaired. (Figure 1.2) Repairing seriously deteriorated reinforced concrete is difficult and costly. Even after the repair is complete, and even if more advanced materials such as high performance concrete, stainless steel or epoxy coated rebar are used, reinforced concrete is still subject to deterioration due to rebar corrosion. Therefore, it is necessary to develop an efficient long-term monitoring system that can detect rebar corrosion before it becomes a serious problem.

Loss of concrete cover due to rebar corrosion

Corroded rebar at the Guggenheim Museum, New York

Figure 1.2 Examples of the concrete deterioration caused by rebar corrosion.
(Photo courtesy of Charles Bransby-Zachary)

This thesis is initiated with the interest in searching for suitable corrosion monitoring systems that help in the preservation of important reinforced concrete buildings. Over the last two decades, Structural Health Monitoring (SHM) has become a major research topic in the civil engineering field. The primary objective of most of the researches on SHM is to prevent failures of civil infrastructures such as dams, bridges, and highways. SHM is not a completely new concept since there have been continuous efforts in monitoring the health of structures. However, traditional monitoring methods were largely dependent on scheduled visual observations and

heuristic assumptions with mathematical models of predicted behavior of structures. On the other hand, the modern SHM is computer-based system, which consists of sensors for data acquisition, a communication system, and data analysis program. (Huston 2011, 1) Recent extraordinary advances in electrical engineering, communications technology and computer science have facilitated the development of more comprehensive, efficient and cost effective structural health monitoring systems.

The purpose of this thesis research is the evaluation of the hardware of Structural Health Monitoring systems specialized for the preservation of reinforced concrete buildings.[1] Figure 1.3 shows the desirability scale of the sensor node (hardware) types by its power source and communication method. The most suitable type of sensor node for reinforced concrete building monitoring is a wireless and battery-free device so that it can be embedded in the concrete. By embedding the devices in concrete, it is possible to place sensors close to the rebars, which will allow collecting more accurate information of rebar status. In addition, embedding sensors makes it easier to deploy them throughout the structures since they can be held tightly by concrete matrix. This eliminates the possibility of losing sensors. Furthermore, embedding sensors will make them invisible so that monitoring is possible without degrading the aesthetics of building.

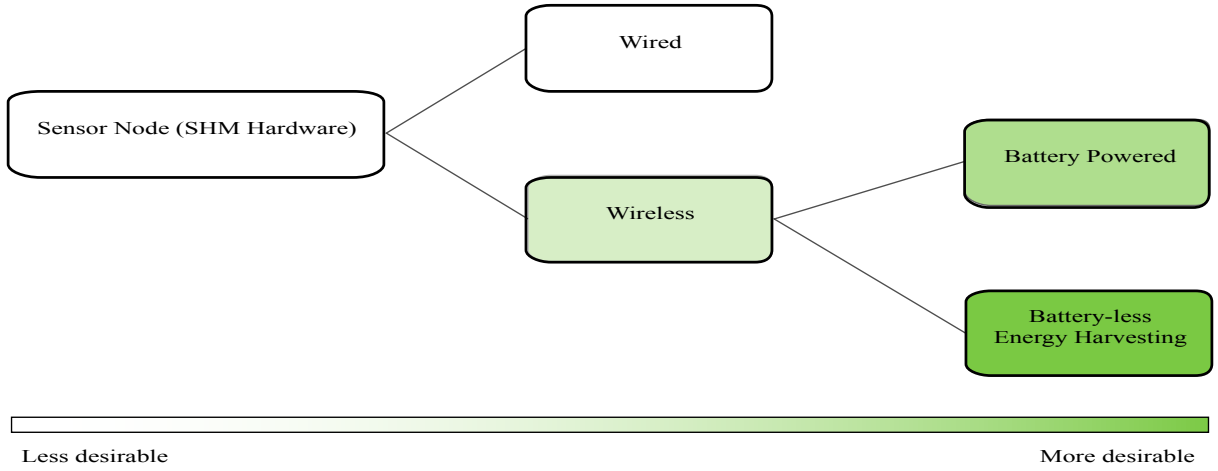

Figure 1.3 A desirability scale of sensor node types

1. Structural Health Monitoring system comprises hardware and software elements. The hardware element is a sensor node including a sensor and a sensing platform, which is the instrument that helps the operation and communication of the sensors. The software elements consist of damage modeling and damage detection algorithms. (Gopalakrishnan, Ruzzene, and Hanagud 2011, 5)

Although wired sensing methods are still most commonly used, wireless sensors have been extensively studied during the past few years in order to eliminate the significant problems in the installation and long term use of wired sensors. (Mukhopadhyay 2011, 5) Using wireless sensors can provide cost effective solutions for SHM. For example, Sukun et al. developed a prototype wireless system that costs about $600 per sensor node compared to thousands of dollars for a node with the same functionalities in a traditional wired network. (Sukun et al. 2007, 1) A wireless monitoring system is not only less costly, but also eliminates the visual disturbance caused by cables connecting sensor nodes and data collecting devices. Despite such advantages, wireless monitoring has not yet been fully accepted in the field because of the lack of stability of current wireless sensing technologies. In order to be widely accepted as a reliable means of monitoring device, it has to overcome the problems related to the propensity for interruption in data recording.

Wireless sensor nodes can be categorized into battery powered and battery-less devices. While a battery powered type operates using limited amount of power, battery-less devices harvest energy from various sources such as light, motion, vibration, strain, and RF (radio frequency). (S.W. Arms and D. Yeary 2009, 195) A fundamental drawback of the battery powered sensing device is the battery life. At some point, batteries in the sensing device need to be replaced. This is especially problematic if sensors are embedded inside of reinforced concrete. Drilling numerous holes into the building to change batteries is not a viable option. On the other hand, as long as sensor nodes are able to harvest energy they can operate perpetually without power source maintenance. (S.W. Arms and D. Yeary 2009, 204) Furthermore, sensing devices can be much smaller by eliminating the battery. The size of the sensing device is an important issue when embedded in concrete because the more space the sensing device occupies in the concrete unit, the lower the overall strength of the concrete structure will be.

A wireless and battery-free sensor node can be realized by utilizing RFID (Radio Frequency Identification) systems, which comprise a reader (interrogator) and tags (transponders). RFID tags are attached to products and this allows the items to be remotely detected by the interrogator within

its reading range, which can be a few inches to several feet, depending on the frequency used for the communication. Due to its fast reading rate and long reading range, RFID has been widely used in the retail business for efficient asset identification and product tracking for more than 30 years. In recent years, extensive research efforts have been made to incorporate passive RFID devices into Wireless Sensor Networks (WSNs). WSNs "consist of a number of sensor nodes that have the ability to sense the environment, process the collected data, and disseminate the processed data to one or more sinks." (He, Demirkol, and Heinzelman 2010, 1) Traditionally, sensor nodes used in WSNs have been powered by batteries. Researchers saw the marriage of passive RFID and WSNs as a solution for the power constraints of sensors used in WSNs. (Liu, Cheng, and Li 2009) The wireless monitoring system evaluated in this thesis is based on the framework of WSNs.

The objective of this research is to propose an efficient corrosion monitoring system for reinforced concrete structures, especially tailored for buildings. The system consists of sensing devices, interrogators, and a computer program for data processing and analysis. This thesis focuses on the development of the prototype sensing device using the off-the-shelf Generation-2 UHF (Ultra High Frequency) Passive RFID tags. A detailed explanation on RFID technology is found in Chapter 2. The sensing device evaluated in this study is a binary sensor that turns off or stops responding to the reader when exposed to a corrosive environment. The sensor is designed to detect environments that lead to the corrosion of the steel reinforcement in concrete. The sensing devices can be embedded before concrete is poured over the rebar grids. Since the sensing devices are distributed before concrete casting or pouring, the location of each sensor is known. This allows for the creation of a corrosion map of the reinforced concrete structure. Therefore it would be possible to develop a highly efficient corrosion monitoring system for both new construction and after repairs in concrete.

This research is an effort to provide another option to the building maintenance method rather than to develop a monitoring system that will take care of all the issues of the reinforced concrete structure. The sensing method studied throughout this research can be used for

supplementing other types of sensors, which can measure mechanical properties such as strain, shock, and vibration, or environmental conditions like pH, temperature, humidity, and chloride ion concentration. More thorough investigation methods such as Non-Destructive Evaluation (NDE) or even invasive methods like half-cell potential testing can be employed based on the data collected from sensors. Using multi-layer information helps owners, architects, engineers and conservators to understand what the cause of the problem is, when and where the repair is needed, and what type of intervention is necessary. The monitoring system would help us to wisely use time, money, and other resources.

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Chapter 2: Technology Review

Traditionally, corrosion of reinforcing steel bars in concrete has been evaluated by extracting samples from hardened concrete for laboratory analysis to evaluate properties such as moisture content, pH, and concentration of ions including chloride, sodium and potassium ions. Also, field tests such as Linear Polarization Resistance (LPR), half-cell potential, microcell current measurements and resistivity tests are widely used methods for corrosion analysis. Although laboratory tests and field investigations are prevailing and reliable methods for analyzing the condition of concrete, they are time-consuming and expensive. (Johnson and Kulesza 2009, 6) This is especially problematic when large areas need to be analyzed frequently.

Such difficulties have encouraged the development of embedded corrosion sensors for in-situ analysis. However, embedding sensors several inches deep in concrete brings about a new challenge: how are the data retrieved from the sensors? The simplest answer is to embed sensors and connect them to a data logger with cables. One of the early versions of the embedded sensing system for corrosion monitoring was invented in 2001 by Kelley et al. at Virginia Technologies Inc. (Kelly et al. 2004) Their patented device (Figure 2.1), Embedded Corrosion Instrument (ECI), has been used for monitoring corrosion factors including open circuit potential, linear polarization resistance (LPR), resistivity, chloride ion concentration, and temperature. Multiple ECI units can be connected via cables to a data logger, which is not embedded in the concrete, and then the collected data can be downloaded by wireless transceiver and cellular modem without visiting the site. The ECI provides rich information for corrosion analysis of the concrete structure, and it is certainly a cost efficient monitoring method compared to traditional methods. However, it is still relatively costly compared to the wireless sensing methods because of the necessity for cable installation for connecting sensors to data loggers. Also, it is less desirable for building monitoring in that wires and external devices may degrade the aesthetics of building. How do we collect sensor data without using wires?

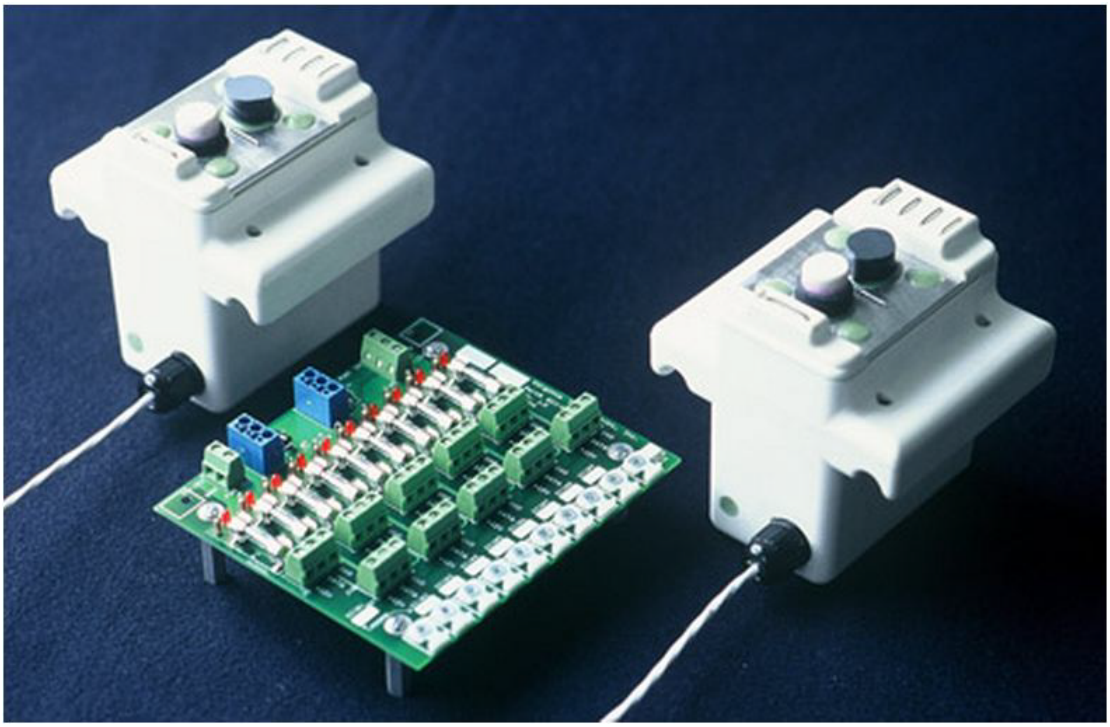

Figure 2.1 Embedded Corrosion Instrument (photo courtesy of Virginia Technologies Inc.)

Even though the ECI system currently being used does not facilitate wireless communication, the inventors of ECI claimed wireless connection between ECI units and the data logger using Radio Frequency Identification (RFID) in their patent. (Kelly et al. 2004) Indeed, many researchers have found that RFID technology to be suitable means for remote sensing for reinforced concrete because of the ability of radio waves to penetrate through concrete mass. Many wireless and battery-less embedded corrosion sensing devices for reinforced concrete structures including Smart Pebble (Watters et al. 2003), Smart Aggregate (Carkhuff and Cain 2003), MEMS Concrete Monitoring System (Johnson and Kulesza 2009), and Passive Wireless Corrosion Sensor (Apblett and Materer 2010) and Embedded Wireless Corrosion Sensor (Apblett, Ley, and Materer 2012) are based on the RFID technology. Since the RFID is the core of wireless and battery-less sensing devices discussed in this study, it is necessary to provide basic information on RFID technology before reviewing the devices mentioned above.

2.1 What is RFID (Radio Frequency Identification)?

The RFID technology is an automatic identification system that has been widely used for more than 30 years. (Rida, Yang, and Tentzeris 2010, 21) Indeed, the RFID system is extensively used in our everyday life. Smart Card that allows authorized people to enter the facilities such as offices and school libraries contains an RFID tag. EZ-Pass used at highway and bridge toll gates also uses the RFID technology. The system is now being integrated into smart phones to allow the Near Field Communication (NFC), which allows applications such as Google Wallet to function. How does it work and what are the components of the system?

The RFID system consists of *tags* (*transponders*) and a *reader* or (*interrogator*). The tags contain information unique to their identification, and they send a response back to the reader once they receive an electromagnetic signal from the interrogator. The basic structure of an RFID system is illustrated in Figure 2.2. The essential components of RFID tags are the integrated circuit (IC) chip (also referred to as IC, chip, or microchip) and the tag antenna connected to the IC chip. Figure 2.3 shows examples of passive UHF (Ultra-High Frequency) RFID tags and Figure 2.4 shows the structure of a passive UHF RFID tag with a dipole antenna.

