SMART AND SUSTAINABLE SUPPLY CHAIN MANAGEMENT: A PROPOSAL TO USE RFID TO IMPROVE ELECTRONIC WASTE MANAGEMENT

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ABSTRACT

Due to the accelerated expansion of technology and improved living standards, electronic product use is increasing exponentially, and this has resulted in rapid degradation of the environment. A large number of waste cell phones were generated in the past few years. According to statistics, the global number of cell phone subscribers exceeded 7 billion in 2015. This increase indicates that there are a huge number of retired cell phones. According to available data, nearly 400 million waste cell phones are generated each year in the world. Of these, only 1 percent are recycled properly, and the collection rate in the US is between 10 and 20 percent. This improper disposal of waste cell phones is posing a great threat to the environment and human health because cell phones contains toxins that have been associated with severe health problems. Meanwhile, proper recycling of cell phones is likely to generate high profits. In this paper, we first identify the root causes of the low return rate of cell phones and take a design science approach to solving the problem. We reject the traditional assumption that return rate is exogenous in nature and suggest a novel recovery system to control the return rate of obsolete cell phones. The proposed system uses Radio Frequency Identification (RFID) devices to improve the end of life/end of use (EOL/EOU) management of cell phones. A mathematical model is formulated for the proposed system to minimize the cost of the system and a numerical example also given. Managerial insights are given to assist the designer of the system in some critical decisions.

Keywords: RFID, Waste management, EOL/EOU management, Cell phone supply chain management, return rate

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1 INTRODUCTION

In a very short period of time cell phones have become an integral part of life and have emerged as a ubiquitous electronic product (Li et al. [1]). According to the World Bank, the total active cellular subscribers reached 7.216 billion with a total population of 7.347 billion in 2015 (Mobile cellular subscriptions [2]). In terms of manufacturing and purchasing, more than 1.6 billion cell phones were sold globally in 2010 alone; even greater numbers were sold in the ensuing years (Silveira and Chang [3]; Welfens et al. [4]). The main reason behind the huge sales is the rapid replacement of cell phones by consumers, which is driven by technological innovation. Cell phone manufacturers are rapidly producing new models by adding different features, which cause the consumer to replace their phones. This increases the replacement frequency, and, as a result, the electronic waste from cell phones increases exponentially. In fact, cell phones have the shortest life cycle of all electronic products, and research proved that more than 50% of the phones have life cycles between three to six months, and almost 90% of phones have lifecycles less than a year (Chan and Kai Chan [5]). The technical lifetime of a cell phone, as believed by the manufacturers, is 10 years, while the average estimated replacement time is 1 to 2 years (Geyer and Blass [6]). The replacement frequency is increasing with time. In 2018, the average life is likely less than that reported in the literature. Thus, a majority of the cell phones that enter into waste streams may still have value (in terms of performance and durability). Hence, these can be reused, recycled, refurbished, or remanufactured if properly collected and recovered.

Despite the high disposal rates, the collection rate of cell phones is very low, and we don't even know the fate of a very large number of obsolete cell phones. Welfens, et al. [4] reported that in the US more than 300,000 cell phones are discarded every day. Silveira and Chang [3] reported that the collection rate of EOL/EOU cell phones in the United States is less than 10%. Geyer, and Blass [6] cited a report from the US Environmental Protection Agency, which estimates that the collection rate in the US is below 20%. According to a US Geological Survey report (Sullivan [8]), almost 130 million mobile phones would be retired annually in the US by 2005. The same reports further stated that almost 500 million EOL/EOU mobile phones would have accumulated in different storage areas waiting for proper disposal or recycling. The report further states that less than 1% of the total obsolete phones are discarded and recycled properly.

Much of the previous research concerned with the cell phone supply chain management (SCM) focuses on waste generation rate, existing collection systems, recycling processes, and associated risks (Silveira and Chang [3]; Jang, and Kim [7]; Welfens, et al. [4]). The majority of the published papers studied the existing return systems and pointed out the problem of low returns in the cell phone SCM including works by Welfens, et al. [4], Geyer and Blass [6], Sullivan [8], Ongondo and Williams [9], and Wilhelm et al. [10]. However, no published research explicitly considers solutions for the problem of low return rates. To bridge the gap, we proposed an advanced collection system as an innovative recovery program for obsolete cell phones. The system utilized the internet of things (IoT) (viz. RFID tags, readers, and sensors) to increase the return rate of EOL/EOU cell phones. The main restrictive assumption so far in this regard is the thought that cell phone return is an exogenous process and is outside the direct control of the manufacturer or the collection firm. This research takes a design science approach to reject this assumption and enable manufactures and collectors to control cell phone collection quantity through RFID technology. The existing literature founds two main reasons that contributed to low returns in the cell phone SCM, 1) discarding into municipal waste and 2) a hibernation period (which author practiced himself). This paper focuses on the possible solutions to the previously mentioned two problems and introduces a smart and novel recovery system that minimizes the hibernation period and facilitates the separation of discarded cell phones from municipal waste.

The remainder of the paper is structured as follows. Section 2 provides a brief review of related literature. The problem is defined in Section 3. Section 4 explains the proposed system. Section 5 provides a mathematical model, important insights for managers, and cost justification of the proposed system. Section 6 concludes the paper.

2 LITERATURE REVIEW

This section gives literature related to product return in the cell phone SCM, which is focused on three questions: (i) Why it is important? (ii) what is the current situation of cell phone recycling in the world? And (iii) what are the potential risks related with improper disposal?

