The Reader Collision Problem

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Abstract— **We introduce the *reader collision problem*, the problem of allocating frequencies over time to Radio Frequency IDentification (RFID) tag readers such that their interference with one another is minimized. RFID systems are comprised of readers and tags. Readers communicate with tags using Radio Frequency (RF) signaling to obtain the identifier and other data stored on the tag. A reader may interfere with the operation of other readers in the RFID system. The two principal types of reader-to-reader interference are frequency interference, two or more readers communicating on the same frequency at the same time, and tag interference, two or more readers attempting to communicate with a particular RFID tag at the same time. All reader interference caused by the operation of an RFID reader is referred to as a reader collision. Reader collisions prevent the colliding readers from communicating with all of the tags in their respective reading zones; therefore, collisions must be avoided to ensure proper and timely communication with all tags. We define the *reader collision problem* and present several graph coloring formulations for variants of the problem.**

Keywords— **RFID systems, scheduling, frequency assignment.**

I. Introduction

Radio Frequency IDentification (RFID) systems consist of Radio Frequency (RF) tags and networked RF tag readers. The tags themselves are typically comprised of integrated circuits connected to antennae. RFID systems are designed primarily to uniquely identify objects by affixing a tag containing a unique identifier to every object of interest. Additional information about the object may also be stored on the tag. This information can range from static identification numbers to user written data to sensory data. The readers initiate communication with the tags and query the tags for information stored on them.

Passive tags do not contain an on-tag power source such as a battery. They obtain their operational power by harvesting energy from the reader's communication signal, and use that energy to power internal functionality and communication with the reader. The reliance upon energy harvesting limits both the communication range and functionality of passive tags.

Active tags do contain an on-tag power source such as a battery. The on-tag power source enables active tags to perform complex functions and complex communications with the readers and possibly other tags.

Many applications have been developed to take advantage of the primary function of RFID systems, to identify objects. Within supply chain management applications, this functionality is used to enable monitoring, in real-time, of the location of all tagged objects within the supply chain. Accurate, real-time data about the location of all objects within the supply chain is necessary for the efficient management of the supply chain.

Within segments of the supply chain that exhibit chaotic and sometimes random object placements and movements, a retail environment for example, RFID tag readers must be arranged such that all RFID tags affixed to objects, regardless of where they are within that supply chain segment, can communicate with at least one tag reader. Without such a reader network, accurate real-time information about the location of all objects within that supply chain segment is not obtainable.

All tag readers have a finite space around them within which they can communicate with tags. This space is referred to as the reader's *interrogation zone.* A reader arrangement that "covers," or tiles, the entire space within a supply chain segment will have overlapping interrogation zones at many locations within that space. This is because the interrogation zones of the readers normally do not conform to tilable shapes, and reader redundancy helps to ensure communication with all tags.

Readers whose interrogation zones intersect can interfere with one another, often to the point where neither reader will be able to communicate with any tags located within their respective interrogation zones. Readers may also interfere with one another's operation even if their interrogation zones do not overlap. Such interference is due to the use of radio frequencies for communication, and is similar to the interference experienced in cellular telephone systems. Interference detected by one reader and caused by another reader is referred to as a *reader collision.*

The RFID system must be designed so as to maximize the desired communication with all tags (which requires the minimization of the number and frequency of reader collisions). This can be done by the judicious allocation of frequencies over time to the readers in the RFID system. Though similar to the Frequency Assignment Problem experienced in cellular telephone networks, the reader collision problem has several unique features, such as tag interference, due to the low functionality of the tags and practical system operating constraints. In this paper, we define the reader collision problem and investigate several variants of the problem and their corresponding graph coloring problem formulations.

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The remainder of this paper is organized as follows. In Section II we formally define the reader collision problem. Section III reviews several concepts that are used throughout this paper. Section IV presents several reader collision problem variants and their corresponding graph problem formulations. Finally, Section V summarizes our work and presents avenues for future research on the reader collision problem.