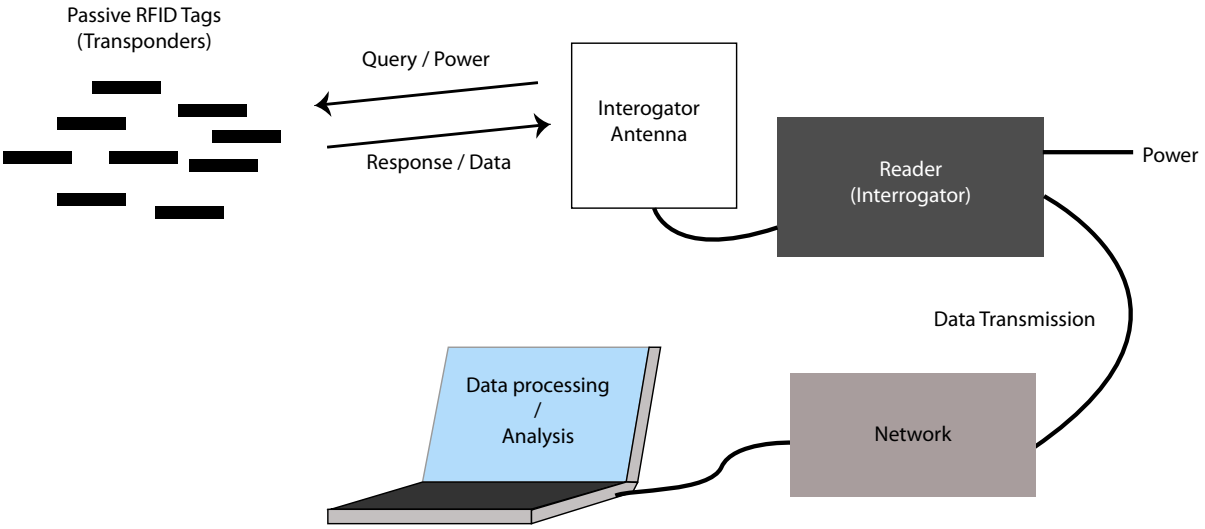

Figure 2.2 Basic structure of passive RFID system

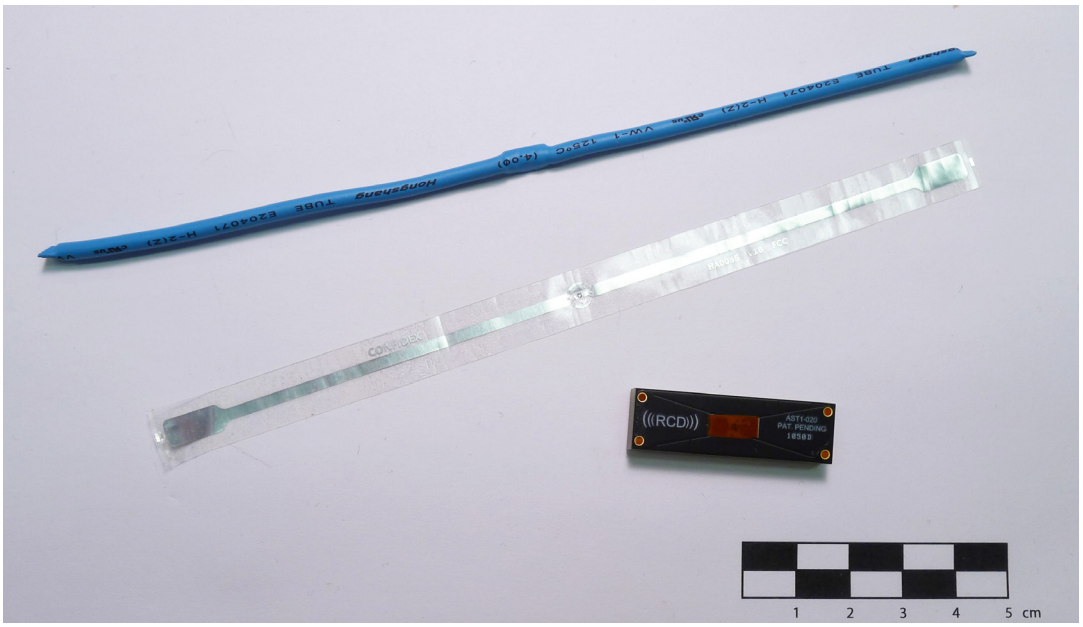

Figure 2.3 Examples of passive UHF RFID tags

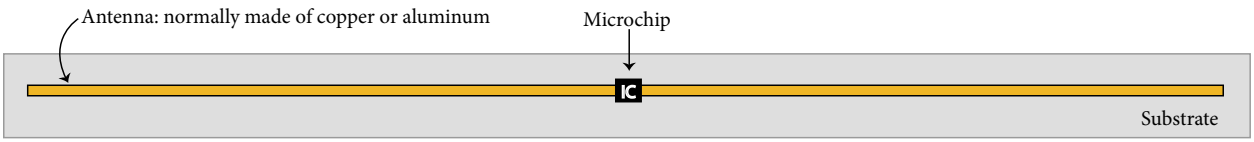

Figure 2.4 The structure of passive UHF RFID tag with a dipole antenna

The microchip not only carries tag information but also harvests power from the electromagnetic field generated by the interrogator. The antenna is an integral part of the RFID tags. Lozano-Nieto clearly defines the function of the antenna.

> "The purpose of the antenna in the transponder of an RFID system is multiple: first, it has to collect power from the electromagnetic field generated by the reader. In addition, the antenna must transfer the collected power to its load that is the chip in the transponder in order to turn it on. Finally, the antenna must radiate the data signals generated by the chip back to the interrogator." (Lozano-Nieto 2011, 13)

The shape and size of the antenna have significantly influence on the RFID communication, and different types of antenna are used in different frequency bands.

Frequency bands for the RFID system can be divided into Low Frequency (LF), High Frequency (HF), Ultra-High Frequency (UHF), and Microwaves. Table 2.1 shows general information of the frequency bands used for passive RFID tags. Normally, the higher the frequency, the faster is the read rate and the longer the read range. However, higher frequency means that it is

more affected by metals and more subject to attenuation when traveling through water. (Lozano-Nieto 2011, 8)

Frequency Band		Frequency Range (wavelength)	Typical Frequencies Used in RFID Systems	Approximate Operating Range of Passive tags
Near Field	Low Frequency (LF)	100 kHz – 500 kHz	125 kHz, 134 kHz	Few inches
	High Frequency (HF)	10 MHz – 15 MHz	13.56 MHz	3 feet
Far Field	Ultra-High Frequency (UHF)	400 MHz – 950 MHz	866 MHz (Europe), 915 MHz (USA)	20 feet
	Microwaves	2.4 GHz – 6.8 GHz	2.4 GHz, 5.8 GHz	15 feet

Table 2.1 Commonly used frequency bands for RFID systems[1]

These frequency bands can be categorized into two different type of coupling: Near-field/inductive coupling and Far-field/backscatter coupling. "Coupling is basically the transfer of electromagnetic energy from one medium (reader/tag) to the other medium (tag/reader)." (Karmakar and Roy 2010, 22) Low frequency and high frequency use inductive coupling whereas ultra-high frequency and microwave use backscatter coupling. Use of the different energy transfer methods affects the distance over which the power can be transferred, which also governs the read range. As indicated in their name, the Far-field (Backscatter) coupling method offers significantly longer communication distance compared to the Near-field (inductive) coupling method.

There are two different types of RFID tags: active and passive. Active tags generally have extended reading ranges because of the use of the onboard battery. However, passive RFID tags are the most commonly used because of their low cost, small size, and simple architecture. Since they harvest energy from the interrogator for operation, it is suitable for wireless and battery-free communication. Therefore, the passive RFID tags will be the backbone of this research.[2]

1. The table was made based on information from following references: (Lozano-Nieto 2011, 8) and (Karmakar and Roy 2010, 31 - 32) The maximum read range shown in the table is not a fixed value, but rather an approximate figure. It should be noted that the maximum read range can be affected by various factors such as the size and the type of tags and reader antenna. Furthermore, the maximum reading range is when it is used in air.

2. Although the interrogator (reader) is the most important port of an RFID system after the tags, this part is intentionally excluded in order to confine the scope of this study.

2.2 Previously developed wireless and battery-less sensing devices

As discussed above, passive RFID technology makes wireless and battery-less sensing possible. Based on this technology, many different sensing devices have been developed. The following four sensing devices were selected for a review because they are specially designed for corrosion monitoring of reinforced concrete structures: Smart Pebble (Watters et al. 2003), Smart Aggregate (Carkhuff and Cain 2003), MEMS Concrete Monitoring System (Johnson and Kulesza 2009), and Passive Wireless Corrosion Sensor (Apblett and Materer 2010) and Embedded Wireless Corrosion Sensor (Apblett, Ley, and Materer 2012). Any other sensing devices, which measure mechanical properties such as strain, vibration or fatigue, despite their importance, are excluded from this review.

The inventors tend to publish their research after they file the patent. Sometimes even after a patent is granted, detailed research papers on such devices are not readily available. This was especially the case for the invention of Johnson & Kulesza and Apblett et al.[3] Because of the nature of patent, which discloses the invention in a vague way and tries to cover a broad range of similar devices, it is difficult to determine if the devices are truly useful for real world application. Nevertheless, reviewing the previous development is a good way to learn about the technological trend, and helpful for proposing a suitable corrosion monitoring system for the preservation application.

2.2.1 Smart Pebbles™

Watters et al. at SRI International developed Smart Pebbles™ (Figure 2.5), a wireless sensing device for monitoring chloride ion concentration in concrete bridge decks.[4] (Watters et al. 2003) Its name originated from the similarity of its size (about one cubic inch) and weight to a

3. Apblett et al., were granted their first patent in 2010 (US 7,675,295), but there is no academic article published regarding the earlier invention. The information on their invention other than the patent is only available in *Winter 2011 OkTC Newsletter*. (Materer and Ley 2011)

4. The project was completed in cooperation with FHWA (Federal Highway Administration) under sponsorship of California Department of Transportation.

typical piece of the rock aggregate used in infrastructure construction. It consists of a chloride ion threshold sensor, an antenna made of a copper coil, and a microchip. It can be queried remotely for locating it, transferring the sensor data, and harvesting energy from radio-frequency. The radio frequency used for the device is 125 kHz (Low Frequency).[5] The architecture of Smart Pebbles™ is well illustrated in Figure 2.6.

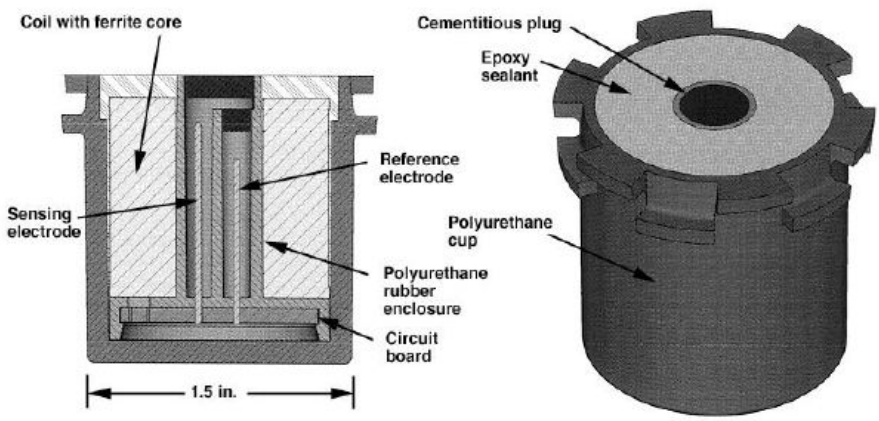

Figure 2.5 Smart Pebbles™ (drawing courtesy of Watters et al.)

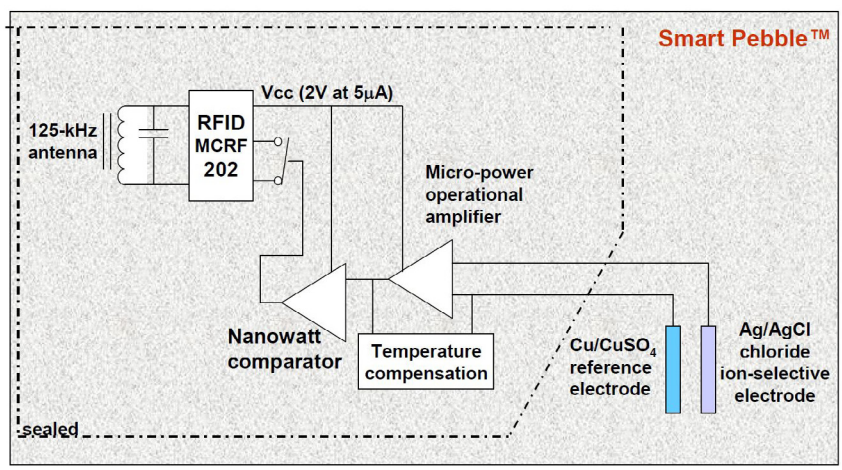

Figure 2.6 Architecture of Smart Pebbles™ (drawing courtesy of Watters et al.)

It is embedded at the depth above the steel reinforcement so that the sensor can detect chloride ion ingression before chloride ions reach the rebars. According to the developers, it can be interrogated from a distance of 6 inches, when embedded in concrete.[6] The electrochemical chloride

5. Although the possible use of 13.56 MHz (High Frequency) RFID chips for the future devices was mentioned, there is no further information on this research.

6. Despite the fact that no direct mention on specific depth for the location of Smart Pebble can be found, it seems that the developers set 4 inch for their experiment environment.

ion threshold sensor consists of two electrodes: a chloride ions sensitive electrode and a reference electrode. The measured quantity is the potential difference between the two electrodes. When the chloride ion concentration is under a pre-determined threshold value, the RFID transponder responds to the interrogator queries with its 32-bit identification code, but when the chloride ion concentration is above the threshold, the sensor changes state and the RFID tag responds to interrogator queries with the inverted identification code. Therefore, it is a binary sensor, which acts like a switch, and cannot measure and record the actual chloride ion concentration.

The researchers found that the electrochemical sensor has limited stability. In fact, this is the most significant drawback of chemical sensors. Any other sensing devices using chemical sensors will have limited service life because of the sensor instability over time. The researchers also mentioned possible development of sensors for other important quantities such as pH, conductivity, moisture, polarization resistance, and temperature. However, there is no more information available on the additional research.[7]

2.2.2 Smart Aggregate

Carkhuff and Cain at the Johns Hopkins University Applied Physics Laboratory developed Smart Aggregate (Figure 2.7) in 2003. (Carkhuff and Cain 2003) Despite their similar name, Smart Aggregate and Smart Pebble are quite dissimilar devices. The fundamental difference is that Smart Aggregate uses a microcontroller whereas the Smart Pebbles uses a microchip. A microcontroller contains a microprocessor and memory, clock, and other systems such as ADC (analog-to-digital convertor) and an on-board temperature sensor.[8] Due to its computation capability, a microcontroller is much more powerful and versatile than the simple microchip while performing all the functions of a microchip. Owing to the use of the microcontroller, Smart Aggregate is able to *measure* the sensor output.

7. The SRI International, the assignee of the patent, does not provide any information of Smart Pebbles on their website.

8. The MCU (microcontroller) used in Smart Aggregate does not include a temperature sensor.

However, the microcontroller consumes much greater amounts of energy compared to the microchip. This has a significant effect on the maximum operation range of the device. The more energy is consumed, the closer the energy source needs to be located. Therefore, there is a tradeoff when choosing either a microchip or microcontroller. It seems that the use of the microcontroller led the researchers to use high frequency (HF) for the communication band because a high frequency band offers a slightly longer read range compared to the low frequency used by Smart Pebble™.[9]

Upon selecting sensors, the researchers looked at environmental parameters such as pH, chloride ion concentration, oxygen level, concrete conductivity, and temperature. Of these, conductivity and temperature sensors were incorporated. For conductivity measurement, two electrodes, which are switchable constant current sources, were used. For temperature measurement, they used National Semiconductor LM20. The strength of this device is that it contains plural analog channels where sensors can be connected. Therefore, it allows the multiple sensors to be applied so that various properties such as pH, pressure, strain, stress, vibration, etc. The researchers indicated that they will keep upgrading the device for less power consumption and application of different types of sensors for pH and chloride ion concentration measurement. Unfortunately, it appears that no further research has been carried out.

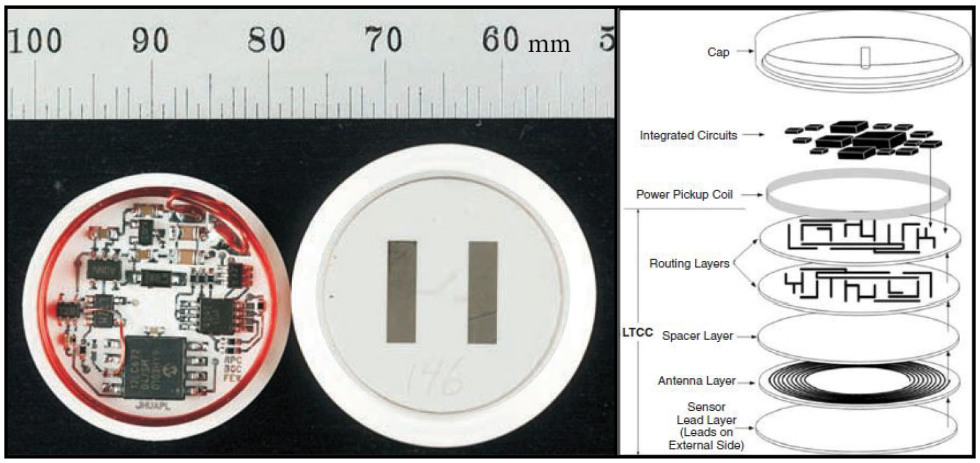

Figure 2.7 Smart Aggregate (photo courtesy of Carkhuff and Cain)

9. Smart Aggregate uses two different wavelengths: 1 MHz for powering the device and 10.5 MHz for data retrieving. "Power is transmitted to the device via near-field induction coupling, while data are transmitted out of the device by a modulated radio frequency (RF) signal." (Carkhuff and Cain 2003, 20) It seems that they concluded that using 1 MHz induction field would provide sufficient power to the device embedded 4 to 6 inches within the concrete.