2.1 Recycling in the cell phone supply chain management

The main aim of EOL/EOU cell phone management is to prevent them from ending up in municipal waste. There are two main reasons why it is important to manage those wastes independent of municipal wastes. First, they hold hazardous elements which can contaminate the environment if released into soil or water. Second, refurbishing and recycling programs can lead to the retrieval of precious raw materials and investment tied to those cell phones (Khetriwal et al. [11]). Cell phone wastes carry a number of metals and represent a real reserve of metal resources which should not be disposed of but recovered (Protomastro [12]). Therefore, many countries are operating different e-wastes management techniques by adopting legislation and economic tools to implement these systems. According to Ongondo and Williams [9], the exact number of cell phone take-back schemes operating in the world is unknown, and an estimated 102 different schemes are in operation in the UK alone. One important policy developed by the Organization for Economic Cooperation and Development (OECD) is Extended Producer Responsibility (EPR). EPR extend the manufacturer's responsibilities to the post-consumer stage of the product's lifecycle, including take-back, recovery, and disposal (Nnorom and Osinbanjo [13]). The EPR policy is implemented through (i) take-back programs (like regulatory approaches, mandated recycling, minimum recycled content standards, energy efficiency standards, and disposal bans and restrictions), (ii) voluntary industry practices and environmental labeling, and (iii) economic instruments (like the Advance Recycling Fee (ARF), advance disposal fee (ADF), virgin material taxes/subsidies, and deposit/refund schemes) (Nnorom and Osinbanjo [13]).

However, the literature review shows that almost all these approaches to solving this problem never improve the return rate above 27% (achieved in California only in 2009), and even that percentage also showed a drastic decrease down to 13% within two years. As mentioned by Silveira, and Chang [3], electronic product prices in Japan include an EOL/EOU management fee, which the consumer has to pay, and the return rate for cell phones in 2009 was reported to be 20%. The Ministry of Environment South Korea initiated a waste deposit program in 1992. This program requires manufacturers to deposit a cost in proportion to their production and retrieve the amount in proportion to the recycled products. Unfortunately, the program was not successful, and the government had to abolish it because the manufacturer simply deposited the charges and did not make any effort to recycle. The competitive environment requires firms to invest all the available financial resources in its core activities. Manufacturers are usually against the implementation of these policies and laws because they prefer to avoid costs related to take-back activities. Despite the legislative requirements and obvious environmental benefits, a rational manufacturer avoids take-back activities due to the unclear economic viability of reuse options. The basics of any take-back system relies on the return rate of the used products, which is traditionally considered to be an exogenous variable and out of the direct control of the manufacturer. This assumption is the root cause of failure and provides a way for the manufacturer to skip its responsibilities by calling it an "out of control process". If the quantity of return products is considered to be a controllable variable, then the manufacturer can be forced to collect all the products sold previously. Thus, we will focus on developing a system in which return rate is directly under the manufacturer's control. We reject the idea that firms must passively accept product returns, and we devised a system for return rate control, and developed a product acquisition system in which EOL/EOU products can be traced and retrieved with the help of RFID technology.

2.2 Financial, environmental, and health risks related to the improper disposal of cell phones

Hibernation is one of the two reasons for the low return rates for unused cell phones. Usually, the unused cell phones are kept in drawers, storerooms, and other areas after the consumer stops using them. This is a huge loss of financial resources according to the US geological survey (Sullivan [8]). According to INFORM, Inc. (a non-profit organization), an estimated 500 million discarded phones accumulated in customer storage by 2005. The total investment tied to these 500 million phones is estimated to be $314 million. According to Ongondo and Williams [9], 50-90 million cell phones are lying in drawers and cupboards in the UK.

Apart from the monetary losses, these cell phones are a great threat to human health and the environment. A cell phone may contain more than 40 elements including antimony, silver, barium, copper, cobalt, chromium, gold, iron, lead, nickel, palladium, tin, aluminium, and zinc. Majority of which are identified as potentially harmful that can cause reproductive, neurological, central nervous system, immune system, and kidney problems (Silveira, and Chang, [3]; Wu et al. [14]). Landfilling is not the solution for electronic product disposal, and it can even cause serious problems. For instance, high concentrations of lead and cadmium were found in rice from a waste recycling area in China, and the soil was found to be severely contaminated by copper, cadmium, and mercury (Fu et al. [15]). These phones are also causing pollution by contaminating household wastes, soil, wildlife, water and marine life. Therefore, it is important to manage EOL/EOU cell phones in an environmentally friendly manner. Serious actions are required to improve recycling in this sector, and the hurdles should be removed by approaching the problem in novel scientific ways.

3 PROBLEM DESCRIPTION

The studied literature suggests the importance of recycling and remanufacturing in the cell phone industry. EOL/EOU product management is mandatory in many sectors, however, in cell phone industry the discarded phones are not properly recycled. They are likely to end up in municipal waste and can cause serious health related problems because they cannot be separated from municipal waste. Literature review identified two main reasons for the low return rate of cell phones: discarding them into municipal waste and hibernation. The small size is the main reason for both problems. Due to their smaller size, people do not take care of the retired cell phones and throw them away in municipal waste. Even environmentally conscious consumers also neglect this problem, because they do not realize the huge risks associated with a small cell phone. The second reason that contributes to fewer returns is hibernation of the unused cell phones. Usually, the unused cell phone is kept in a drawer, storeroom, or other storage after a consumer stops using it.

Therefore, it becomes crucial for researchers to work out the problem and develop new approaches designed to improve the return rate. The return rate of cell phones should reach almost 100% due to financial losses and the threat to human health and the environment. The designed return and collection procedure must achieve the highest possible return level. This paper is the first step in this regard and uses IoT to improve the collection and separation of cell phones and other small electronic products (for example digital cameras) from municipal waste. RFID has the potential to alleviate the risks related to unrecycled cell phones by improving the return rate and separating the discarded phones from municipal waste. The main function of RFID technology is to detect objects that are tagged with the RFID tag. The combination of RFID and the internet produce a system that can provide real-time information about the global location and status of the products. This is a required feature that can be used in the cell phone industry to mitigate the risks and financial losses and to improve product return rate. The primary purpose of this study is to propose a system using RFID to make the return of EOL/EOU products to manufacturers under the control of the collector. Thus, we reject the assumption that return rate is an exogenous variable.