II. The Reader Collision Problem

A. Overview

The reader collision problem models the task of assigning radio frequency spectrum over time to a set of RFID readers. The reader collision problem is related to the well-studied frequency assignment problem [9] [11] [3] [10] [5] [8]. The frequency assignment problem models the task of assigning radio frequency spectrum to a set of radio frequency transmitters, such as cellular telephone base stations. In the frequency assignment problem, the mobile devices, e.g., cellular telephones, communicating with the base stations are assumed to be high functionality devices that are able to differentiate between base stations and aid in the communication process with a particular base station. In contrast, the mobile devices communicating with the radio frequency transmitters in the reader collision problem are assumed to be very low functionality RFID tags that are neither capable of differentiating between readers nor capable of otherwise aiding in the communication process with a particular reader. Specifically, a tag is not capable of choosing a single frequency for communication. Instead, it responds to and cannot differentiate between all communications over a wide range of frequencies. This assumption is valid for passive RFID tags and many commercially available active tags.

RFID reader systems encounter many different types of constraints on their operation than do more traditional systems, such as cellular telephone networks, for which the frequency assignment problem has been studied. These different constraints are primarily due to the minimal functionality contained within an RFID tag, the usage patterns in the RFID system, and the more stringent regulations on the use of the free radio frequency spectrum used by RFID systems.

For the reader collision problem, let Vrepr esent the set of all readers with $v_i \in V$ corresponding to reader i, and let $f(v_i, t)$ denote the set of frequencies assigned to v_i at time t by the assignment rule f. A feasible assignment of frequencies over time must satisfy certain frequency range and interference constraints, F and I respectively. The frequency range constraints may involve either the span of the frequencies assigned or the order (integer number) of frequency channels assigned. The system interference constraints are more variable and often involve the number of resources (both tags and readers) denied service, the percent of time a particular resource is denied service, or the error rate for the combined system.

An optimal assignment of frequencies over time globally minimizes a cost function that depends upon the particular objective of the problem. A common objective that we will consider in this paper is: minimize the time for all readers to communicate given a fixed frequency allotment (i.e., fixed frequency span or fixed order of channels). The system variables we may adjust are frequency and time.

Intuitively, we can assign two readers different times to operate or different frequencies to prevent them from interfering. (We elaborate on these concepts in the following sections.) If possible, we would like to minimize the time span required to let all readers communicate at least once. That is, all readers should be scheduled to communicate as often as possible. Furthermore, given a limited frequency allotment, we would like to reuse frequencies by taking advantage of the spatial nature of radio signal propagation which dictates that signal power is a function of distance from the emitting source, e.g., an RFID reader. That is, readers that are sufficiently separated physically can use the same frequency for communication at the same time without interfering with one another.

Communicating during time intervals when no other reader is communicating is another method of preserving spectrum. A technique that interleaves communication times on the same frequency is called a Time Division Multiple Access (TDMA) process. A TDMA process is required when the number readers that can collide is greater than the number of fixed frequencies available for use by the system. More complex communication techniques, such as Code Division Multiple Access (CDMA), are not typically used in RFID systems due to the increased tag complexity and high on-tag power requirements.

B. Frequency Range

We often use the term channel instead of frequency when describing a problem or a constraint. Technically, there is a difference. Frequency corresponds to a single wavelength of a continuous sinusoid. A continuum of frequencies in some medium (we consider free space) is a channel with frequency range equal to the difference between the maximum and the minimum frequencies defined for the channel. In RFID systems, the frequency spectrum, F, is partitioned into K mutually exclusive subintervals C_i of equal length which we define to be *channels*, that is,

$$\begin{aligned} F &= \{C_1, C_2, \dots, C_K\} \quad | \quad C_i \cap C_j = \emptyset, \\ & \qquad i, j = 1 \dots K, \ i \neq j, \\ & \qquad C_1 \cup \cdots \cup C_K = F, \end{aligned}$$

where the index of each channel is a positive integer, assigned ascending with frequency. Channel and frequency are typically used interchangeably since the center or *carrier frequency* of a channel often represents the entire channel with the understanding that the carrier frequency has a defined channel bandwidth associated with it.