2.2.3 Sensor for Monitoring Environmental Parameters in Concrete

Johnson and Kulesza at Advanced Design Consulting USA, Inc. invented the "Sensor for monitoring environmental parameters in concrete" in 2003.[10] (Johnson and Kulesza 2009) This device is unique because it employs an active material for sensing, which is liable to respond to at least one environmental parameter in concrete such as moisture content, temperature, pH, and ion concentration including chloride, sodium or potassium ion. The active materials suggested in the patent are dielectric material and a hydrogel.[11] Change of the status of the active material causes a change a capacitor or MEMS (Microelectromechanical systems) device. The capacitive element, which is illustrated as C2 in Figure 2.8, is a part of a RFID L-R-C circuit where L is the antenna's inductance, R is resistance and C is capacitance. Therefore, the change in the capacitive element (C2) results in shifting of the resonance frequency of the device within the assigned frequency band. Consequently, it is possible to measure the change in the environmental parameter by comparing the changed resonance frequency to the original resonance frequency. Since the sensor device also returns a unique identification number, it is possible to correlate the collected data to the location of the sensor.

The assigned frequency band for the device is not specified in that the patent tries to cover every possible frequency band used in the US. However, the inventors particularly emphasized on the use of the 13.56 MHz for the excitation of the device and 27.125 MHz for the re-radiation of signal. On the other hand, it appears that the 915 MHz (UHF) is almost neglected by the inventors despite the long communication range of UHF based devices. Since there is no more information on whether there is a prototype or it is actually tested in the field, it is not possible to review more than what the patent provides.

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10. It was filed on Dec. 10, 2003 and patented on Jun. 23, 2009. Assignee is Advanced Design Consulting USA, Inc., Lansing, NY (US). Patent number is US 7,551,058 B1.

11. "Dielectric materials that respond to pH are well known in the art and include, but are not limited to: PMMA, poly(2-hydroxyethyl methacrylate (HEMA)) and hydrogels such as copolymerized N-isopropyl acrylamide (NIPAAm) and acrylic acid (AAc). In one embodiment, acrylic acid (AAc), which is sensitive over the range of 2-12, is used." (Johnson & Kulesza, 2009, pp. 15 - 16)

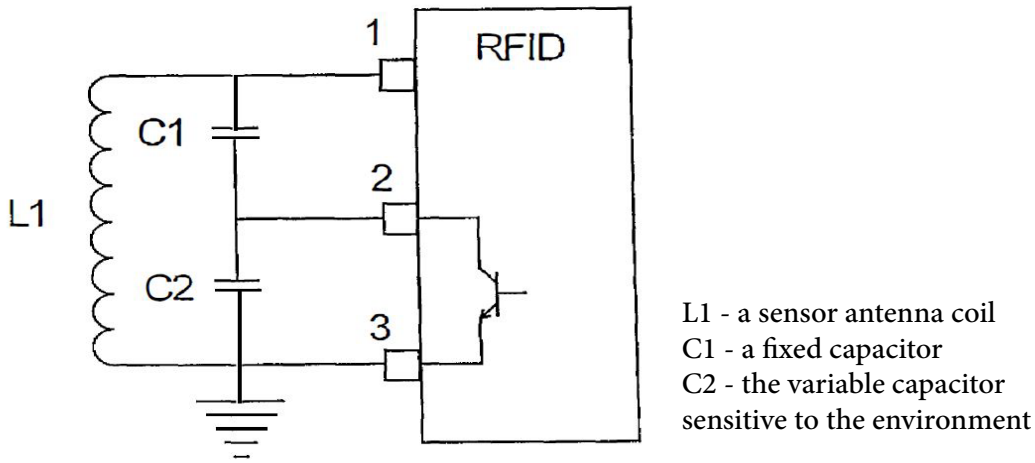

Figure 2.8 Drawing of the L-R-C circuit (drawing courtesy of Johnson and Kulesza)

2.2.4 Passive Wireless Corrosion Sensor and Embedded Wireless Corrosion Sensor

Apblett, et al. at Oklahoma State University invented the Embedded Wireless Corrosion Sensor in 2010. (Apblett, Ley, and Materer 2012) It is based on their previous invention "Passive Wireless Corrosion Sensor" in 2009. (Apblett and Materer 2010) In the first invention, they developed a sensing device that uses a corrosion sensitive material, which resembles the monitored object (i.e. steel reinforcement), as a part of the tag antenna. (Figure 2.9) When the sensor is exposed to corrosive environment, the corrosion sensitive material creates a non-conductive link between the antenna and the microchip. This triggers the sensor to stop responding by significantly dropping the performance of the tag antenna. Because the device is only able to provide on/off status, it is binary. In another embodiment, several sensitive materials or triggers varying their thickness can be employed so that the different level of corrosion can be detected. The sensor sends out information whether the corrosion is insignificant, substantial, or severe based on the status of each of the corrosion sensitive elements with different thickness. In this case, a CMOS (complementary-symmetry metal-oxide-semiconductor) chip is necessary to perform the computation, which is impossible when using a microchip.

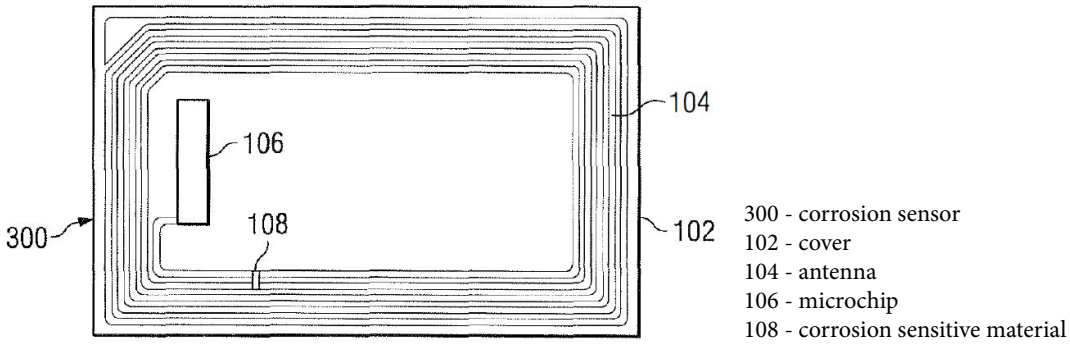

Figure 2.9 Structure of the Passive Wireless Corrosion Sensor
(drawing courtesy of Apblett & Materer)

Since this device is designed from a modification of already available commercial high frequency RFID tags, it is not only simple, but also cost efficient. Despite such advantages, the invention has two drawbacks. First, it is difficult to know that if the tag stopped responding because of corrosion or a malfunction of the sensor. Second, it is difficult to control the sensor's sensitivity, which is determined by the thickness of the corrosion sensitive material. It is also difficult to know whether a certain thickness would be too sensitive or too insensitive. (Roberti 2010)

In the second invention made in 2010, the microchip is replaced with a microcontroller, which is programmed to harvest energy from the antenna and test for the status of the corrosion sensitive element, and then transmit the test results back to the interrogator. The microcontroller tests the continuity or resistance of the corrosion sensitive material. If the resistance is infinite, there may be a significant level of corrosion. The prototype sensor (Figure 2.10) presented in 2011 "can respond with different identification numbers based on the status of up to four trigger links." (Materer and Ley 2011, 7)

Figure 2.10 A prototype Embedded Wireless Corrosion Sensor.
The device is roughly the size of a quarter.
(photo courtesy of Mater & Ley)

Unlike the first invention, whose device stops responding once the corrosion sensitive material is corroded, the sensing device of the second invention continues to work even after the sensitive materials are corroded. This is because the corrosion sensitive material is not a part of the tag antenna, which was the case for the first invention. This solves the first problem of the first invention, for which it is difficult to say if the corrosion happened or the device is broken. However, it appears that the second problem of controlling the sensor's sensitivity still needs to be solved because the inventors proposed using different thicknesses of the triggers for detecting different levels of corrosion.

Another difference between the first and the second inventions is the change of antenna from the flat square antenna to a coiled copper antenna. This means that the operation frequency band of the device was changed from high frequency to low frequency. The inventors explained that the reason for choosing low frequency band.

> "Although the sensor of the present disclosure may be able to operate with RFID systems of almost any frequency, the intended use of the sensor, being buried within a concrete structure, may dictate that the most useful frequencies are along the order of kilohertz rather than in the megahertz bands. In one embodiment, the frequency will be about 125 KHz. At this frequency, the supplied energy may come from magnetic induction in the near field range. The 125 KHz frequency is virtually transparent to soil, concrete, paper, water, conductive liquids and slurries." (Apblett, Ley, and Materer 2012, 2)

However, they did not explicitly mention the limitation of using low frequency band, which has a very short read range of only a few inches. Therefore the interrogator needs to be located in very close proximity to the sensor.[12]

2.3 A different approach

The table 2.2 is the summary of the four examples reviewed in this chapter. It shows that all of the devices operate in the frequency bands using the Near-field (inductive) coupling, which

12. It is noticeable that the device invented by Carkhuff and Cain, which also uses a microcontroller, operates in high frequency while the device invented by Apblett et al. uses low frequency.

offers the relatively short communication range of a few inches to less than a foot. The maximum reading range of the devices includes the depth of embedded sensors from the concrete surface, which is usually 2.5 to 3 inch deep. Therefore, the interrogator has to be located close, less than a foot, to the concrete surface to read the sensor data. Such a short range may be sufficient for a certain situations when using a portable interrogator. However, the short range devices are less desirable for building monitoring because some areas can be difficult to reach.

Inventors	Frequency	Target parameters	Processing device	Approximate Size	Max Read Range
Watters et al.	LF	Chloride ion concentration	Microchip	1 cubic inch	Approx. 6”
Carkhuff and Cain	HF	Temperature & Resistivity	Microcontroller	About size of a quarter	Approx. 6”
Johnson and Kulesza	HF	Environmental parameters	Microchip	Unspecified	Approx. 10”
Apblett and Materer (2009)	HF	Corrosion	Microchip	Unspecified	Unspecified
Apblett et al. (2010)	LF	Corrosion	Microcontroller	About size of a quarter	Unspecified

Table 2.2 Summary of the previously developed sensing devices

The four sensing devices focus on corrosion monitoring of concrete bridge decks because it was the primary interest of the inventors or their funding group. Therefore, a vehicle loading a portable interrogator can drive over the monitored area where the sensors are embedded as many time as desired. On the other hand, in case of the building, the areas that are prone to the corrosion due to weathering are the exterior elements such as walls and parapet, which are vertical elements. Therefore, it is difficult to imagine someone holding a portable interrogator climbing up and down the building every day, week or even month. What would be the alternative method for monitoring buildings?

Sensing devices operating in the ultra-high frequency (UHF) band would offer more options for a building monitoring system because of the significantly longer reading distance of UHF systems compared to the devices using Near-field coupling (LF and HF). The reading range of typical UHF systems is roughly twenty feet or even more depending on the specifications of

the transponder and the interrogator. Therefore, a monitoring system using UHF would be less constrained by the reading range. This would allow for a stationary interrogator, which is capable of using multiple antennas kept at different angles. Since the focus of this research is a building monitoring system, the interrogators will be installed inside of the building, and it would be easy to provide power to the stationary interrogators. By deploying several interrogators equipped with multiple antennas, it would be possible to create a wireless monitoring zone covering the entire building. This configuration would help realization of a fully automated real-time monitoring system.

However, despite of the great advantage of having long reading range, UHF systems are known for their poor performance in the vicinity of water and metals. Water absorbs UHF electromagnetic waves and metals reflect UHF electromagnetic waves. Moreover, concrete being a dielectric material causes the loss of electromagnetic field. (Antoine 1998) The electromagnetic waves dwindle when they pass through concrete due to the complex permittivity and conductivity of concrete. (Punjala and Makki 2009) It seems that UHF is inadequate for the corrosion monitoring of reinforced concrete structure because steel and concrete, the fundamental materials of reinforced concrete, are known to cause attenuation.

However, in recent years, companies have developed special UHF tags designed to overcome these challenges. For instance, Confidex solved the problem simply by creating a gap between the UHF tag and any interfering metals. RCD technology, on the other hands, designed tags that take advantage of the metallic substrate to which the tag is attached. Sakama invented the passive RFID tag that uses reinforcing bars in a concrete structure as a sub-antenna so that the tag can be mounted close to the reinforcing bars while making the tag size small and widening the reading range. (Sakama 2009) Also, researchers have developed ways to mitigate the problem of the losses of the electromagnetic field caused by concrete's dielectric properties. Rad and Shafai discovered that casing the antenna with a cover layer significantly improves antenna gain when embedded in concrete. (Rad and Shafai 2008) Jeong and Son developed a new UHF RFID tag antenna design

that has a long read range of about 12.8 m (approximately 42 ft.) when embedded in depth of 4 cm (1.6 in.).[13] (Jeong and Son 2011) Seeing promising progress in the current UHF RFID technology, the Intelligent Aggregate System (IAS), based on the Generation 2 UHF Passive RFID technology, is proposed in the following chapter as an efficient monitoring system for reinforced concrete buildings.[14]

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Punjala, S. S., and K. Makki. 2009. Wireless powering of sensors in free space and concrete medium. Paper read at Antenna Technology and Applied Electromagnetics and the Canadian Radio Science Meeting, 2009. ANTEM/URSI 2009. 13th International Symposium on, 15-18 Feb. 2009.

13. "The proposed antenna consists of a ceramic patch, a parasitic patch (PP), and a metal cavity (MC). The gain of the proposed antenna is highly improved using a PP and an MC because they decrease the electromagnetic energy flow into the concrete floor and increase the directivity and radiation efficiency of the antenna." (Jeong and Son 2011, 1)

14. Generation 2 transponders can be read by the interrogator from any other manufacturers. It is also more reliable and support faster read rate than Generation 1 transponders.

Rad, M. F., and L. Shafai. 2008. Embedded microstrip patch antenna for structural health monitoring applications. Paper read at Antennas and Propagation Society International Symposium, 2008. AP-S 2008. IEEE, 5-11 July 2008.