3.1 Using RFID to increase return rate and recycling

To address the explained problem, we propose a novel system that uses RFID to track, collect and separate cell phones from household waste. We first discuss the requirements of the system needed for the effective tracking of EOL/EOU products, followed by an explanation of the proposed. Finally, we developed a mathematical model to reduce the cost of the designed system. Figure 1 provides an overview of how a cell phone moves over different stages during its life cycle. The focus of this paper is the reverse logistics, which can be used to reduce the number of cell phones sent to storage and municipal waste, and it can be used to retrieve cell phones from municipal waste.

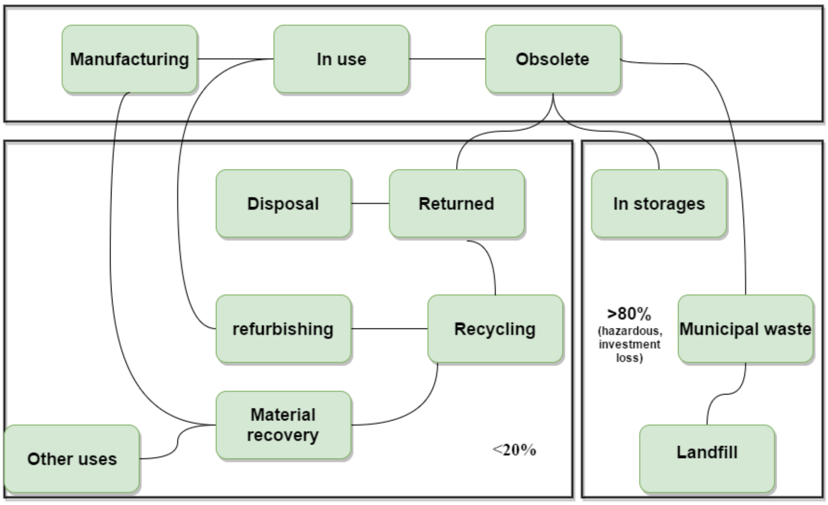

Figure 1: A typical cell phone supply chain

RFID enables the unique identification, monitoring, and tracking of different objects in a real-time environment by using radio waves to transfer the data. RFID works on a principle analogous to that of a barcode but excludes one limitation of the barcode technology (visually being in the line of sight). Each tag transmits a distinctive electromagnetic (EM) signature. The EM waves are captured by a device called a reader when it comes in the read range of the tag. The reader enables a host computer to recognize the object related to that tag (Mason et al. [16]). The data linked to the tag is recalled from the memory of the computer or any associated action that can be triggered. In particular, RFID systems can answer the following three questions who/what/where/and how are you? The answers to all these questions are important in reverse logistics. The answer to “where are you?” is required to solve the problem of tracking the cell phone. “How are you?” would answer whether the phone is working or obsolete. “Who/what are you?” provides the dismantlement information required for the recyclers. Different RFID systems have been designed by researchers, and these systems provide a variety of features. Table 2 summarizes different RFID classes and provides an overview of the features of these classes. The majority of the RFID systems use a Class 1 system, which in many cases is more than enough due to its simple use, lower cost, and applications.

In simple RFID systems, a tag is attached to each item that is to be tracked. The tag is made from a tiny integrated circuit (IC), called a tag-chip, which is connected to a small antenna and can be built in a variety of shapes. The tag-chip contains read-only or read-write memory, which stores the required information and can be read by a reader. A reader is a device that is connected to a network and can send, data, commands, and power to a tag (RFID Solutions [18]).

Table 1: Classification of RFID systems on the basis of features

Class	*Tag*	*Communication type*	*Description*
Class 1	Identity Tags, Pure passive	Tag to Reader	Read only, Tag can store a unique object identifier only, communicate with a reader or active tags of class 5.
Class 2	Higher Functionality Tags, Pure passive	Tag to Reader	Extend class 1 with read/write memory, communicate with a reader or active tags of class 5.
Class 3	Semi- Passive Tags	Tag to Reader	Tags with internal integrated battery for operating, communication in the absence of a passive tag reader.
Class 4	Active Ad-hoc Tags	Tag to Tag Tag to Reader	Internal power source, can communicate with other active tags (other Class 4 and Class 5 Tags) and readers.
Class 5	Reader Tags	Tag to Tag Tag to Reader	Most sophisticated system, can communicate with the reader, active (Class 4 and Class 5), and passive tags (Class 1, Class 2, and Class 3).

Source: Mason [16], Engels and Sarma [17]

4 THE PROPOSED SYSTEM

It should be clear now that there is a huge problem regarding EOL/EOU management of cell phones. This problem requires a novel solution approach. Therefore, we proposed a method to embed RFID tags in cell phones during manufacturing. For the primary purpose, i.e., tracking of hibernated cell phones, the tag does not need any information except to be present in the read range of the reader. Once the phone is obsolete and the user keeps it in storage, the phone battery dies after some time and it becomes impossible to find the phone. The proposed RFID tag system can be used to locate the position of the phone. RFID tags do not need power from the cell phone battery and can respond to the reader even when the phone battery is completely dead, or the phone is without a battery. Once the reader receives the signal, the presence of the phone is noted in the read range of the tag. The location of the phone is then traced by using a location tracking system. An accelerometer is used to determine whether the phone is hibernated or in use. The accelerometer senses the motion and if the phone has not moved in some specific time, the phone is declared hibernated and retrieved from the storage place. Tracking a cell phone in household waste is much easier than locating a hibernated cell phone. This can be done by passing the waste containers through RFID gates. When a container having a discarded cell phone is passed through the gate, the tag receives the signal from the reader, actuating a system that produces a sound. Thus, the cell phone can be traced. Alternatively, the truck that collects waste from the waste bins is equipped with RFID system, when it approaches a waste bin that contains a discarded cell phone the system produces a sound that informs the driver about the presence of a cell phone in the waste bin. Before collection, the cell phone is retrieved from the waste bin. Figure 2 shows the proposed application of RFID in the EOL/EOU management of cell phones.