C. Interference

Interference can only be defined with respect to a receiver. That is, any signal is considered to interfere with another signal if and only if it affects the desired signal as seen by the receiver. Consequently, even though frequencies are assigned to transmitters, measurements at receivers define the resulting levels of interference. An RFID reader is both a transmitter and a receiver for its transmissions. A passive RFID tag uses the reader's own transmission to communicate with the reader. The reader's transmission is typically either reflected or load modulated for the communication. Thus, an RFID tag is simply a receiver and not a transmitter. (A cellular telephone, in contrast, is both a receiver and a transmitter.) For a particular RFID system, the controllable interference is a function of frequency and distance.

There are two primary types of controllable interference experienced in RFID systems: reader-to-reader frequency interference and multiple reader-to-tag interference. The following two sections examine the causes of these two types of interference.

C.1 Reader-to-Reader Frequency Interference

Reader-to-reader frequency interference, or simply frequency interference, occurs when a reader transmits a signal that interferes with the operation of another reader, thus preventing the second reader from communicating with tags in its interrogation zone. This type of interference occurs when the signal transmitted by a reader is of sufficient strength when received at a second reader that the signal masks or jams communication from tags to the second reader. Interrogation zones need not overlap for reader-to-reader frequency interference to occur.

A simple point source communication model may be used to identify readers that may have a frequency collision. As a point source of radiation, each reader v_i, $i = 1, \dots |V|$, broadcasts uniformly and omnidirectionally. Let d be the reuse distance, the minimum distance at which a frequency used by both reader v_i and reader v_j will not cause a reader collision. Let $D(v_i, v_j)$ be the distance between readers v_i and v_j, $i \neq j$. If $D(v_i, v_j) < d$ and $f(v_i, t) = f(v_j, t)$, then readers v_i and v_j may experience a frequency collision.

C.2 Multiple Reader-to-Tag Interference

Multiple reader-to-tag interference, or simply tag interference, occurs when one tag is simultaneously located in the interrogation zones of two or more readers and more than one reader attempts to communicate with that tag at the same time. In this type of interference, each reader may believe it is the only reader communicating with the tag while the tag is in fact communicating with multiple readers. The simple nature of RFID communication can cause the tag to behave and communicate in undesirable ways that interfere with the communicating readers' abilities to communicate with that tag and other tags in their respective interrogation zones.

A simple model to identify readers that may have a tag collision is the spherical interrogation zone model for a point source of radiation. Let D_i be the maximum interrogation zone distance, the maximum distance at which reader v_i may communicate with a tag. Recall that $D(v_i, v_j)$ is defined to be the distance between readers v_i and v_j, $i \neq j$. If $D(v_i, v_j) < D_i + D_j$, then readers v_i and v_j may experience a tag collision. More complex models such as those that accurately model antenna radiation patterns, environmental noise, and other environmental conditions may also be used to determine a specific reader's interrogation zone.

III. Preliminaries

A. Graph Basics

A graph $G = (V, E)$ is a pair of finite sets where the set Vcon tains the *vertices* of the graph and the set E contains distinct unordered pairs of vertices called *edges*. Vertices v_i and v_j, $v_i, v_j \in V$, are said to be *adjacent* if they are connected by an edge, that is if $(v_i, v_j) \in E$, and edge (v_i, v_j) is said to be *incident* to vertices v_i and v_j. The *degree* $\deg(v_i)$ of vertex v_i is the number of edges incident upon it. The maximum degree of graph $G = (V, E)$ is defined as $\Delta(G) = \max_{v \in V}\{\deg(v)\}$.