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Chapter 3: Intelligent Aggregate System

As discussed in Chapter 2, the ultra-high frequency (UHF) band would be suitable for the Intelligent Aggregate System because of its long communication distance. Although the UHF band ranges from 400 MHz to 950 MHz, the frequency discussed in this research is 915MHz since it is the US standard for the passive RFID system. The monitoring system can be categorized into three areas: sensing, data collecting, and computing. (Figure 3.1)

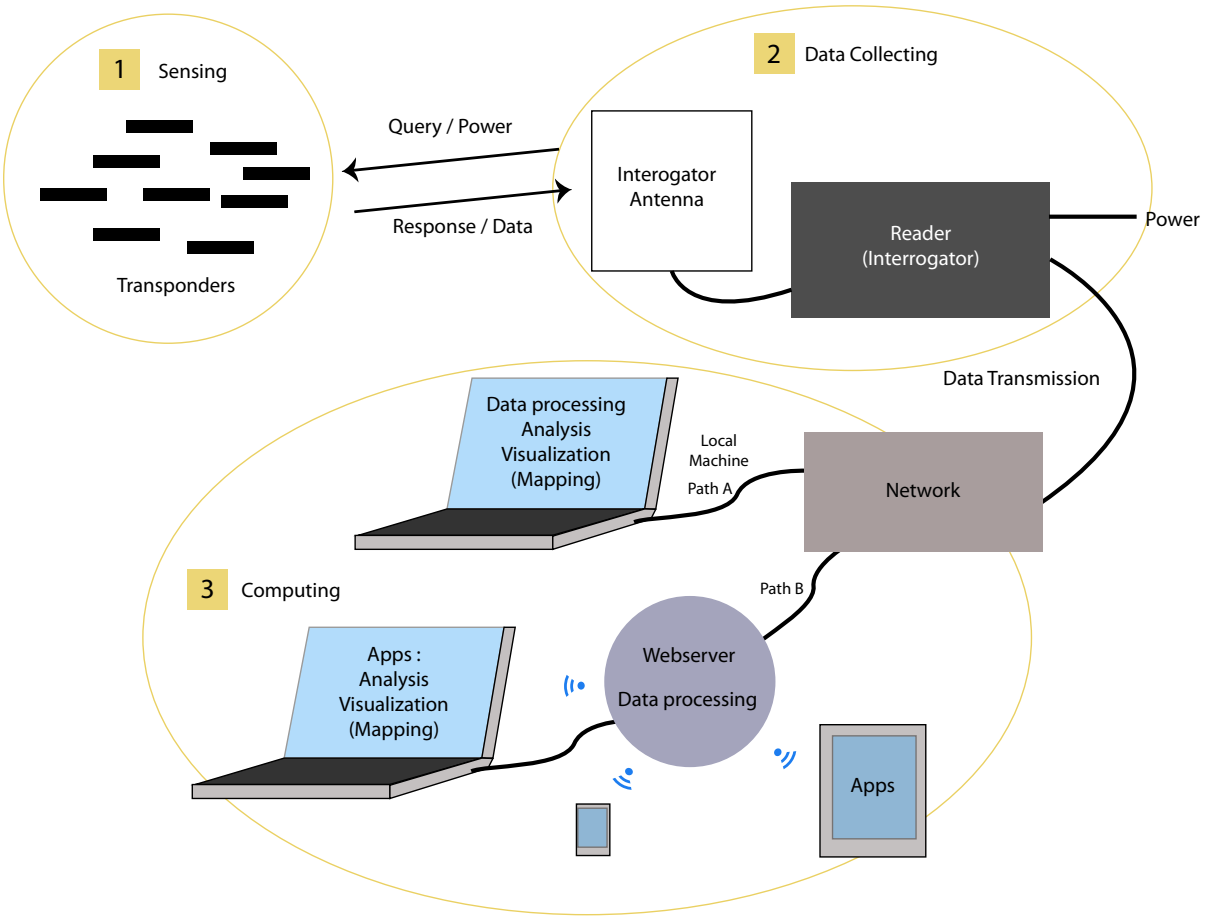

Figure 3.1 Structure of the Intelligent Aggregate System

The sensing area is where the sensing devices measure or detect the target parameters, which is corrosion of rebar in the case of the Intelligent Aggregate System. The devices embedded in the concrete to sense the environmental condition of the reinforced concrete belong to this area. At the data collecting area, the interrogators provide power to the sensing devices and set up the

communication with the sensing devices via the interrogator antenna. Then the data collected by the interrogators is transmitted to the computing area, where the data can be stored, interpreted and analyzed. Each of the elements has significant influence on the efficiency of the monitoring system; therefore, it is ideal to develop the whole system together for the best performance.

However, this thesis research is about introducing the concept of the wireless monitoring system in the context of historic preservation and building maintenance, rather than trying to develop every single element of the entire monitoring system, since it is only possible when cooperating with experts in antenna, RFID, and electrical and computer engineering. In order to prove the feasibility of the Intelligent Aggregate System, the designs of the prototype sensing device are presented and tested to verify their validity. The prototype sensing device designed in this study is named as Intelligent Aggregate (IA) due to their sensing capacity and nature of being embedded in concrete. The prototype device will be the proof of the concept rather than a fully functioning device. In this chapter, the design of the prototype Intelligent Aggregate is introduced. Then, the mechanism of the Intelligent Aggregate System (IAS) based on Intelligent Aggregate as a sensing device is explained. However, first and foremost, it is essential to understand the tag antenna based sensing, the sensing principle behind the whole system presented here.

3.1 Tag Antenna Based Sensing

The aim of this thesis is to find an appropriate wireless monitoring system for the corrosion of the steel reinforcement in concrete buildings. Generally, it takes a relatively long time to develop serious corrosion in the reinforced concrete buildings.[1] In contrast, the reinforcements in the concrete bridge decks or roadbeds can be severely corroded in a short period of time because of high concentration of chloride ion from deicing salts. Therefore, it is particularly important to use a sensor that is reliable and stable over long period of time for building monitoring. The longevity of the sensor is an important issue for embedded sensing devices because its limited life would

1. The rate of corrosion development is site specific and micro environment sensitive.

bring the same problem as battery replacement in other systems. If the sensor is damaged before the corrosion becomes a problem, the sensing device is useless or even misleading. In addition, the sensors should be able to operate with a small amount of energy provided from the microchip or microcontroller. Furthermore, the sensor size should be small since the application is to embed the sensing device in concrete. The author initially looked for pH, chloride ion concentration, and corrosion sensors fulfilling the requirements stated above. Unfortunately, such sensors were commercially unavailable for this research.[2]

The prototype Intelligent Aggregate employs the tag antenna based sensing, which uses the tag antenna as sensing means as opposed to the methods using the microchip or microcontroller as a sensing interface. This method does not utilize external sensors, which can become unstable over a long period of time.[3] The principle of the tag antenna based sensing is based on relating the changes in tag performance to the changes of target parameters such as corrosion, strain and loading in a target environment or location. In other words, the sensing mechanism is based on tag antenna attenuation with respect to the changes in the monitored environment. In addition to the benefits of avoiding issues from the external sensors, the tag antenna based sensing method also provides a cost effective solution for the wireless monitoring system since it uses the tag antenna as a sensor with little or no modification of a conventional RFID tags.[4]

One of the examples of the antenna based sensing is the RFID Deflection Sensor system proposed by Bhattacharyya, et al. at the Auto-ID Labs of MIT. (Bhattacharyya, Floerkemeier, and Sarma 2009) They tested the feasibility of the tag antenna based sensing system for detecting structural deformation by utilizing the degradation of passive UHF tags performance in the presence of metal, which is a well-known limitation of the UHF RFID system. Their system consists

2. Initially, WISP (Wireless Identification and Sensing Platform), which is a multi-purpose wireless sensing platform developed by Intel, was selected as a sensing platform. (Smith et al. 2006) Unfortunately, sensors compatible with WISP were unavailable for the specific aim of this research.

3. The long term stability problem was especially evident in Smart Pebble ™. (Watters et al. 2003)

4. The cost of RFID tags is determined by their complexity and structure. Of many different types of RFID tags, durable tags, "which can be mounted on metal, reusable plastic containers, or other items that can encounter harsh environmental conditions," cost average of 75.0¢ to $3.50. (Sirico and Davenport 2011)

of a conventional RFID reader, passive UHF RFID tags and a metal plate attached to the structural member to be monitored. The location of RFID tag is fixed while the metal plate moves as the structural member deforms under loading. (Figure 3.2) The researchers found that the closer the metal plate is located to the tag, the more power is required to turn the microchip on, and the less backscatter power emitted from the tag is received by the reader.

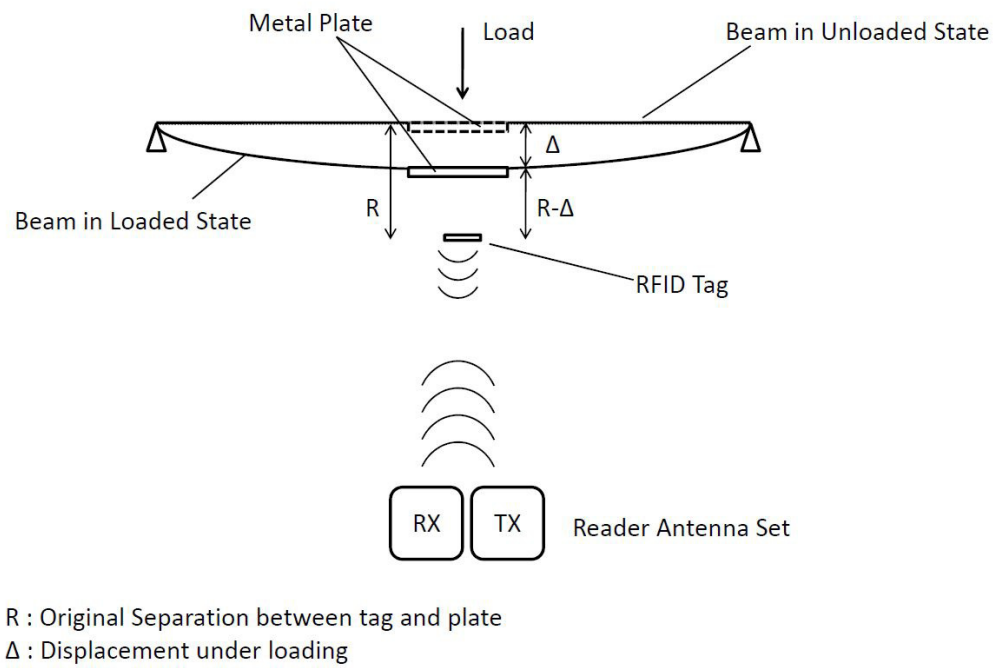

Figure 3.2 RFID Displacement sensor setup (drawing courtesy of Bhattacharyya, et al.)

Another example of tag antenna based sensing is the Passive Wireless Corrosion Sensor invented by Apblett and Materer at The Oklahoma Transportation Center (OkTC) of Oklahoma State University.[5] (Apblett and Materer 2010) Different from the researchers at the Auto-ID Labs, who did not make any change to a RFID tag, they modified the antenna of a conventional HF (high frequency) RFID tag to have a corrosion sensitive material linking the tag antenna and the IC. (Figure 2.10) The corrosion sensitive material becomes non-conductive once severely corroded and this cuts off connection between the tag antenna and the IC, making the tag to stop responding.

5. Please see 2.2.4 Embedded Wireless Corrosion Sensor in Chapter 2.

Therefore, this is somewhat different from the research at the Auto ID lab since it utilizes the reduction of usable antenna length as a cause of attenuation.

Despite the differences, the principle of the sensing mechanism of the RFID Deflection Sensor system and the Passive Wireless Corrosion Sensor is the same in that they both utilize the tag antenna performance as a sensing metric. Since IA also follows the principle of the tag antenna based sensing, it is necessary to understand the principle of the antenna based sensing, utilizing antenna impedance alteration. Therefore, first and foremost, it is important to understand what the impedance is. The impedance can be expressed as, $Z = R + jX$, where Z is impedance, R is radiative resistance, j is a phase of voltage and current, and X is reactance, which consists of inductance (X_L) and capacitance (X_C). The impedance variation occurs when these parameters change, and they are mostly influenced by the type of metal, shape, length and thickness of the antenna.

When RFID tags are designed, the antenna impedance (*Za*) is designed to conjugately match the IC impedance (*Zc*) as close as possible so that the amount of transmitted power required for activating the chip can be minimized. (Rida, Yang, and Tentzeris 2010, 29-30) Therefore, by deliberately altering the antenna impedance, it is possible to dissipate the performance of the passive RFID tags. In the previous examples, each method utilizes impedance change in slightly different ways. The RFID Deflection Sensor system utilizes the mismatch of the IC impedance (*Zc*) and the tag antenna impedance (*Za*) altered by the presence of metal plate, which resulted in an increase of the reflection coefficient $\Gamma_{tag} = Zc - Za / Zc + Za$. Consequently, increased reflection coefficient reduces the power available to the chip. (Bhattacharyya, Floerkemeier, and Sarma 2009, 97)Floerkemeier, and Sarma 2009, 97 In case of the Passive Wireless Corrosion Sensor, the antenna impedance is modified due to the reduction of the useable antenna area. A prototype IA is designed by following the principle of the tag antenna based sensing.

3.2 Design of the Intelligent Aggregate (IA)

The design of the prototype Intelligent Aggregate is based on the off-the-shelf Generation 2 UHF Passive RFID tags equipped with a dipole antenna. A dipole antenna is one of the most commonly used antennas for UHF RFID tags because it is the closest real analogue to an isotropic antenna, which is "an imaginary antenna that radiates in an omnidirectional fashion (spherical) with equal intensity in all directions."[6] (Karmakar and Roy 2010, 25) Also, a dipole antenna is most commonly used because it is easy to match input impedance from the tag antenna to the IC impedance. (Rida, Yang, and Tentzeris 2010, 62) Since a half-wave dipole is the archetypal antenna for the UHF RFID system, it was selected for the base structure of the IA.

The sensing mechanism of the device in the Intelligent Aggregate System is quite similar to the Passive Wireless Corrosion Sensor (Apblett and Materer 2010), which employs a corrosion sensitive material, which, when corroded, significantly degrades the communication ability of the antenna. The corrosion sensitive material chosen for the prototype Intelligent Aggregate is a carbon steel wire resembling the carbon steel reinforcements that have been most commonly used in concrete. If the monitored reinforcement is epoxy coated rebar, the corrosion sensitive material should be coated with the same thickness of epoxy layer.[7] It is important to use the corrosion sensitive material, which has the same properties as the monitored metal so that the corrosion can be detected as accurate as possible. The corrosion sensitive materials are located at each side of the dipole antenna for stimulating the dissipation of the tag antenna performance. The corrosion sensitive material is named a trigger, since it triggers the change of the antenna performance. The total length of the IA's antenna including the triggers is 16.5 cm, which is the length of a half-wave dipole antenna. Since "the wavelength for the typical UHF RFID frequency of 915 MHz is approximately 33 cm," the length of a half-wave dipole antenna is 16.5 cm.[8] (Lozano-Nieto 2011, 26)

6. A dipole antenna radiates uniformly in one plane (donut shape radiation pattern).

7. However, the epoxy coated trigger was not tested in this study.

8. This length can be derived from an equation, $\lambda = c / f$, where λ is wavelength, c is speed of radio waves, and f is frequency. The speed of radio waves is 3×10^8 m/s, and the frequency used in the US is 915MHz, which can be converted as 915×10^6 Hz. Therefore, the wavelength is roughly 33cm, and since the wavelength of half-wave dipole is $\lambda/2$, it is 16.5 cm.

The prototype IA utilizes U-shaped external triggers roughly at mid-point of the tag antenna, yet a little bit closer to the IC; therefore, the linear length of the IA is 14 cm.[9] (Figure 3.3) The location of the triggers was chosen rather empirically for this prototype design. The triggers link the Part A and Part B. Under normal environment when the corrosion is negligible near the rebar, IA uses the full length of the antenna (Length A). However, when corrosion becomes severe, the exposed triggers corrode and become non-conductive or disconnect Part A from Part B. This significantly shrinks the usable area of the tag antenna from Length A to Length B, which changes the antenna impedance, making the IA to unreadable from the same distance with the same power transmitted from the reader. Therefore, if the device stops responding, it is reasonable to assume that the area where the IA was embedded has become a corrosive environment. Since the multiple IAs will be deployed in a known location, the clusters of the communication failure with the IAs will indicate the high possibility of the rebar corrosion in those areas. As the IA functions as a switch rather than measuring quantitative data, it is a binary sensor that only informs whether the threshold value set up by the user is crossed or not. Then, how do we know whether the non-responding status of IA is resulted from corrosion, not from the malfunction of the device?

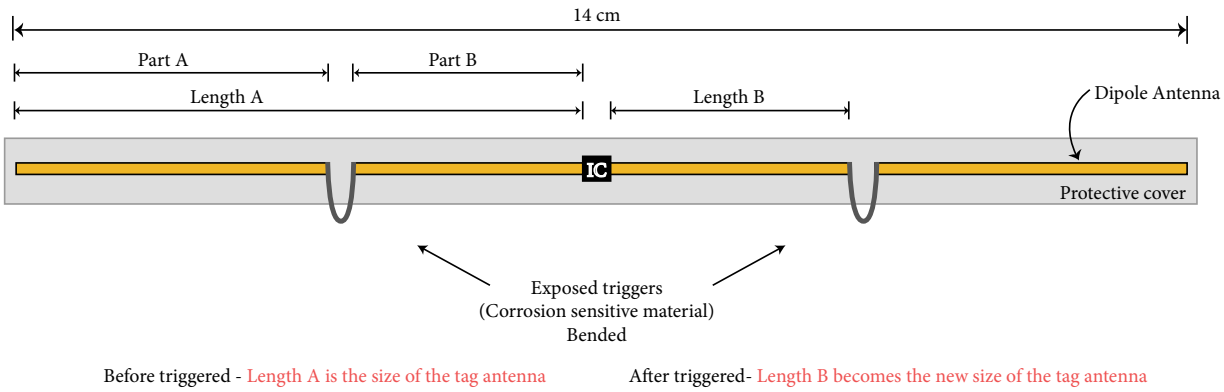

Figure 3.3 Structure of the prototype IA

The antenna performance of IA is proportional to the power transmitted from the reader, which can be controlled at the reader side. Therefore, it would be possible to identify the triggered

9. However, the total length of the antenna is still 16.5 cm. The influence of the trigger shape (straight or U-shape) was found to be negligible.

device by sending higher power to the device.[10] (Figure 3.4) For instance, the IA using the antenna Length A can be initially tuned to be readable at the transmit power over 20 dBm at a certain distance from the interrogator. At the same time, the IA with the antenna Length B can be tuned to be readable at the transmit power over 30 dBm. Once triggered, the device will not be readable at 20 dBm because it only uses the Part B as its antenna. However, it will be still readable at 30 dBm as the initial setting is made to the IA with the antenna Length B can be readable at 30 dBm at a certain distance from the interrogator. Therefore, if one of the IAs stop responding, it would be possible to check if the main part using antenna Length B is still functioning by transmitting 30 dBm power from the reader. By using this method, it would be possible to verify whether IAs are not responding due to the proper operation of the triggers or the malfunction of the device.