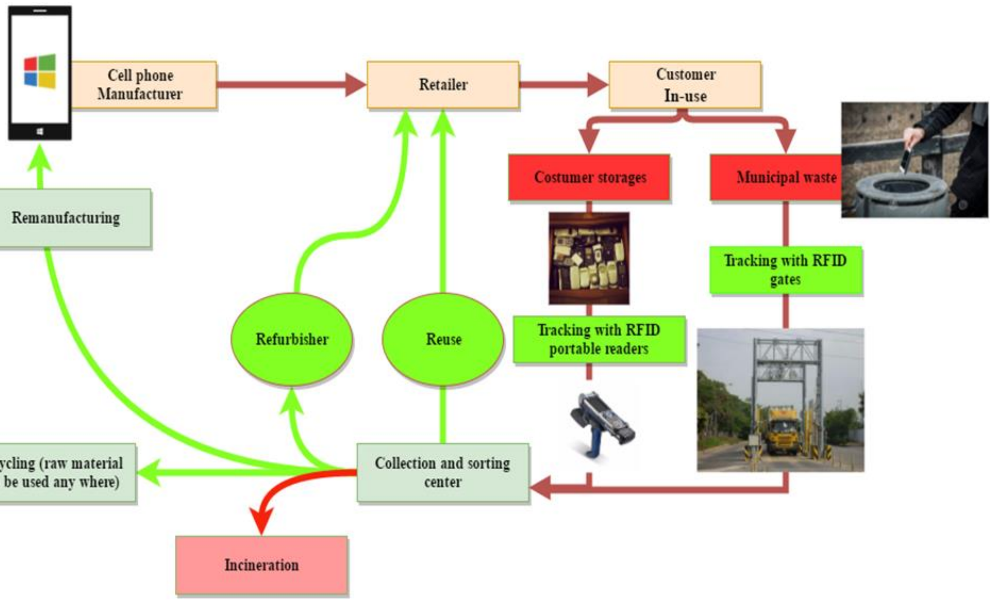

Figure 2: The proposed RFID based system

4.1 Structure of the proposed system

The system consists of the RFID hardware and software that provides a user interface and connection to google maps or any other maps to give the location of the cell phone. The RFID hardware consists of tags and readers. Tags are embedded into the cell phones, and the readers are portable and can be carried anywhere. During operation, the reader continuously interrogates the presence of tags in its read range. It should be noted that reader interrogation frequency is directly related to the power consumption of the tag. In the current context, this is not a problem because tags are not supposed to be interrogated again and again. Sensors are also embedded in the tag to monitor cell phone performance, and an accelerometer senses