A *multigraph* is a graph in which a pair of vertices may have more than one edge connecting them. If the edge set E of a multigraph is partitioned into K distinct sets, then we have a multigraph that is a family of K graphs $G_1, G_2, \dots, G_K$ on the same vertex set. We represent such a family of graphs by $G = (V, E_1, E_2, \dots, E_K)$.

B. Simple Graph Coloring and Cliques

The *coloring* of a graph $G = (V, E)$ is defined to be an assignment of colors to the vertices V such that no two adjacent vertices (i.e., vertices connected by an edge) have the same color. Colors are typically defined to be the set of nonnegative integers. A coloring that assigns c colors to G is termed a *c-coloring*. The least number of colors in any such assignment is defined as the *chromatic number* of the graph G and is denoted by $\chi(G)$. If readers require only a single channel for communication, then the chromatic number may coincide with the required number of channels.

A *clique* in a graph $G = (V, E)$ is a set of nodes $V_C \subseteq V$ such that any pair of nodes $v_i, v_j \in V_C$ is adjacent in G. The order of the largest clique in G is called the *clique number* and is denoted by $\omega(G)$. In every graph G

$$\omega(G) \leq \chi(G) \leq \Delta(G) + 1$$

where $\Delta(G)$ denotes the maximum vertex degree of graph G.

Simple graph coloring problems, that is, problems where the objective is to determine the chromatic number of an arbitrary graph G, belong to the hardest class of problems from a complexity theoretic point of view. Computing the chromatic number is $\mathcal{NP}$-hard [2] and approximating the chromatic number up to a factor of n^ϵ for a constant $\epsilon > 0$ is impossible unless $\mathcal{P} = \mathcal{NP}$ [7]. However, polynomial time algorithms exist for coloring several families of graphs including bipartite graphs, interval graphs, comparability and cocomparability graphs, planar graphs, and partial k-trees for a constant k [6] [4]. The text by Jensen and Toft [4] provides a comprehensive overview of graph coloring.

C. Set Coloring

A straightforward extension of the simple graph coloring problem is to assign a set of colors, as opposed to a single color, to each vertex. This *set coloring*, or *set assignment*, problem corresponds to problem instances where, for example, an RFID reader requires multiple time intervals to communicate with all tags in its interrogation zone.

Simple set assignment problems can be modeled and solved by coloring a vertex replicated form of the original graph. Given a graph $G = (V, E)$ with associated demands $r(v_i)$ at each vertex $v_i \in V$, the graph G' is obtained by replacing each vertex $v_i \in V$ of the graph G by a clique of size $r(v_i)$ with each vertex in this clique having edges to the same vertices as v_i in G. The set coloring of G is equivalent to the simple graph coloring of G'.

D. T-coloring

Additional constraints can be placed on the separation between colors assigned to adjacent vertices. These constraints are given in the form of a set of integers called a T-set. The simple graph coloring problem has a T-set of $\{0\}$ The T-coloring variant of the graph coloring problem was introduced by Hale [3]. The T-coloring problem is defined as follows: given a graph $G = (V, E)$ and a set T of non-negative integers, a T-coloring of G is an assignment $f : V \rightarrow Z_+$ such that if two vertices v_i and v_j are adjacent, then $|f(v_i) - f(v_j)| \notin T$.

E. Modeling the Reader Network

The reader network of the RFID system is easily modeled as a complete undirected multigraph $G_R = (V, E_R) = (V, E_{R(1)}, E_{R(2)})$. The set of vertices V represent the tag readers. The set of edges $E_{R(1)}$ represent potential frequency interference between readers. The set of edges $E_{R(2)}$ represent potential tag interference between readers. A weight, or cost, may be associated with each edge to indicate the potential amount of interference possible.

An interference graph $G = (V, E) = (V, E_1, E_2)$ is derived from the reader network multigraph $G_R = (V, E_{R(1)}, E_{R(2)})$. Vertices in the interference graph still represent tag readers. The edges E in the interference graph are a subset of the edges E_R in the reader network graph, i.e., $E \subseteq E_R$. Edges in the interference graph represent interference that may actually be experienced during reader operation. Thus, only edges with a weight above a certain threshold are included in the interference graph.