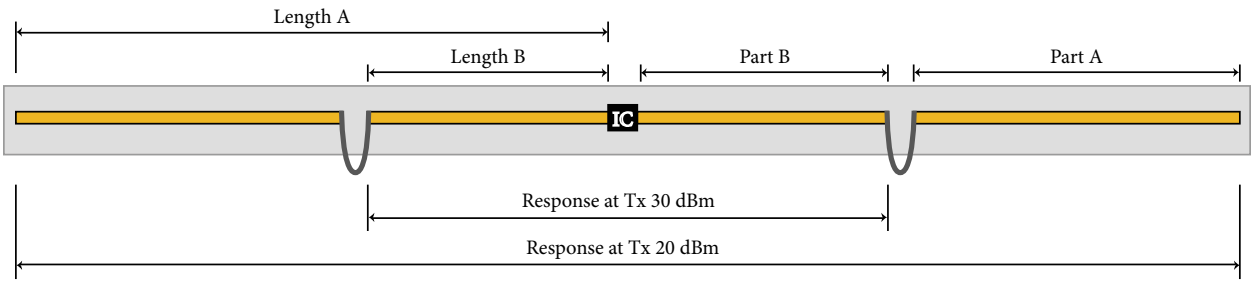

Figure 3.4 Example of initial antenna setting*

* Please note that Tx 20 and Tx 30 is exemplary transmit power. As long as the initial power level is set lower than the power used for the verification of the device survival, it is acceptable to use any desired power level.

3.3 Design of Intelligent Aggregate System (IAS)

The parameter causing the dissipation of the performance of the sensing devices is corrosion of the exposed triggers. When assuming that the Intelligent Aggregate will work as designed, it is possible to think about the application of the device in a larger framework of the Intelligent Aggregate System. Individual IAs can be installed during either a large scale project, such as restoration project or new construction, or relatively small repair work such as concrete patching.

10. "Radiofrequency regulations limit the transmit power by the reader antenna to 36 dBm in North America." (Bhattacharyya, Floerkemeier, and Sarma 2009, 97)Floerkemeier, and Sarma 2009, 97

IAs are installed near the reinforcement before the concrete is poured or repair is made. Therefore, the location of each IA is known. This spatial information can be used to map the sensors throughout the monitored structure. Since each IA is assigned a unique id, just like the conventional RFID tags, it is possible to create a database of the sensors' locations and their status information (corroded/ non-corroded) collected through the RFID communication.

Once IAs are installed and their location is recorded in the database, the communication link between the sensing devices and the interrogator(s) is established after the concrete cures. The resolution of the sensor data depends on the density of the sensing devices in a given area. At the beginning, all of the IA should be readable from the interrogator, and this means there is no significant corrosion to trigger the sensor. When a certain area becomes a corrosive environment, the corrosion sensitive materials of IA is triggered, which makes the IA stop responding to the interrogating system at an initial transmit power setting. (Figure 3.5)

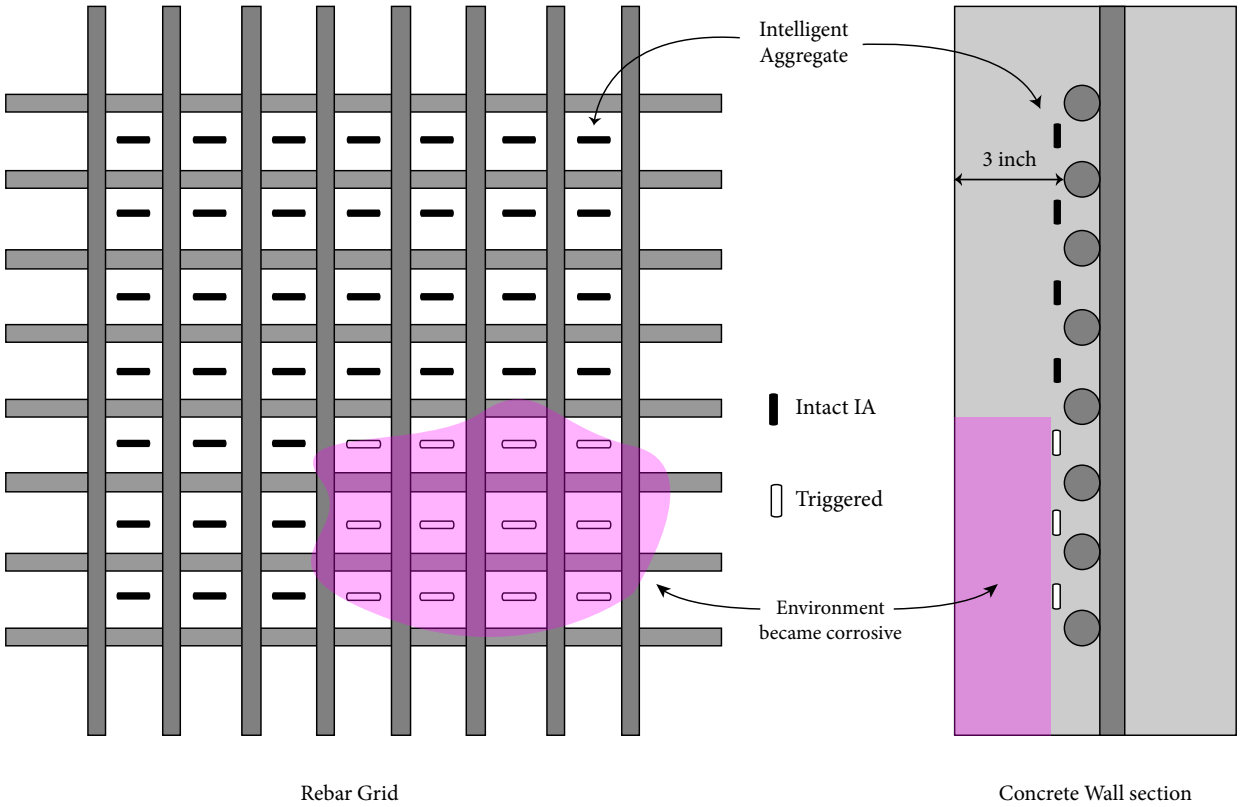

Figure 3.5 Status change of IA due to corrosion of the triggers

In this particular scenario for the corrosion monitoring of a reinforced concrete building, sensors (IAs) are embedded in the concrete and the stationary interrogator (reader & reader antenna) is located at the distance where it can read signals back from the multiple IAs. (Figure 3.6) The stationary interrogator is at a fixed distance from the IAs. Therefore, the factors significantly affecting the performance of the IAs are a) the level of transmit power (Tx) from the interrogator and b) the performance of the IAs' antenna. As mentioned earlier, the level of transmit power can be controlled by the system for the verification purpose. If necessary, several numbers of the readers with the multiple antennas can be deployed in the structure being monitored to ensure the communication between the IAs and the interrogators. In some cases, the IAs can be embedded in selected areas and the interrogator also can be located at that position. This will be particularly useful when monitoring repaired areas.

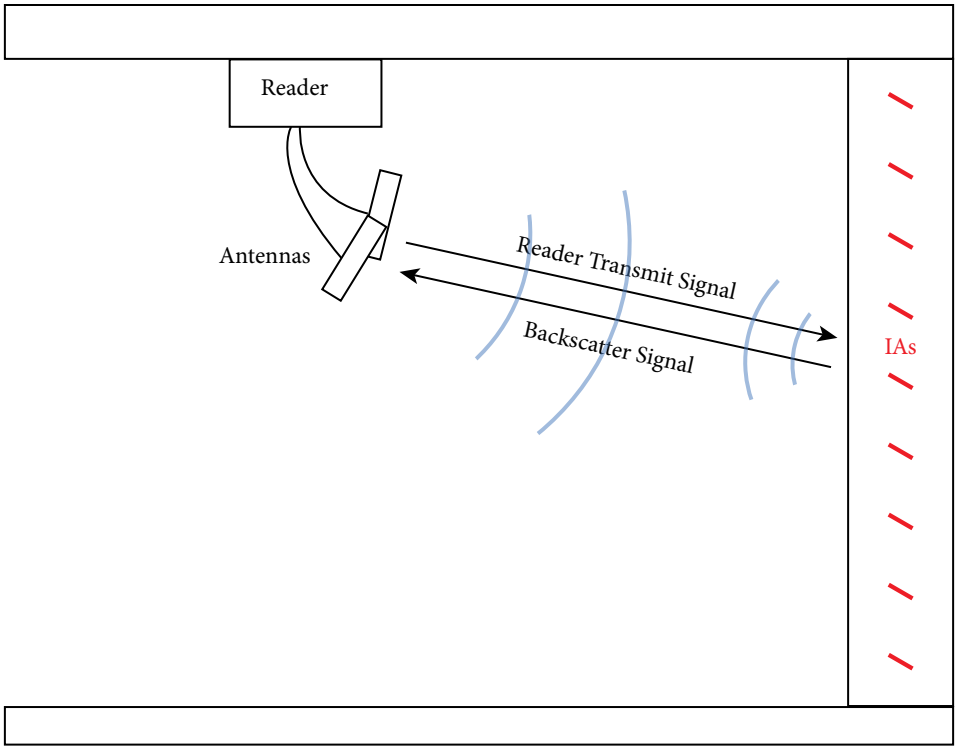

Figure 3.6 Basic structure of the monitoring system based on IA

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Chapter 4: Proof of the Concept

The Intelligent Aggregate System is established on two premises. First, the passive UHF RFID tags are readable when embedded in reinforced concrete. Second, the prototypes of the Intelligent Aggregate are triggered as designed. Therefore, two different sets of experiments were conducted to prove these hypotheses. In this chapter, the details of the experiments are described with the test results. Then, the issues found from the experiments are discussed.

4.1 Performance of the Passive UHF RFID Tags

What first needs to be confirmed is whether the passive UHF RFID tags can communicate with the interrogator when they are embedded in reinforced concrete. The experiments for this research were conducted in a hallway of the research facility as opposed to conducting tests in an anechoic chamber, which eliminates the phenomena affecting the tag performance such as multi-path effects, interference and fading of radio waves. However, in the real environment such interferences happen frequently. Since this research is interested in examining the feasibility of realizing the Wireless Corrosion Monitoring System rather than developing the best performing system, it is preferred to conduct the test in environment that resembles the field situation.

In addition, the structure of the prototype IA is based on the commercially available off-the-shelf passive UHF RFID tags, which have not been tested for their performance in reinforced concrete by the tag manufacturers. Therefore, it is important to test them prior to evaluating the prototype IA based on those tags. After consulting with RFID tag manufacturers, Survivor tag from Confidex, Sentry-Metal tag from RCD, and FT-1002 from TROI were selected. (Figure 4.1) The Sentry-Metal tag and the Survivor tag are specially designed for application in metal rich environments. Also, the performance of TROI FT-1002 has been tested inside of concrete by the manufacturer. However, none of these products has been tested in reinforced concrete. Passive UHF RFID tags, which work when embedded in reinforced concrete, have been studied for the last

few years, but they are not yet commercially available.[1]

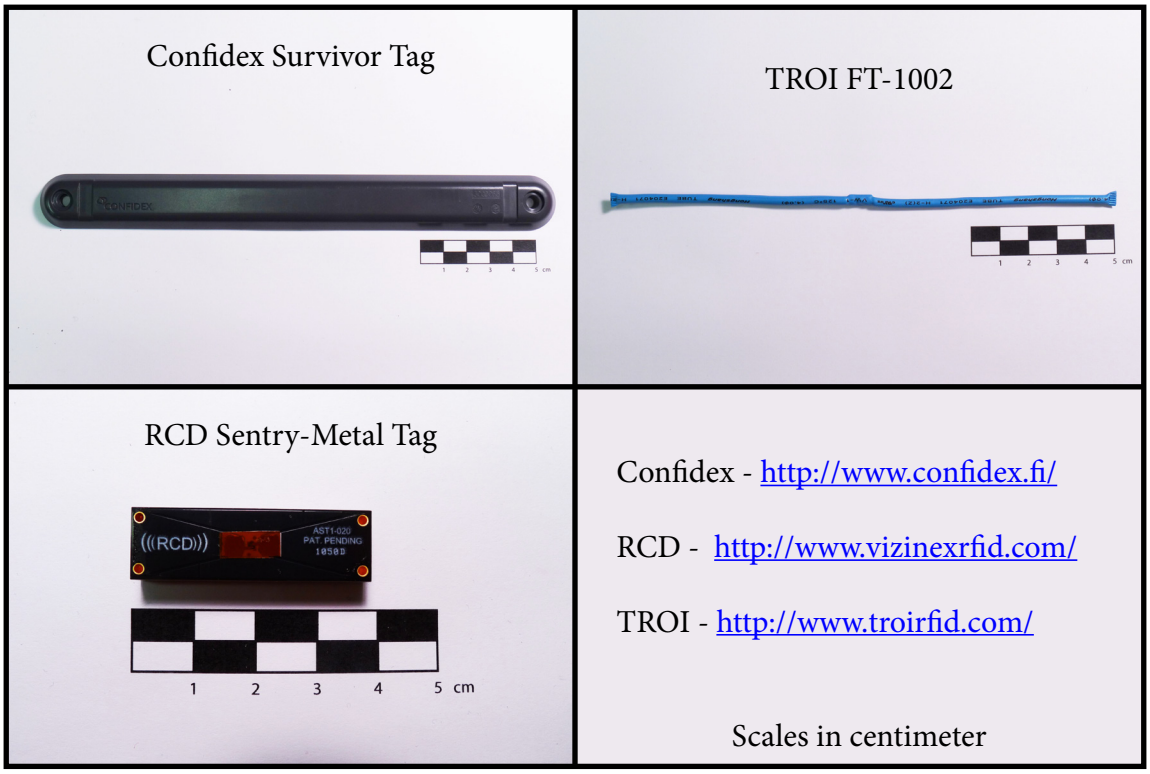


Figure 4.1 Commercial RFID tags used for the performance test (scales in centimeter)

The performance of the tags was tested in three different conditions, in air, attached to a rebar grid, and embedded in reinforced concrete at 1.5 inch depth, so that the influence of a rebar grid and reinforced concrete can be found. Here, the performance of the tags was determined by an end-user metric, which is "the maximum read distance of a tag by a commercial reader in a given environment." (Aroor and Deavours 2007, 170) The samples were loaded on a cart and this cart was moved away from the RFID reader until the tags stop responding. (Figure 4.2) For the interrogation side, a fixed UHF Gen 2 RFID tag reader (Speedway IPJ-R1000, Speedway) and a circularly polarized reader antenna (S9028PCL, Cushcraft) were used. For the data collection, MultiReader v6.6.1(Impinj) was used. The same test method was used for the evaluation of the prototype IA as well.