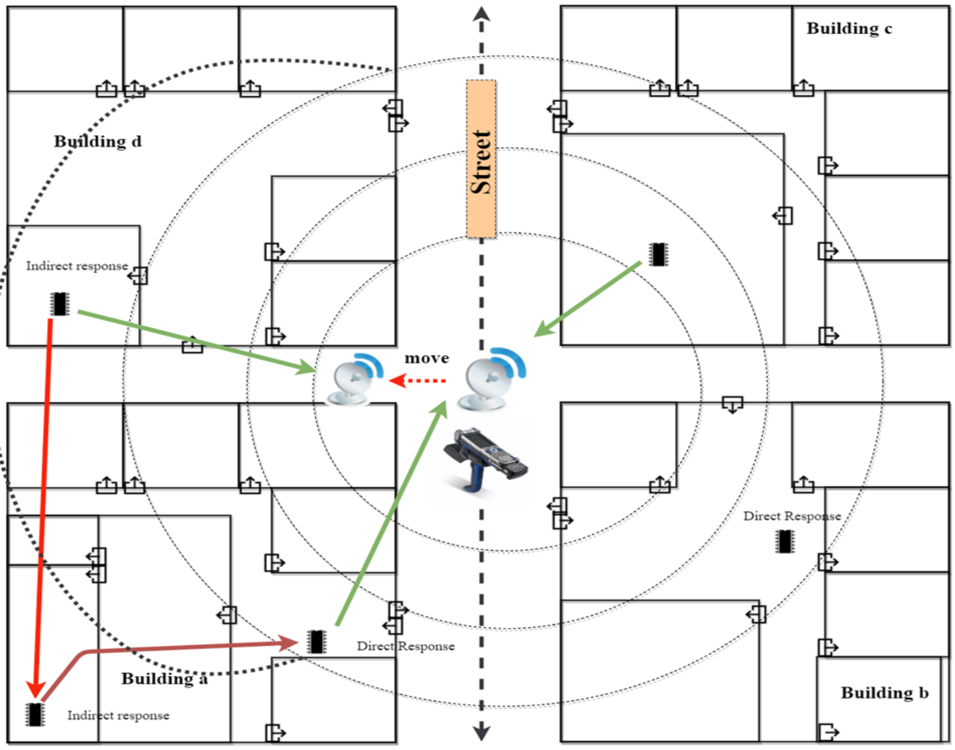

Figure 3: Tag response to reader and reader-tag

the movement and stores the data in the tag. Once the tag is connected, the data are transmitted that show whether the phone is in use or obsolete. The storage period (sensor data) is a user defined parameter and depends on the storage capacity of the tag-chip. Figure 3 shows the indoor tracking of cell phones. The tag can communicate directly with the reader or indirectly through another tag. In this way an ad-hoc network can be created on demand, thus reducing the number of required readers. The retrieval phase is costly and cannot be done frequently or for few cell phones. Therefore, to minimize the cost, this paper divides the complete process into two phases, 1) initial tracking, 2) final tracking and retrieval. The first phase is basically a lengthy data collection phase, in which the collection agency gathers location data for obsolete cell phones. The data is accumulated in a database and after enough data are collected, the second phase is launched in which obsolete cell phones are tracked accurately and retrieved.

4.1.1 Initial tracking

Active tags capable of tag to tag communication are used in the proposed system. This means that each cell phone tag can communicate with another tag. But, if a tag shows movement its data, it is immediately discarded by the reader tag. On the other hand, if the accelerometer does not show movement of the unit within a specified period, the reader tag activates the onboard Global Positioning System (GPS) and determines the coordinates of the reader phone. This data is immediately sent to the collection agency database through an automatically generated message along with the received signal strength (RSS). The tracking algorithm for initial tracking is shown in Figure 4. The message consisted of the information of the stationary tag (perspective tracking tag), the location of the reader tag, and the RSS. When a reader-tag (tag in a cell phone that is in-use) senses a hibernated cell phone in its read range, it determines the location information from the GPS system (already installed in cell phones) and sends the information (coordinates) to a central data managing server. This provides the information that a stationery tag is present inside the read range of the transmitted coordinates, thus providing a rough idea where a hibernated cell phone is present. An estimated distance between transmitted coordinates is calculated from the RSS using the following formula (Series [22]),

$$\mathrm{RSS(dB)} = 20\log_{10}\mathrm{f} + \mathrm{N}\ \ \log_{10}\mathrm{d} + \mathrm{L_f}\,(\,\mathrm{n}\,) - 28 \tag{1}$$

$$\mathrm{d} = \frac{28 + \mathrm{RSS} - \mathrm{n}\,\mathrm{L_f} - 20\,\mathrm{f}\log_{10}}{\mathrm{N}\log_{10}} \tag{2}$$

Where,

f	frequency (MHz)
N	distance power loss coefficient
d	distance between reader tag and tracking tag (m)
L_f	floor penetration factor of the signal strength loss (dB)
n	number of floors

Table 2 provides details related to power loss coefficient (N) and floor penetration factor (L_f) for office and commercial buildings.

When enough data about obsolete phones are collected, the second phase is launched in which an RFID tracking system is deployed to the specific areas. The exact location of the tag is now determined, and all the obsolete phones are retrieved and sent to the collection centres for inspection. Based on the quality, the cell phones are then sent to a reuse market, or for refurbishing, remanufacturing, recycling, or incineration.

Table 2: Calculation of power loss coefficients N, floor penetration loss factors L_f (with n being the number of floors penetrated) for indoor transmission loss

FREQUENCY		Office	Commercial
Distance power loss coefficients, N	900 MHz	33	20
	1.2-1.3 GHz	32	22
	1.8-2.0 GHz	30	22
	4 GHz	28	22
	60 GHz	22	17
Floor penetration factor L_f (dB) with n being the number of floors penetrated	900 MHz	9 (1 floor), 19 (2 floors), 24 (3 floors)	
	1.8-2.0 GHz	15+4(n-1)	6+3(n-1)
(Series [22])			

4.1.2 Final tracking and retrieval

The tracking agency (manufacturer, government or recycler) schedules the final tracking and retrieval of cell phones from those areas indicating the presence of a hibernated cell phone. The retrieval frequency is user defined and decided based on the number of hibernated cell phones initially detected in phase one. A search is launched when enough phones are detected. We suggest the use of the LANDMARC system for the indoor final tracking and retrieval of a cell phone. The LANDMARC tracking system was developed by Ni et al. [19], and it uses the concept of reference tags to accurately determine the position of the tracking tag. The search area is divided into subareas by placing reader and reference tags in a specific manner as shown in Figure 5. This reduces the search area and makes it easy to determine the location of a cell phone. For example, a cell phone in the white home is sensed by reader 1 and reader 9, while a cell phone in the black home is sensed by reader 1 and 3. The distance of the phone from the reader is then calculated based on the LANDMARC system.