The basic interference graph may be extended to model additional constraints. The most common additional constraints experienced in RFID reader systems are due to multiple time demand at a reader and frequency separation constraints. The requirement that a reader i be allocated multiple time slots (assuming a discrete modeling of time) is represented by a function p_i that is associated with vertex $v_i \in V$. Any allocation of frequency over time that satisfies this time requirement will provide reader i with p_i time units to communicate with tags in its interrogation zone. Unless otherwise specified, $p_i = 1,\ i = 1, \ldots, |V|$.

Frequency separation constraints may be required when simultaneous communication on two nearly identical frequencies may cause an unacceptable level of interference. Frequency separation constraints pertain to frequencies allocated to readers i and j such that $(v_i, v_j) \in E$. Frequency separation constraints are easily modeled using T-sets with $T = \{0\}$ being the default T-set.

IV. Graph Formulations

The reader collision problem may be formulated and solved as a graph coloring problem. Let $G = (V, E)$ be a basic interference graph as defined above. We note that the edges due to frequency interference force the use of multiple frequencies within a single time slot, and the edges due to tag interference force the use of multiple time slots regardless of how many frequencies are used. Consequently, frequency interference and tag interference often form orthogonal sets of constraints allowing the corresponding problems to be solved independently.

We consider several reader collision problem formulations in the remainder of this section. We first consider problems containing only frequency interference constraints. We then consider problems containing only tag interference constraints. Finally, we consider problems containing both frequency interference and tag interference constraints.

A. Frequency Interference

When only frequency interference exists within an RFID reader system, the simple reader collision problem is equivalent to the co-channel frequency assignment problem which, in turn, is equivalent to the simple graph coloring problem. The simple frequency constrained reader collision problem may be stated as follows,

$$\begin{aligned}
&\text{Instance: } G = (V, E) = (V, E_1) \\
&\text{Find: } f : V \rightarrow Z_+, \\
&\qquad \text{s.t. } (v_i, v_j) \in E \longleftrightarrow f(v_i, t) \neq f(v_j, t).
\end{aligned}$$

RFID readers may only communicate on one channel at a time. Therefore, allocating a reader multiple channels does not improve its communication bandwidth.

The co-channel frequency assignment problem was first formalized as a simple graph coloring problem by Hale [3]. Hale considered two objective functions for the co-channel frequency assignment problem, the discrete number of channels used in the solution, called the *order*, and the difference between the highest frequency used and the lowest frequency used in the solution, called the *span*. Clearly, the minimum order of a co-channel problem is simply $\chi(G)$.

When frequency separation constraints are present, the simple graph coloring problem does not sufficiently model the reader collision problem. However, a T-coloring of the interference graph $G = (V, E)$ does correspond to a solution of the frequency constrained reader collision problem. Cozzens and Roberts recognized this correlation for the co-channel frequency assignment problem, and they proved several results regarding optimality criteria [1]. Cozzens and Roberts refer to the minimum order for the T-coloring of graph G as the T-order, denoted by $\chi_T(G)$.

Theorem 1 (Cozzens and Roberts [1]) For any graph G and any T-set such that $0 \in T$, $\chi_T(G) = \chi(G)$.

Theorem 1 proves that the order of any T-coloring of any graph is just the chromatic number of the graph.

Since RFID systems operate within the free ISM frequency bands, the number of available frequency channels is limited. The exact number of available channels depends upon the local regulations and the design of the RFID system. In many instances the number of available channels is less than the chromatic number of the interference graph. This is particularly true of the lower frequencies used within RFID systems. For example, the 13.56 MHz ISM band extends from 13.553 MHz to 13.567 MHz, but for practical reasons this frequency range may be divided into a single channel only.