1. For more information about the recent researches, please see (Jeong and Son 2011) and (Rad and Shafai 2008).

Figure 4.2 Experiment of the performance of the tags on the rebar grid

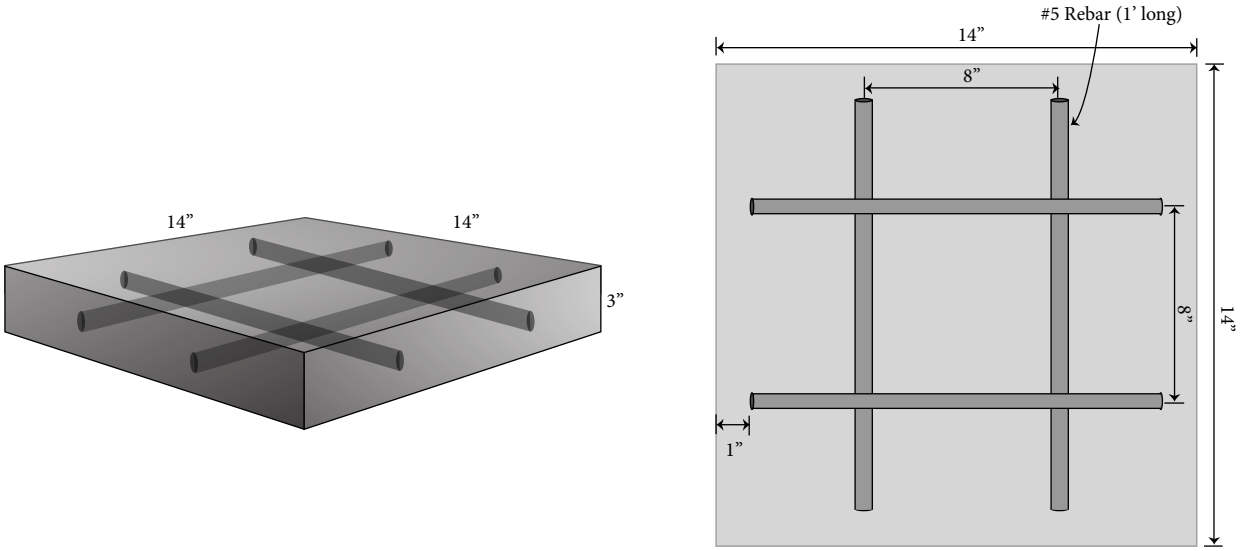


Figure 4.3 Dimension of the concrete specimen (14” x 14” x 3”)

Figure 4.3 shows the reinforced concrete specimen used for the experiment. For the reinforcement, number 5 rebar is used. Three inches was chose for the thickness of concrete

specimen based on the ACI code 7.7.1 (b), which is for the cast-in-place concrete (non-prestressed) exposed to earth or weather. (ACI Committee 318. 2002) The thickness is important factor because it determines the degree to which the RF signal should propagate through the concrete to read the tags. Since the rebar grid is located at the center, the tags are embedded at 1.5 inch depth.

In order to create the specimen, premixed Sakrete 5000 Plus High Strength Concrete Mix was used. The water to cement ratio was 4 quarts (3.7 L) of water to 80 lb (36.2kg) of Sakrete 5000 mix as recommended by the manufacturer. The rebar grid, which carries tags on its surface, is placed at the midpoint, and the concrete mix poured on top of the rebar. Figure 4.4 shows the process of making the specimen. Each tag was attached on the front and back side of the rebar in order to see if there is any significant difference if the tag is located behind of the rebar.

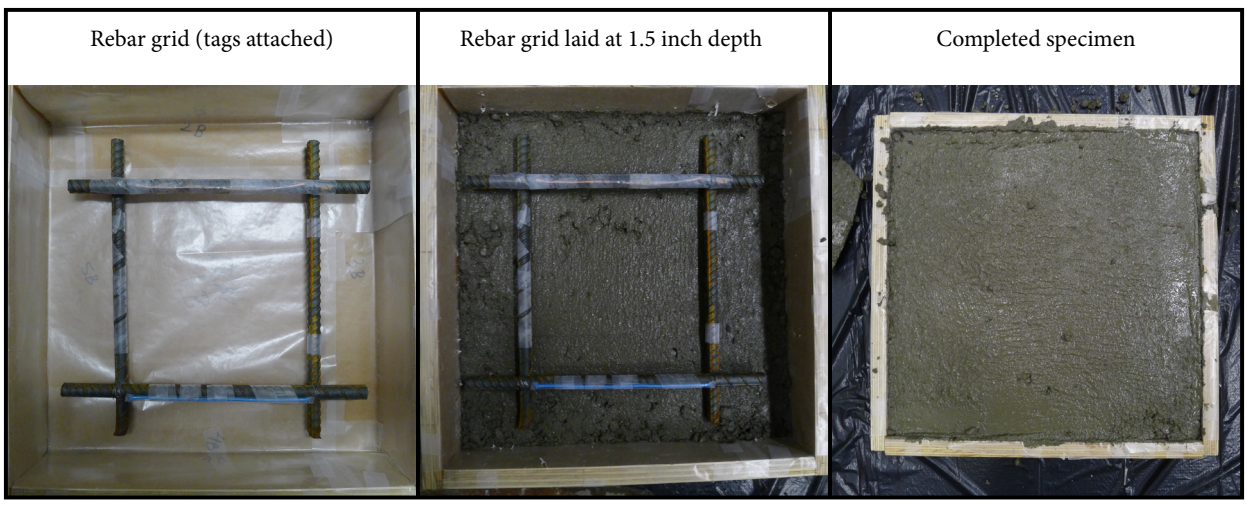
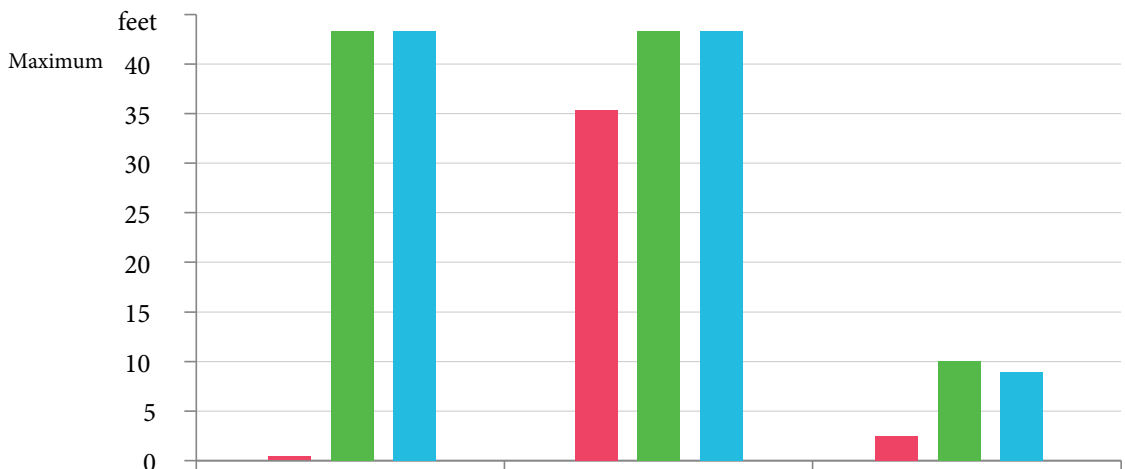


Figure 4.4 The concrete specimen used for the experiment

The performance of the passive UHF RFID tags was tested after the concrete specimens illustrated in Chapter 3 had fully cured after 28 days. The transmitted power from the RFID reader was 30 dBm, the maximum power available at the reader so that the maximum performance of the tags can be compared in different situations. Due to space limitations in the experiment environment, the maximum reading distance was set to 40 feet, which already exceeds the 20 feet reading distance of passive UHF RFID tags known in the literature.[2]

2. Please refer to Table 2.1 in the Chapter 2.

Chart 4.1 shows the test result of the tags' performance in three different situations. In air, the tags showed long reading distance, over 40 feet, except for Sentry-Metal from RCD. This is because the Sentry-Metal tag is designed to work best when it is mounted on metal surface. When mounted on the rebar grid, the reading distance of Sentry-Metal tag was significantly increased, roughly 35 feet, as expected. No significant change of performance observed for Survivor tag and FT-1002 when they are attached to the rebar grid. However, a substantial performance decrease occurred when they were embedded in the concrete. A roughly 75% decrease in reading distance was observed for Survivor and FT-1002. Sentry-Metal tag showed almost 93% decrease of the maximum reading distance. Nevertheless, the reading distance of the tags, especially Survivor and FT-1002, was still much longer than what the devices operating in LF (low frequency) and HF (high frequency) bands can offer. Furthermore, in recent years, there have been active researches to enhance the passive UHF RFID tag performance when embedded in reinforced concrete. (Rad and Shafai 2008; Jeong and Son 2011) These new researches will be mentioned in Chapter 5.



Accuracy ± 6 inch	In Air	On the rebar grid	Embedded in Concrete
RCD Sentry-Metal	0	35'	2.5'
Confidex Survivor	Over 40'	Over 40'	10'
TROI FT-1002	Over 40'	Over 40'	9.6'

*Note: Due to the limited space of the experiment environment, the maximum threshold distance of the tags' performance was set to 40 feet. Therefore, anything over 40 feet was indicated as Over 40 feet.

Chart 4.1 Test results of tags' performances at 30 dBm transmit power

4.2 Validity of the Intelligent Aggregate Design

As the passive UHF RFID tags are proven to be working when embedded in reinforced concrete, it is possible to test the validity of the design for the prototype Intelligent Aggregate, which uses one of the tags tested in the previous experiment as a base structure. Between Survivor and FT-1002, each of which showed fairly good performance in reinforced concrete, FT-1002 was selected for the base structure of IA prototypes because the incorporation of the corrosion sensitive trigger to the tag antenna is easier for FT-1002. FT-1002 uses an antenna made of copper wires as opposed to the Survivor tag's antenna made of aluminum powder printed on the substrate. (Figure 4. 5) Therefore, simply cutting copper wires allows attaching the triggers to the antenna conveniently.[3]

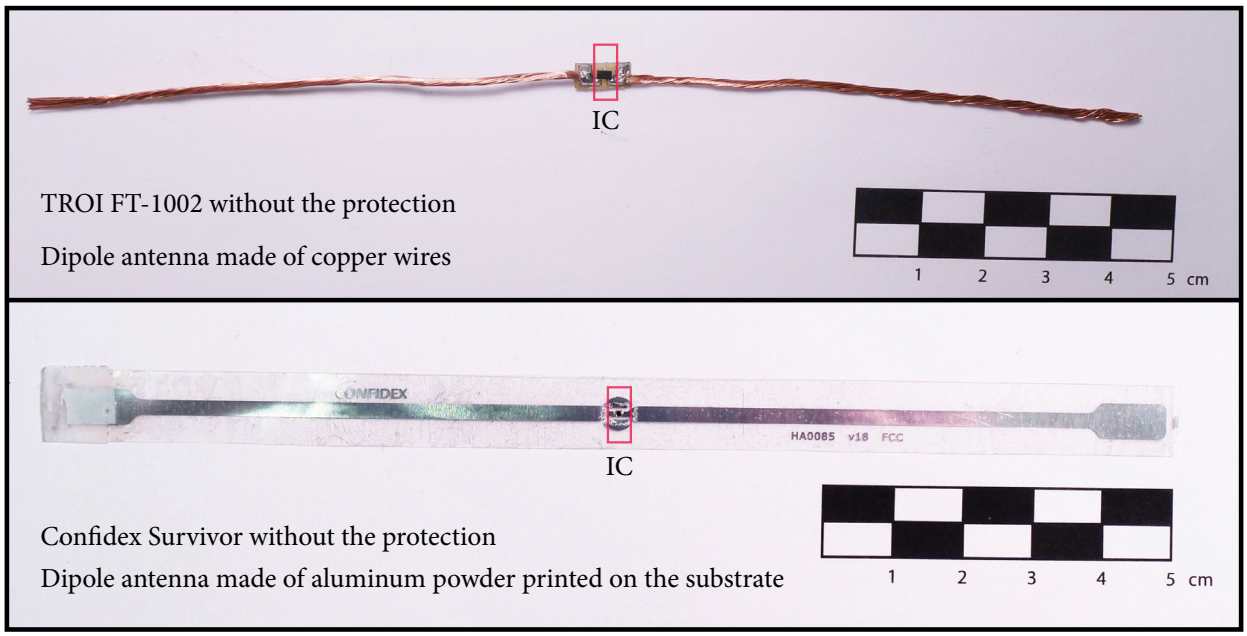


Figure 4.5 The bare structure of the tags

Based on the design presented in Chapter 3, the prototype Intelligent Aggregate was made. For the corrosion sensitive material, a carbon steel binding wire was used because of its similarity to the carbon steel rebar. The thickness of the binding wire was B&S Gauge 29 (0.29mm) since it is easy to change its shape and reasonably sensitive to be triggered by corrosion so that the triggering function can be verified. Various thicknesses of the triggers were tested to find if the thickness of the triggers has any influence on their sensitivity and the tag performance. The thickness of wire

3. However, the printed antenna may be used for the future research as a cost efficient method.

was increased at a ratio of two to one for each prototype IA. The length of the each trigger is one inch before bending to form a U-shape.[4] The triggers were located roughly at mid-point of the tag antenna, yet a little bit closer to the IC. The location of the triggers determines the length of the main antenna (Part B), which has an important role in checking the survival of the device by sending higher transmit power that can turn the device on with the antenna Part B only. (see Figure 3.5) However, an experiment for finding the optimal location of the triggers was not conducted for this prototype. Then in order to keep the optimal length of the half-wave dipole antenna at 16.5 cm, each side of the original antenna was cut by one inch. Consequently, the total length of the antenna integrated with the corrosion sensitive triggers was set to 16.5 cm and 14 cm when the triggers are folded. As a result, three prototypes of IA (01, 02, 03) were developed. (Figure 4.6)

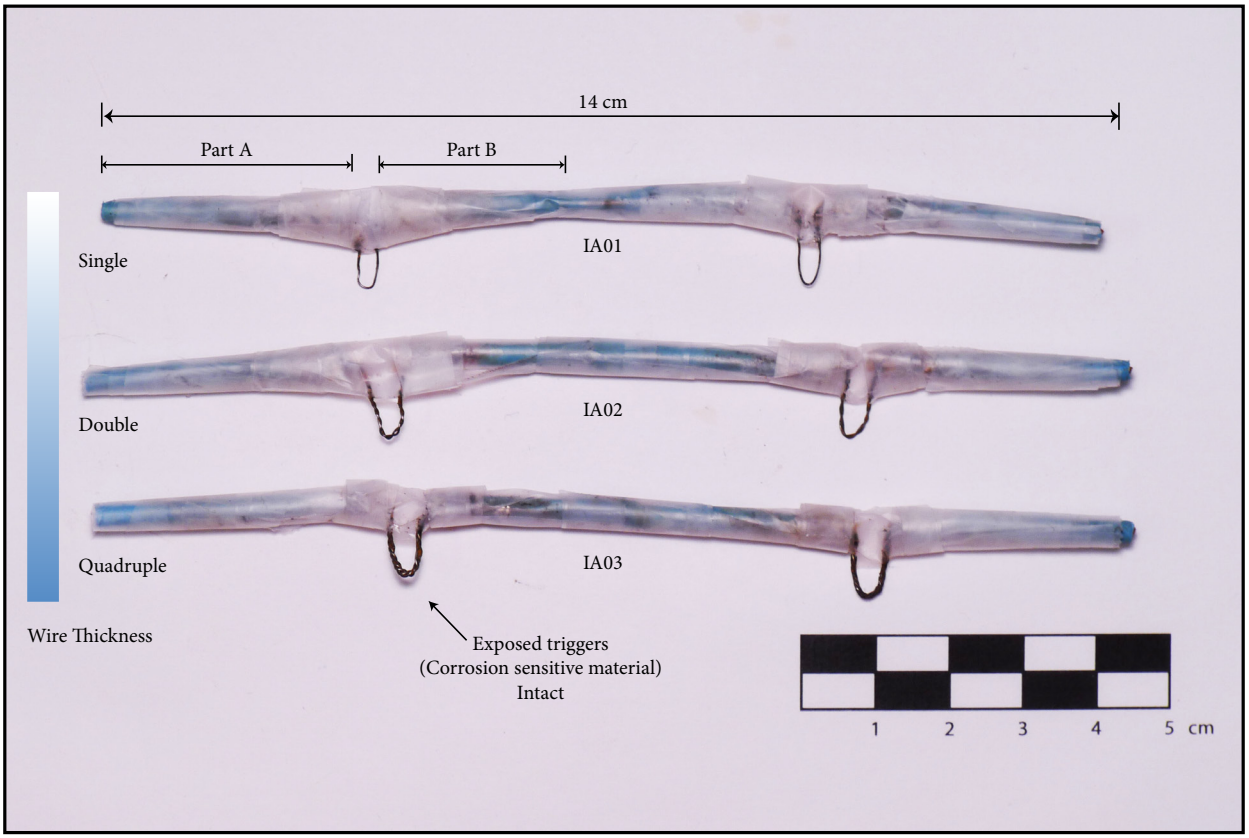


Figure 4.6 Prototypes IA01, IA02, IA03

4. The length of the trigger was rather empirically chosen since one inch length was sufficient for integrating the triggers to the original antenna, yet not too long.