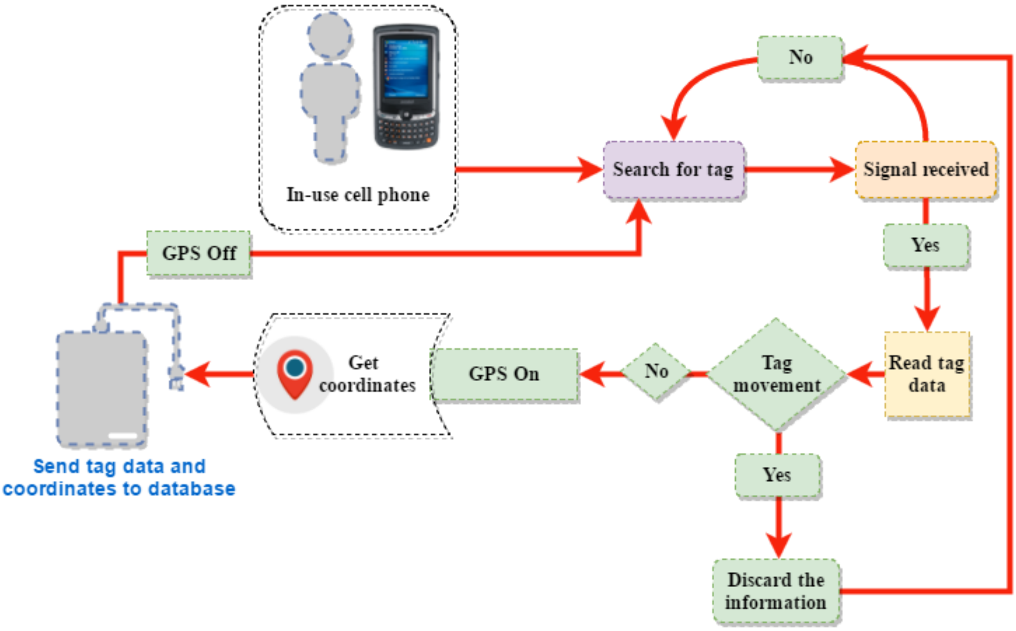

Figure 4: Proposed initial tracking system

4.2 LANDMARC System

The objective of the LANDMARC system is to increase the accuracy of the tracked location with fewer RFID readers. They used the concept of reference tags to accomplish this. Reference tags are placed at fixed and known locations to promote tracking of the unknown tags. LANDMARC reduces the required number of expensive RFID readers, accommodate the environmental effects, and provide accurate information about the location of the tracking tags. LANDMARC focuses on determining the nearest reference tag to the tracking tag by comparing the signal strength of both the reference tag and tracking tag. A weighting average was assigned to every reference tag and it depends on the distance from the tracking tag. The object location is determined by computing the reference tag's real position (which is already known) and the pre-assigned weighting average. For a system consisting n readers, m reference tags and u tracking tags, the signal strength vector of a tracking tag is defined as $\vec{S} = (S_1, S_2, \ldots, S_n)$, where S_i symbolizes the signal strength of the tracking tag observed on reader i. Another vector $\vec{\theta} = (\theta_1, \theta_2, \ldots, \theta_n)$ is defined, where θ_i represents the signal strength of tracking tag. For each tracking tag $p \epsilon (1, u)$, a Euclidean distance vector r_j is defined that shows the signal strength between the reference tag and the tracking tag, which is given as

$$E_j = \sqrt{\sum_{i=1}^{n} (\theta_i - S_i)^2}, \qquad j \epsilon (1, m). \tag{3}$$

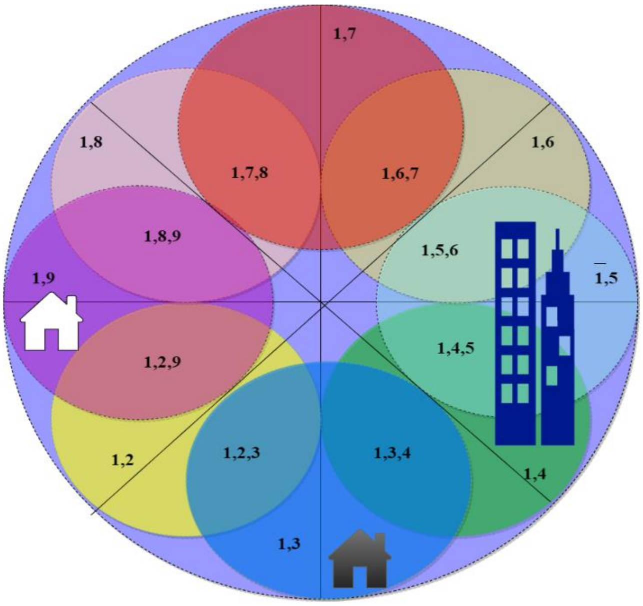

Figure 5: Search area division by different types of readers

For tracking tag i, $\mathrm{E_j}$ is the set of location relationships between the reference tag and the tracking tag. For m reference tags $\overrightarrow{\mathrm{E_j}} = (E_1, E_2, \ldots, E_m)$, the system selects k reference tags, and the tracking location is obtained using the following formula,

$$(x, y) = \sum_{i=1}^{k} w_i (x_i, y_i) \tag{4}$$

Where w_i is weighting factor assigned to the i^{th} reference tag and is determined by formula

$$w_j = \frac{{}^{1}/_{{E_i}^2}}{\sum_{i=1}^{k} {}^{1}/_{{E_i}^2}}. \tag{5}$$

This means the reference tag with the smallest E value has the largest weight.

5 MATHEMATICAL MODEL

It is critical to determine the number of RFID readers that are deployed in the search area to achieve full coverage, because these readers are expensive. On one hand, if we increase the number of readers, the cost might increase very much. On the other hand, if we decrease the number of readers, we might not be able to get full coverage over the entire search space. Therefore, we developed a mathematical model to determine the minimum number of required RFID readers required to achieve full coverage.

We considered two types of readers, 1) type 1 readers with higher sensing power, and 2) type 2 readers with low sensing power. The entire search area is first divided into sub-areas by deploying type 1 readers. To achieve complete coverage, we considered the Disk Sensing Model for type 1 reader deployment. The area covered by each type 1 reader is further divided by placing type 2 readers inside the coverage area. We used the Probabilistic (exponential) Coverage Protocol to minimize the number of type 2 readers. The probabilistic model assumes that the sensing range of a sensor reduces exponentially with distance, while the Disk Sensing Model considers the sensing region as a disk with a certain radius. The probabilistic model is more cost efficient than the Desk Sensing Model. But, we used this model for type 1 reader deployment to reduce the chances of incorrect detection and to increase the sensing power of the system. Readers are advised to study Hefeeda and Ahmadi [20] and Zhang and Hou [21] to understand these two models in detail.