When there are not enough channels available to generate a valid solution to the coloring problem, a basic assumption underlying the graph coloring formulation is violated. Namely, the graph coloring formulation assumes that there are enough colors to determine a valid coloring of the interference graph. In these instances, the channels must be multiplexed over time, and the number of time slots used is to be minimized.

We can formulate these reader collision problems as graph coloring problems in which the colors correspond to frequencies allocated over time. Consider the simple reader collision problem in which there are k frequency channels available for use by the readers. Solving the graph coloring problem on the interference graph $G = (V, E) = (V, E_1)$ yields a coloring with $c \geq \chi(G)$ colors. Let the colors used be sequentially numbered $1, 2, \ldots, c$. Then, vertices colored with one of $1, 2, \ldots, k$ are scheduled in the first time slot. Vertices colored with one of $k+1, k+2, \ldots, 2k$ are scheduled in the second time slot, and so on. The resultant schedule uses $\lceil c/k \rceil$ time slots. Therefore, minimizing the number of colors used to color the interference graph minimizes the number of time slots required to schedule the reader communications.

Now, consider the reader collision problem in which there are k frequency channels available for use by the readers and frequency separation constraints exist. T-coloring so as to minimize the number of colors used will result in a feasible schedule when the colors are divided into time slots as in the simple reader collision problem.

B. Tag Interference

When only tag interference exists within an RFID reader system, the tag reader collision problem is equivalent to a resource constrained scheduling problem. The simple tag constrained reader collision problem may be stated as follows,

$$
\begin{aligned}
&\text{Instance: } G = (V, E) = (V, E_1) \\
&\text{Find: } t : V \to Z_+, \\
&\qquad \text{s.t. } (v_i, v_j) \in E \longleftrightarrow t(v_i) \neq t(v_j)
\end{aligned}
$$

where $t(v_i)$ denotes the set of times allocated to reader v_i.

When all readers require the same amount of time to communicate, the tag constrained reader collision problem is equivalent to the simple graph coloring problem where each color corresponds to a unique time slot. A solution to the simple graph coloring problem, therefore, corresponds to a schedule for the readers to communicate with tags in their respective interrogation zones. Thus, minimizing the number of colors minimizes the number of time slots required to allow all readers to communicate.

Next, consider the tag constrained reader collision problem where the readers require multiple time slots to communicate with tags in their respective interrogation zones. Recall that p_i denotes the number of time units required by reader i to communicate with all tags in its interrogation zone. Consider the problem where the required time units need not be satisfied by contiguous time slots. Given the interference graph $G = (V, E) = (V, E_2)$ we construct the graph G' as follows. Replace each vertex $v_i \in V$ with the independent clique v_i' consisting of p_i vertices. If edge $(v_i, v_j) \in E$, create the set of edges $(v_i', v_j') \in E'$ such that each vertex in v_i' has an edge to each vertex in v_j'. Solving the simple graph coloring problem on graph G' yields a solution such that a color allocated to a vertex in v_i' is not allocated to a vertex in v_j' if $(v_i, v_j) \in E$. Thus, by interpreting the colors as equal length time slots, an optimal simple graph coloring of G' yields an optimal solution to the tag constrained reader collision problem.

When the required time units must be satisfied by contiguous time slots, solving the simple graph coloring problem on the replicated vertex graph G' does not guarantee that a feasible solution will be found. Therefore, we formulate the reader collision problem as a generalized set coloring problem where the required number of colors $r(v_i) = p_i$ and the allowable span of the colors that are allocated to vertex v_i is p_i.

C. Frequency and Tag Interference

Frequency interference and tag interference provide fundamentally different constraints as we saw in the preceding sections. In the general reader collision problem, we may find a feasible solution by considering these two types of interference separately. A generic algorithm for solving the general reader collision problem is as follows. Given the interference graph $G = (V, E) = (V, E_1, E_2)$, solve the tag constrained reader collision problem on $G_2 = (V, E_2)$. The solution to this problem yields a set of groups of vertices, $\{V_1, V_2, \ldots, V_K\}$, where the groupings correspond to a partial order on the vertices $V_1 \prec V_2 \prec \cdots \prec V_K$. Note that a vertex v_i may belong to a single group only. Frequency interference does not occur between readers in different groups since their operation is separated in time. Therefore, the frequency constrained reader collision problem is solved on each group V_j independently. The combined solution is a feasible allocation of frequencies over time to the readers.