The performances of the prototypes IAs before and after the corrosion test were compared using the maximum reading distance method used in the previous experiment. However, this time the maximum threshold distance of 40 feet was not used since the IAs with corroded triggers were still readable over 40 feet away from the reader at 30 dBm transmit power. Therefore, in order to distinguish the performance of IAs before and after corrosion, values over 40 feet needed to be compared. Also, the maximum distance at 20 dBm was measured to find out if the result from the 30 dBm setting is consistent at different transmit power levels. Since the experiment environment had several metal doors, which can reflect radio waves, and other influences from walls, wireless networks, and mobile devices, comparison of the two different power levels was expected to provide more reliable results.[5]

For the corrosion test, the triggers of the prototype devices were frequently sprayed with tap water (pH 5.2) in order to accelerate the corrosion rate. In addition, an incandescent lamp was used to increase temperature to further accelerate corrosion. (Figure 4.7) Since the purpose of the experiment was in evaluating the feasibility of the prototype device, such accelerated corrosion seemed justifiable. Then the triggers were completely dissolved with hydrochloric acid to cause the complete separation between Part A and Part B in order to assure disconnection of the two parts causes degradation of the antenna performance.

Figure 4.7 The corrosion testing under an incandescent lamp

5. If the test were conducted in anechoic environment, more precise test results on the trigger influence on the IA performance would have been collected.

After a week of testing, corrosion of the triggers was evident.[6] (Figure 4.8) The general trend line showed the reduced reading distance after corrosion of the triggers. (Chart 4.2, next page) Based on these results, it is reasonable to assume that corrosion of the triggers successfully lowered the efficiency of the antenna by changing the tag antenna impedance. The thickness variation made by folding the wire did not have noticeable influence on either of the tag's performance or the corrosion sensitivity. If different thicknesses of wires were used, it may influence the trigger and the device performance.

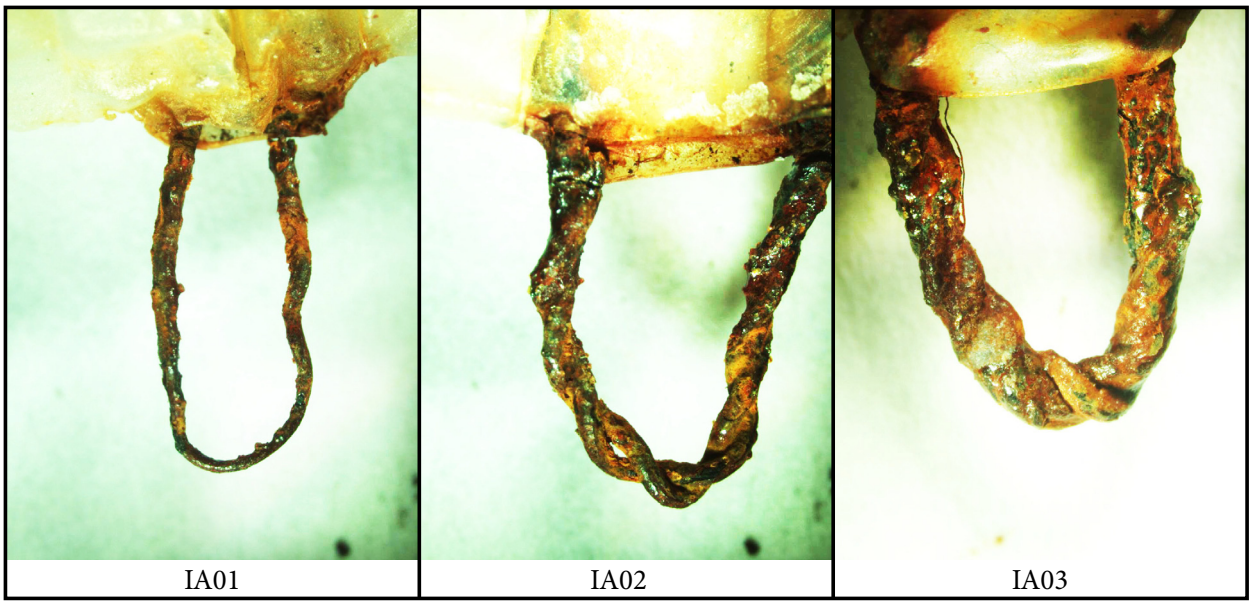


Figure 4.8 Images of the triggers of IA01, 02, 03 (x1.0) after one week of corrosion test

Also, it was possible to prove the concept presented at the end of Chapter 3, which concerned sending higher Tx power to determine whether the device is triggered or the device was broken. By transmitting 30 dBm Tx power to the non-responding devices located at the same distance that were once readable with 20 dBm Tx power before corrosion, the triggered devices were successfully recognized by the reader. Also, the complete disconnection between the Part A and B dramatically decreased the tag antenna performance. The "disconnected" field in Chart 4.2 represents the antenna performance when the triggers are completely dissolved by the hydrochloric

6. There was no significant difference in the performance among the prototype devices with different thicknesses of wires. If the wires with thicker gauge were used, the corrosion sensitivity of the triggers and the antenna performance may have been different.

acid. It should be noted that the tests were made in air rather than in the reinforced concrete. Therefore, it is difficult to assure if the sensing devices would work the same way when embedded in concrete. Nonetheless, the experiment proved the feasibility of Intelligent Aggregate (IA) and Intelligent Aggregate System (IAS).

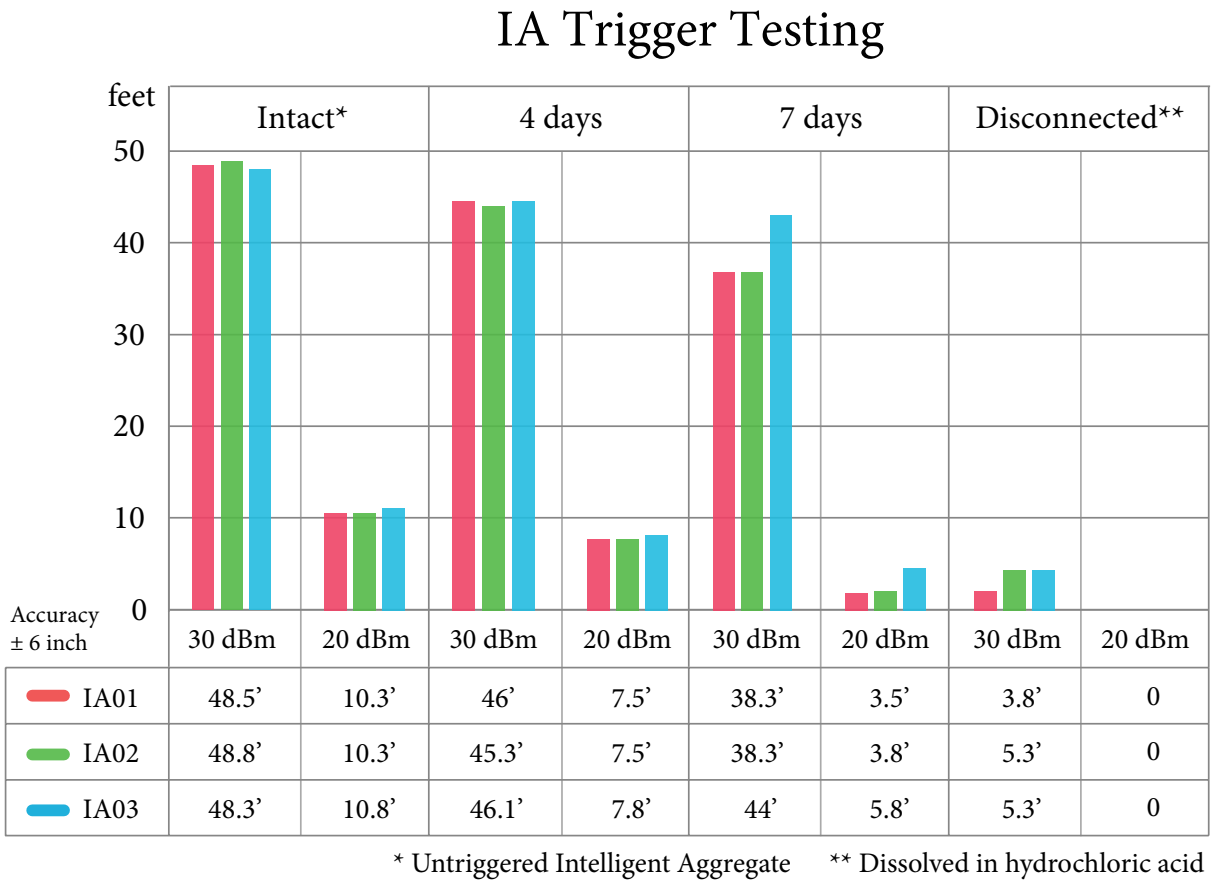


Chart 4.2 IA trigger tests results

4.3 Issues and Discussion

The results of the experiments demonstrate the feasibility of the Intelligent Aggregate System for monitoring corrosion of rebar within reinforced concrete structures. However, there are still several technical issues to be dealt with in order for the device to be fully developed. Such issues can be found at two different scales: the micro scale of individual sensing device (IA); and the macro scale of the entire operating system (IAS).

The micro scale issues are:

- The performance of IA and the operation of the corrosion sensitive triggers need to be tested in reinforced concrete.
- The optimal thickness and length of the corrosion sensitive triggers need to be determined; at the same time, location of the triggers should also be defined.
- The casing design and placement of IA within the concrete should be studied in order to ensure the best performance of the device while limiting any possible problems caused by the sensor embedment.

The macro scale issue is:

- The system efficiency, which is decreased after the sensing devices are embedded in reinforced concrete, needs to be improved for the practical application.

The first micro scale issue brings forth the necessity of additional experiment on the performance of the prototype IA and the validity of the triggers in reinforced concrete specimen. Although the first experiment presented in this paper showed the performance of passive UHF RFID tags is reduced when they are embedded in concrete, it is necessary to test the IA performance when embedded within the reinforced concrete and to determine if the reduction in reading range for the sensing device is similar to or greater than that with unmodified RFID tags. Unfortunately, due to limited number of useable RFID tags, this test was not conducted in this research. In addition, it is difficult to say if the triggers would properly function within concrete in the same way they did in the second experiment presented in this paper, which showed that the antenna performance was reduced when the corrosion sensitive triggers were corroded. Therefore, it will be necessary also to test the trigger operation within reinforced concrete to verify their performance in the application environment.

The second micro scale issue is that it is necessary to know the corrosion sensitive trigger's optimal sensitivity, which is determined by the thickness and length of the trigger. In order to detect rebar corrosion before it causes serious problems, the triggers should be actuated before

or at the same time with the rebar corrosion. However, if they are too sensitive, the device will be deactivated too early even before the serious corrosion happens. In future research, different gauges of wires can be tested to find optimal sensitivity. Also, the different lengths of wires can be tested as opposed to the 1 inch length used in this research. In another embodiment, a prototype device based on printed antennas, which was used by the Confidex Survivor tag, can be designed based on the principle used in this research. In addition, the optimal location of the triggers on the IA needs to be determined. As mentioned earlier, the location of the triggers determines the Length B of the tag antenna as they separate Part A and Part B. (see Figure 3.5) Therefore, it would be necessary to conduct experiments on the IA's performance when triggers are placed at different locations. These future developments, focusing on fine-tuning of the sensing devices, will need to use anechoic chamber and simulation software for more precise calculation of the parameters such as impedance and backscattered energy.

The last micro scale issue is the IA casing and placement methods for the sensing device. The protective cover of the IA needs to be sufficiently robust to endure the heavy weight of concrete poured over the device, and it must be water-tight to protect the IC. Such materials can be polyurethane (used by Smart Pebble ™ and Embedded Wireless Corrosion Sensor) or ceramics (Smart Aggregate). At the same time, the exposed triggers also need to be protected during the concrete pouring process. The triggers may be exposed just enough to actuate the antenna performance degradation. Additionally, the form of the casing may need to be designed to maximize embedment quality in the concrete so that embedment of the sensing devices does not lower performance of concrete by inducing voids around it that could trigger future corrosion processes. Furthermore, placement methods of the sensing device are an important issue to be addressed. When the heavy concrete mix is poured, the sensing devices can deviate from their original locations, and this is problematic as the whole system is based having a detailed knowledge of the IA locations once the concrete is poured. As a result, it is essential to secure IAs at the selected locations. There are several examples of the sensor placement methods in the previous researches and developments. (Figure 4.9) However, these examples have not been evaluated for their influence to concrete integrity and

performance. Thus, in the future researches, it will be necessary to devise appropriate designs and evaluate their influence on the integrity of concrete.

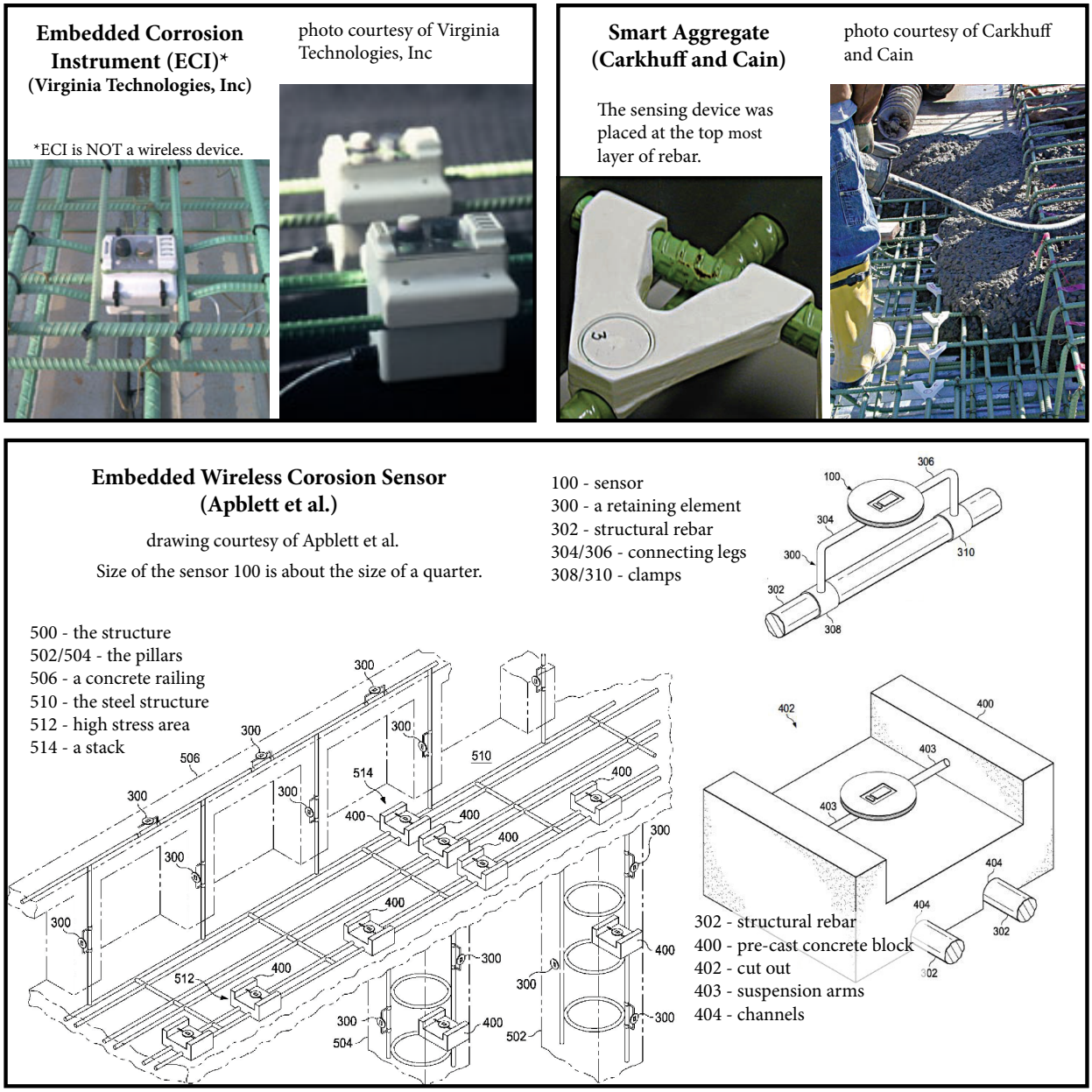


Figure 4.9 Examples of the sensor placing methods

On the other hand, the macro scale issue is related to the overall efficiency of the monitoring system. To be accepted over the traditional wired and battery-based sensing methods, Intelligent Aggregate System must be efficient enough to be practically used. As observed in the first experiment, the tag antenna performance significantly decreases when embedded in reinforced

concrete, where the reinforcing bars reflect radio waves and the concrete hinders the propagation of radio waves. Although RFID tags with a half-wave dipole antenna showed a reasonable reading distance of 10 feet in the testing environment, a longer reading range is still desirable for a more efficient and practical monitoring system. The overall system efficiency is primarily determined by coverage of an interrogation zone, which is the three-dimensional space where the interrogator can provide sufficient energy to power up a passive RFID device and receive backscattered signal from it. The efficient system means it can cover broad interrogation zones using a small number of interrogators, which in turn provide more flexibility in practical application and lowers the system cost by minimizing the number of interrogators.[7] There are two ways to improve the system efficiency: by using more suitable tag antennas to increase the reading distance of the sensing device, and by employing multi-hop communication network. These two solutions can be used together for the optimal system efficacy.