The number of type 1 readers can be determined by achieving complete coverage over area A. According to the disk sensing model, coverage implies connectivity when $2\,S_s \leq S_t$. We used Figure 6 to achieve complete coverage. It is clear from the figure that a complete coverage is achieved if $S_s = 2\,S_t$.

As, $a^2 + b^2 = c^2 \Rightarrow a^2 + b^2 = 4\,{S_t}^2 \Rightarrow \sqrt{\frac{a^2+b^2}{4}} = S_t \Rightarrow a = b = \sqrt{2}S_t$.

The total area is divided into n squares based on the transmission radius (S_t) of type 1 readers as shown in Figure 6. One reader is deployed for each square.

$$f(d) = c_1 \left\lceil\left(\frac{l}{\sqrt{2}S_t}\right)\right\rceil \left\lceil\left(\frac{w}{\sqrt{2}S_t}\right)\right\rceil + c_2\left(\frac{4\ {S_s}^2}{d^2}\right)\left\lceil\left(\frac{l}{\sqrt{2}S_t}\right)\right\rceil \left\lceil\left(\frac{w}{\sqrt{2}S_t}\right)\right\rceil \tag{6}$$

Subject to

$$\sqrt{3}\ \left(r_s - \frac{Log\left[1-\sqrt[3]{1-\Omega}\right]}{\alpha}\right) \quad \geq d \tag{7}$$

$$S_t \geq 2\,S_s \tag{8}$$

Where,

f(d)	Cost of the system ($)
c_1	Price of type 1 reader ($/item)
l	Length of search area (m)
w	Width of search area (m)
c_2	Price of type 2 reader ($/item)
r	Threshold below which type 2 reader can sense the tag with probability 1 (m)
S_s	Sensing radius of the type 1 reader (m)

S_t	Transmission radius of the type 1 reader (m)
α	Decay parameter for sensing with distance
Ω	Reader threshold parameter, where $(0 < \Omega \leq 1)$
d	Maximum separation between two readers to ensure (m).

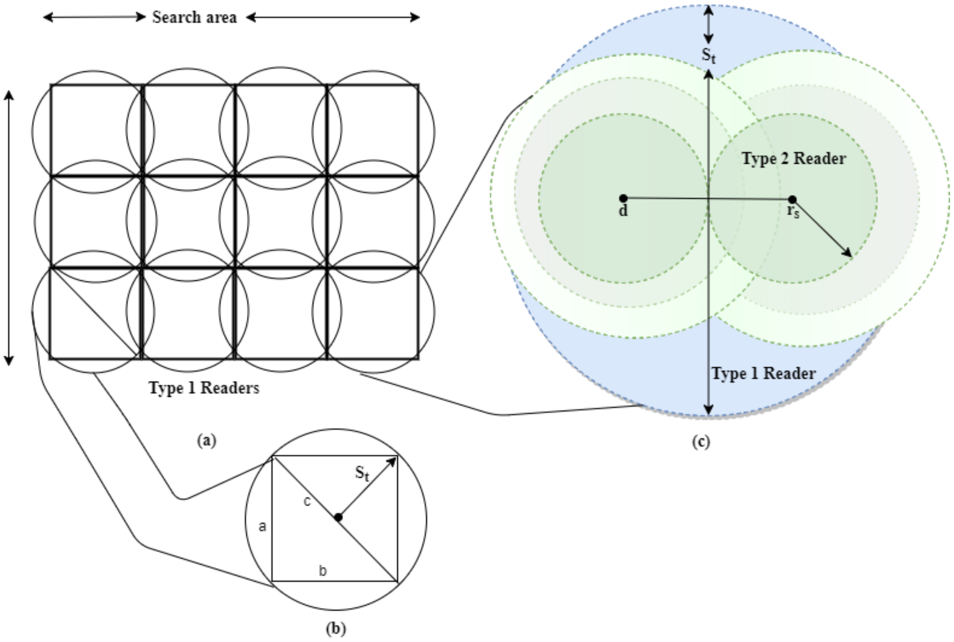

Figure 6: Reader deployment: (a) type 1 reader deployment based on Desk Sensing Model, (b) determination of transmission radius of type 1 readers, (c) type 2 reader deployment based on exponential sensing model

The formulation in (6) assumes that the total search area A is divided into sub-search areas by placing $n = \left[\left(\frac{l}{\sqrt{2}S_t}\right)\right]\left[\left(\frac{w}{\sqrt{2}S_t}\right)\right]$, sensing the reader with S_s as the maximum sensing threshold below which the reader can sense a tag with probability 1. Each sub-search area is again divided into sub-sub-areas by placing $\left(\frac{4\ S_s{}^2}{d^2}\right)$ type 2 readers, where r_s is the maximum sensing threshold below which the reader can sense tag with probability 1, as shown in Figure 6. The constraint in (7) shows that the maximum distance between any two consecutive small readers must be smaller than $\sqrt{3}\ \left(r_s - \frac{Log\left[1-\sqrt[3]{1-\Omega}\right]}{\alpha}\right)$, this is the maximum separation distance between two sensors based on the Probabilistic Coverage Protocol designed by Hefeeda and Ahmadi [20]. The constraint is (8) is based on the Disk Sensing model developed by (Zhang and Hou [21]), and it shows that the sensing radius must be at least half of the transmission radius for type 1 readers, which ensures the connectivity of the system. Figure 7 shows different possible divisions of search area with type 1 readers, and the division of sub search areas with type 2 readers ensures the connectivity and complete coverage.