When there are sufficient frequencies to operate all frequency constrained readers at the same time, then the frequency constraints and the tag constraints are orthogonal. Therefore, the reader collision problem may be solved as two separate reader collision problems. Given the interference graph $G = (V, E) = (V, E_1, E_2)$, solve the tag constrained reader collision problem on $G_2 = (V, E_2)$ to obtain a time slot allocation for all readers. Solve the frequency constrained reader collision problem on $G_1 = (V, E_1)$ to obtain a frequency allocation for all readers. (The frequency allocation may also be performed on the vertex groupings as determined by the solution to the tag constrained reader collision problem.) The combination of these two solutions yields a feasible solution to the reader collision problem that allocates frequencies over time to the readers. Furthermore, if each of the sub-solutions is optimal, then the combined solution is optimal.

We note that in this case the tag interference constraints *dominate* the frequency interference constraints. This is due to the time component of the tag interference. Therefore, the problem of coloring graph G_1 can be simplified by removing redundant edges in E_1 such that $E_1 \bigcap E_2 = \emptyset$. That is, an edge $(v_i, v_j)_1 \in E_1$ may be eliminated if edge $(v_i, v_j)_2 \in E_2$, exists due to tag interference. A feasible solution still results since vertices connected by an edge in E_2 will be allocated different time slots.

In the general reader collision problem we are not guaranteed to find an allocation of frequencies such that all frequency constrained readers may operate at the same time. When the frequency constraints force the use of multiple time slots, the vertex groupings found due to the tag interference provide only a partial order on the reader communication times. The exact communication timings are determined by the combination of the frequency constrained solution and the tag constrained solution.

V. Conclusions and Future Work

In many ways, the reader collision problem is simpler than the frequency assignment problem. Thus, much of the previous work on the frequency assignment problem is applicable to the reader collision problem. However, the time and frequency usage constraints on the readers and the RFID system have a more significant impact on the performance of the RFID system than more traditional systems modeled by the frequency assignment problem. We have explored some of the consequences of the RFID system specific time and frequency constraints. Most notably, the phenomenon of tag interference is specific to the reader collision problem and is not found in the previously studied frequency assignment problems.

Many reader systems are static, that is the system configuration and usage patterns change infrequently. Thus, global off-line algorithms can yield optimal allocations of frequency over time. We have formulated many of these global problems as graph coloring problems on arbitrary interference graphs. The topology of the reader networks may enable more efficient formulations and algorithms. Specific reader network topologies need to be examined to determine if this is indeed possible. In addition, regulations may require more stringent constraints on the functionality of a centralized global algorithm than we have considered here. The reader collision problem must be investigated with these additional constraints.

Regulations in some parts of the world may prevent the use of centrally controlled RFID reader systems. In these countries, the readers must act independently to secure their required communication time. Therefore, distributed on-line algorithms only may be used within the RFID reader systems. In general, these distributed on-line algorithms yield suboptimal allocations of frequency over time. Theoretical and empirical analysis must be performed to develop and evaluate these algorithms for realistic operating conditions.

Additional variables may also be considered within the reader collision problem formulations. For example, the readers need not communicate at the maximally allowed power levels at all times. Varying the signal power from a reader varies the interrogation zone and the frequency and tag interference experienced by and caused by that reader. By allowing the power to be a variable to be solved for in the reader collision problem formulations, a solution may be found allowing the readers to communicate frequently with the tags close to them and infrequently with tags further away. Algorithms that explicitly vary reader power level in addition to frequency and time must be developed and evaluated.

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