First, it would be sensible to try different types of tag antennas for future developments. In recent years, researchers found that a microstrip patch antenna is more suitable type of antenna than a dipole antenna for the applications when embedding RFID devices in reinforced concrete. Rad and Shafai at the University of Manitoba found that using a foam cover layer for example, minimized the effects of concrete on the resonant frequency. The thicker the cover depth, the more gain improvement the antenna acquired. (Rad and Shafai 2008) More recently, Jeong and Son developed a new UHF RFID tag antenna design that has a long read range of about 12.8 m (approximately 42 ft.) when embedded in a depth of 4 cm (1.6 in.). (Jeong and Son 2011) Also, several researchers found that PIFA (Planar Inverted F Antenna), which is another type of microstrip patch antenna, is suitable for powering sensors inside concrete. Due to the large surface it is more efficient for capturing electric field compared to a dipole antenna. (Punjala and Makki 2009; Jin and Ali 2009) Future research may use these types of antenna for increasing the reading range of the sensing device.

7. While conventional RFID tag price is approximately 75 ¢ to $3.50 (Sirico and Davenport 2011), the RFID reader costs around $ 1,000 or more (2011- 2012 market value), which further increases when the reader antenna price is added.

Another way to enhance the monitoring system is using multi-hop network, which can significantly increases the efficiency of Wireless Sensor Networks (WSNs). While the prototype Intelligent Aggregate System is a kind of WSNs, it is designed based on single-hop network scenario, which only allows connection between the interrogator and the tags, not between tags. Surendra and Zawodniok reported the feasibility of multi-hop RFID network based on passive UHF RFID system, which is based on backscatter communication from the RFID tags. (Figure 4.10) Normally, distance from the interrogator is inversely proportional to the backscatter signal power. Therefore, the further the tag is away from the interrogator, the shorter the communication distance is. In the multi-hop networking system, "the tags act as scattering devices, which receive the backscatter signal from a tag and scatters it to another." (Surendra and Zawodniok 2011, 1150) They explained the structure of the passive multi-hop network as:

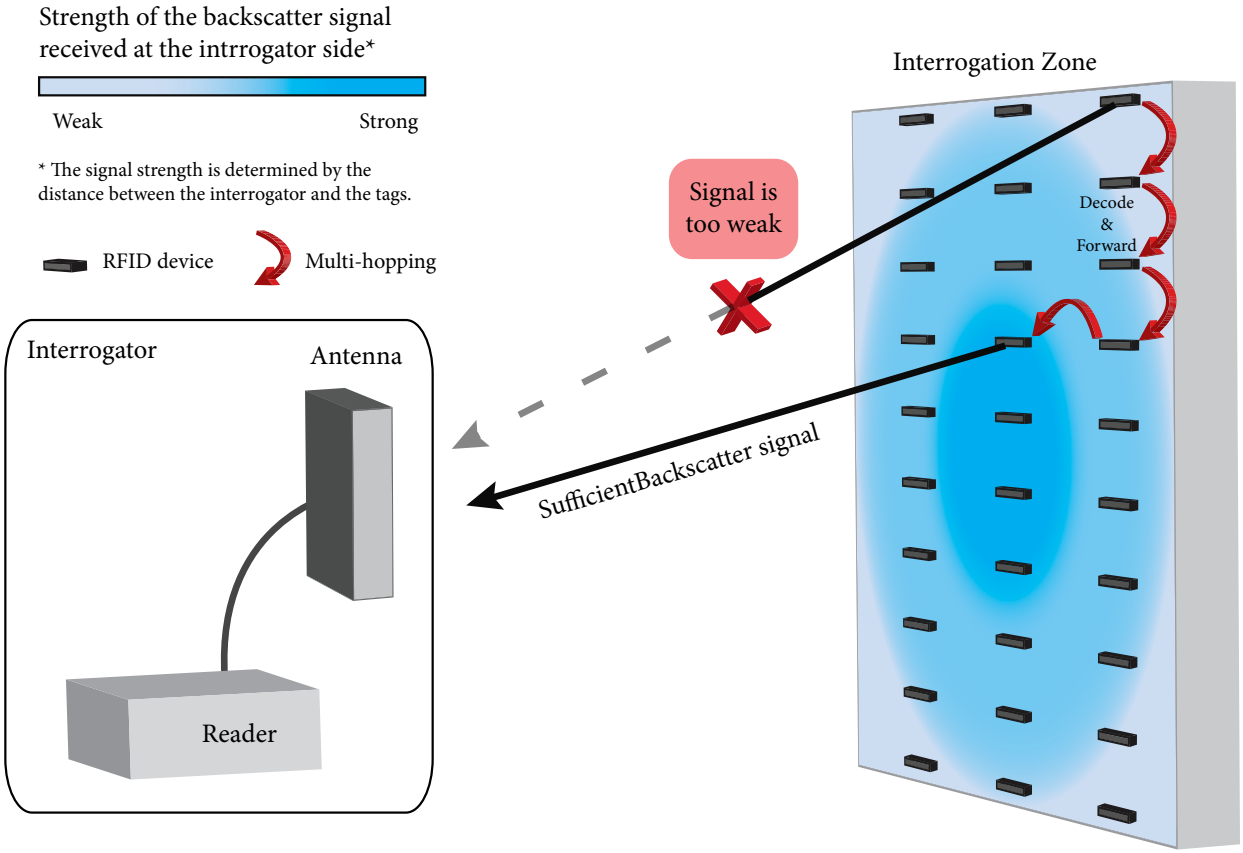


Figure 4.10 Overview of the multi-hop framework based on passive UHF RFID system

> "By employing multiple tags in between the reader and the farthest tag it is possible to make the backscatter reach the reader. The backscattered signal hops between multiple tags that are in the propagating path. There is no need to generate a backscatter signal of high power from the tag. The effective range can be improved by employing multiple tags." (Surendra and Zawodniok 2011, 1151)

Therefore, this network scheme allows creation of larger interrogation zones, which in turn increase the efficiency of the monitoring system while lowering the cost compared to the current version of the IAS, which is designed based on one-hop network scenario.

However, it is uncertain whether the prototype Intelligent Aggregate System following the antenna based sensing principle would be compatible with the multi-hop networking. While the multi-hop system is based on relaying data from one RFID device to another, the prototype IA discussed in this paper is designed to be degraded when it is triggered by corrosion. Therefore, one triggered device may create a non-responding zone although some IAs in the area have not been triggered by corrosion. In this scenario, the computational RFID tags using microcontroller and external sensors such as MEMS (Microelectromechanical Systems) may be more suitable. In the future, the next generation of IA may be developed using these technologies.

4.4 System Maintenance and Update

Besides the technical issues mentioned above, it is equally important to discuss how to update and maintain the system so that it can operate stably for a long period of time. In fact, it is the same concern for any kind of system permanently or semi-permanently installed in a structure. Examples are not limited to Structural Health Monitoring (SHM) systems, but include rehabilitation and protective technology like Cathodic Protection (CP). Because electronics and wireless technologies change rapidly, the system installed today may become outdated before the structure reaches its life expectancy of 50 to 100 years.

Moreover, the proposed monitoring system involves physical embedment of the sensing

devices in the reinforced concrete structure. Once embedded in concrete, the sensing devices are not going to be exposed unless the monitored area is opened for repair or demolition. Therefore, update and maintenance of the system is limited to the data collecting and computing area.[8] This may raise a concern over the validity of the system operation after several decades. However, this does not necessarily mean that the monitoring system will not operate properly in the future. It may be outdated and less efficient relative to the future technology, but the system will still operate as long as the RFID technology exists and the upgraded interrogator and software can communicate with the embedded sensors. Since RFID has been widely used in our society for numerous applications and still has enormous potential, it is unlikely that RFID will become completely obsolete anytime soon. Furthermore, the embedded sensing devices are intended to be maintenance free, and this was the main reason why battery-less sensing devices were considered to be ideal for the corrosion monitoring of reinforced concrete. This is why it is important to design a robust and reliable sensing device.

8. Structure of the proposed monitoring system (Intelligent Aggregate System) described at the beginning of Chapter 3 shows the three different areas: sensing, data collecting, and computing area. Therefore, only data collecting and computing area are available for update and maintenance.

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Chapter 5: Future Research and Conclusions

5.1 Future research

As reiterated throughout the paper, this thesis research is a part of greater efforts in searching for an efficient wireless monitoring system for reinforced concrete structures and repairs. Therefore, the prototype Intelligent Aggregate and Intelligent Aggregate System design proposed in this research needs to be further polished and modified through additional researches in order to be used in field application. The future researches on IA and IAS are not limited to following the tag antenna based sensing principle, which was employed as a foundation of the prototype design proposed in this paper.[1]

As discussed in the last part of the previous chapter, the system efficiency can be immensely improved when employing the multi-hop framework. Thus, it is necessary to investigate whether the prototype IA following the antenna based sensing principle would be compatible with the multi-hop framework. At the same time, it is necessary to study a different approach using a wireless and battery-less sensing platform operated on a microcontroller (MCU), which is capable of computation and data processing, controlling the wireless communication and multiple sensors, and managing memory and power. Recently, tremendous efforts have been made in researches for a sensing platform based on passive RFID technology. This so called Computational RFID technology is still in its infancy, but it has an enormous potential in development of efficient and reliable wireless monitoring system.

The most well-known example is probably WISP (Wireless Identification and Sensing Platform), developed at Intel Research Seattle in 2006. (Smith et al. 2006) Since its first prototype came out, successive researches have been performed in collaboration with the researchers around the globe.[2] Liu et al. also proposed a smart node for RFID Wireless Sensor Networks, which has

1. One of the main reasons for selecting the tag antenna based sensing principle was because the suitable sensor was unavailable for the research.

2. The latest version of the prototypes, WISP 4.1 DL was evaluated at the beginning of this research, but it was removed from the research since there was no suitable sensor commercially available. Nevertheless, WISP was

the similar concept to the Intel WISP.(Liu, Cheng, and Li 2009) The research group at University of Massachusetts, Amherst is currently leading the development of UMass Moo, which is the upgrade version of Intel WISP. (Fu et al. 2011) Especially, UMass Moo has improved capability for controlling multiple sensors. This means that it allows a single sensing device to use plural sensors to measure or detect different parameters such as temperature, humidity, pH, chloride ion concentration, and corrosion rate. Although the current stage of the Computational RFID development is based on single-hop framework, it is expected to include the multi-hop function in the future.

If the Computational RFID sensing platform were selected, it is inevitable to employ sensors to collect information. As mentioned in Chapter 3, the sensor compatible with a sensing platform and reliable over long period of time was not available for this research. Therefore, there needs to be further researches on development of sensors, which have small size, long service life, and extremely low power consumption so that they can be incorporated into the sensing platform.[3] It appears that Microelectromechanical Systems (MEMS) would allow development of such sensors. MEMS are systems that consist of small electrical and mechanical components for sensing purpose. The typical overall size of MEMS device is less than 1mm. (Lee 2010, 1) As mentioned in Chapter 2, Johnson and Kulesza proposed sensing device utilizing pH sensitive hydrogel as an active material producing a capacitive change in the MEMS device. (Johnson and Kulesza 2009) In addition, Qui and Park reported the possibility of chloride ion sensitive hydrogels. (Qiu and Park 2001, 334-335)

Based on what have been discussed in this study, the next generation Intelligent Aggregate System will incorporate the following technologies but not limited to: passive Ultra-high Frequency (UHF) RFID, a microprocessor based sensing platform equipped with several different sensors, and lastly, multi-hop framework. (Figure 5.1) When these technologies are combined, it would be possible to realize a fully automated real-time wireless monitoring system for reinforced concrete structure and repair.

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embedded in a reinforced concrete for its performance evaluation and it was able to read the onboard temperature sensor data at approximately 6 feet distance from the RFID reader.

3. The energy budget of WISP 4.1 DL is approximately 1mA for 1ms. Therefore, in order to be operated by the WISP, the sensors must have energy consumption less than 1mA/ms.

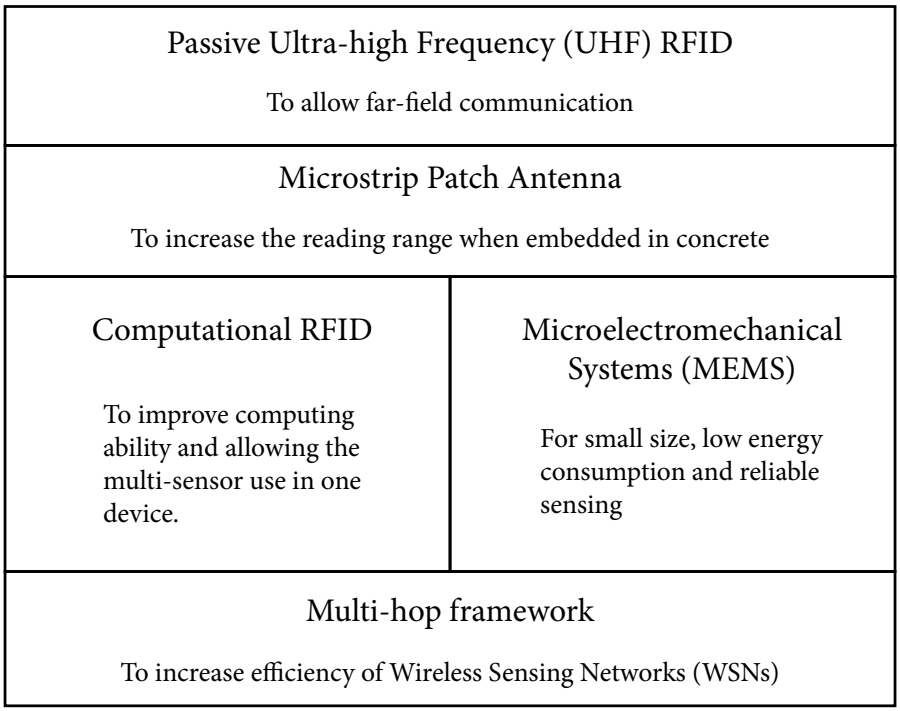

Figure 5.1 The structure of the future Intelligent Aggregate System

5.2 Conclusions

Substantial efforts are put into preservation projects, but often little care is given once the project is finished. A long-term monitoring system can provide invaluable information about the conditions of a building and building materials. Such information may help owners, architects, engineers and conservators to understand what the cause of the problem is, when and where the repair is needed, and what type of intervention is necessary. This can help prevent small problems from becoming large problems. Thanks to advances in computer, electrical and communication technology, it is possible to design highly efficient wireless monitoring system specialized for the preservation application.

In this thesis, the feasibility of the wireless and battery-less corrosion monitoring device and system for reinforced concrete structure was evaluated. Based on passive UHF RFID technology, the prototype Intelligent Aggregate and Intelligent Aggregate System was designed following the tag antenna based sensing principle. The test results showed that wireless and battery-less corrosion

monitoring system can be achieved with Intelligent Aggregate. At the same time, it was found that significant additional researches need be conducted for development of the practical Intelligent Aggregate System. Nonetheless, this research is meaningful in that it is the first attempt to utilize passive RFID based wireless monitoring system for preservation application.

Furthermore, the framework of the system presented here can be applied to any other types of structures although this research was focused on the corrosion monitoring of reinforced concrete buildings. For example, it can be applied to sense corrosion of the anchors used in stone veneer and curtain wall buildings. If equipped with sensors like accelerometer or strain gauge, it is possible to sense mechanical properties caused by structure deformation. There are enormous potential in the wireless sensing technology in the field of preservation, and our efforts to care for historic buildings would be greatly improved by utilizing the system. It is time for the preservation professionals to actively engage with this new paradigm of wireless sensing technology for more effective built environment management.

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List of Figures

List of Tables and Charts