We used the Kuhn-Tucker method to solve the problem. Based on Kuhn-Tucker method, we first formed a Lagrangian, which can be written as

$$\begin{aligned}\mathcal{L} \ &= c_1\left[\left(\frac{l}{\sqrt{2}S_t}\right)\right]\left[\left(\frac{w}{\sqrt{2}S_t}\right)\right] + c_2\left(\frac{4\ S_s{}^2}{d^2}\right)\left[\left(\frac{l}{\sqrt{2}S_t}\right)\right]\left[\left(\frac{w}{\sqrt{2}S_t}\right)\right] \\ &\quad - \lambda_1\left(\sqrt{3}\left(r_s - \frac{Log\left[1-\sqrt[3]{1-\Omega}\right]}{\alpha}\right) - d\right) + \lambda_2(2\,S_s - S_t). \qquad (9)\end{aligned}$$

The maximum distance between two nodes can be obtained by applying the Kuhn-Tucker conditions.

$$\frac{\mathrm{d}\mathcal{L}}{\partial d}=0,\qquad \frac{\mathrm{d}\mathcal{L}}{\partial \lambda_1}=0,\qquad \frac{\mathrm{d}\mathcal{L}}{\partial \lambda_2}=0,$$

$$\lambda_1\left(\sqrt{3}\,\left(r_s-\frac{Log\left[1-\sqrt[3]{1-\Omega}\right]}{\alpha}\right)-d\right)=0,$$

$$\lambda_2(2\,\mathrm{S_s}-\mathrm{S_t})=0,$$

$$\lambda_\mathrm{i}\geq 0.$$

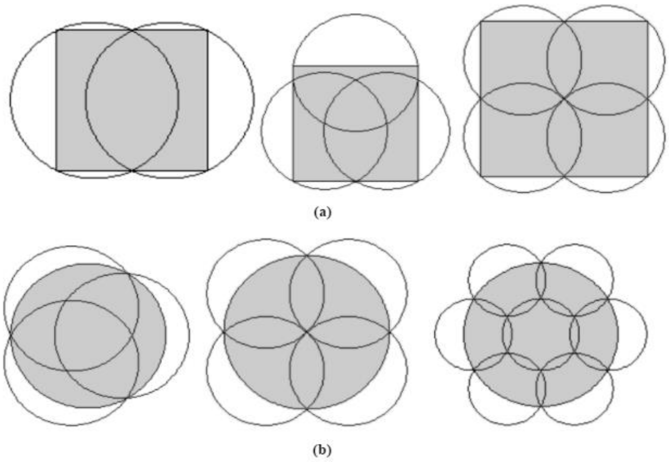

Figure 7: Different possible division of search area into smaller areas, (a) possible division of search area into smaller areas with type 1 readers, (b) a single type 1 reader coverage area division through type 2 readers

5.1 Numerical example

This section provides a numerical example to study the behaviour of the mathematical model. The values of input parameters are: $c_1=\frac{\$300}{type\ 1\ reader}$, $l=600\ m$, $w=600\ m$, $r_s=15\ m$, $c_2=\frac{\$200}{type\ 2\ reader}$, $S_s=20\ m$, $\alpha=0.05, \Omega=0.999$. The model is solved for different values of the search area, and the results are summarized in Table 3.

Table 3: Optimal results of the model based on the proposed solution methodology

l	w	d^*	Number of type 1 readers (x^*)	Number of type 2 readers (y^*)	Total cost
100	600	24.43	22	59	18391
600	600	24.43	121	325	101153
900	900	24.43	256	687	214010

The results show that the number of type 1 readers is highly dependent on the search area, and it linearly increased with an increase in the search area. However, the number of type 2 readers / type 1 readers remains the same. The distance between two type 2 readers is not influenced by total search area. However, it does change with changes in the transmission radius of type 1 readers. This means that the transmission radius of type 1 readers should be an integral multiple of the sensing radius of type 2 readers.

6 CONCLUSIONS

The literature review showed a very low recycling rate in cell phone SCM due to two main reasons, 1) discarding phones into municipal waste and 2) a hibernation period. This paper focused on possible solutions to the previously mentioned two problems and introduced a novel smart recovery system that minimized the hibernation period and facilitated the separation of discarded cell phones from municipal waste. Hundreds of different collection systems are currently operated around the world to recover obsolete phones, but they all failed and produced no results. The main reason for the failure is the exogenous nature of return rate in existing systems. In all these systems, the return rate is out of direct control of collector and solely based on consumer will. Because of the small sizes of the phones, consumer psychologically neglected the associated huge risks despite attempts to educate consumers. This paper rejected the traditional assumptions and proposed a system that brought return rate under collector control by enabling obsolete cell phone tracking. The proposed system utilized IoT (viz. RFID tags, readers, and sensors) to increase the return rate of EOL/EOU cell phones. Return rate in the cell phone supply chain can reach up to 100% using this system, and each and every phone that is out of use can be tracked, recovered and recycled. A tracking system was designed to increase return rate of hibernated cell phones from storage, and the system focused on determining the locations of hibernated cell phones, retrieval from storage, and proper recycling. The designed system jointly exploits the traditional indoor localization techniques and the tools offered by advanced cell phones to assist in tracking of hibernated cell phones. A separation system was also designed to separate obsolete cell phones from municipal waste.

Additionally, this research simultaneously considered the cost of implementation along with the design of the system. Therefore, a mathematical model was developed to minimize the number of required readers for the tracking system, thus reducing the total cost of the designed system. The mathematical model was developed based on the Disk Sensing Model and the Exponential Sensing model to ensure proper coverage, detection, and location. An indoor localization system LANDMARC was utilized to find the coordinates of the tracking cell phone. This research can be extended in the future by considering the green image of the manufacturer. A firm can get a competitive advantage over its competitors by producing green products that are 100% recyclable.

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