RFID-Based Networks – Exploiting Diversity and Redundancy *

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In this article, we outline a research agenda for developing protocols and algorithms for densely populated RFID based systems covering a wide geographic area. This will need multiple readers collaborating to read RFID tag data. We consider cases where the tag data is used for identification, or for sensing environmental parameters. We address performance issues related to 'accuracy' and 'efficiency' in such systems by exploiting 'diversity' and 'redundancy.' We discuss how tag multiplicity can be used to improve accuracy. In a similar fashion, we explore how reader diversity, achieved by using multiple readers with potentially partially overlapping coverage areas, can be exploited to improve accuracy and efficiency. Finally, we show how multiple antennas in a reader can be used to improve accuracy and access rates by utilizing antenna diversity. RFID tag/sensor data can be highly redundant for the purpose of answering a higher level query. For example, often the higher level query needs to compute a statistic or a function on the sensory data obtained by the RFID sensors, and does not need all the individual sensor readings. We outline the need for efficient tag-to-reader communication, and reader-to-reader coordination to effectively compute such functions with low overhead.

I. Introduction

RFID (radio frequency identification) is an automatic identification system that consists of two components – readers and tags [10]. A tag has an identification (ID) stored in its memory that is represented by a bit string. The reader is able to read the IDs of the tags in the neighborhood by running a simple link-layer protocol over the wireless channel. In a typical RFID application, tags are attached or embedded into objects in need of identification or tracking. In the most common application of RFID (e.g., supply-chain management) the tags simply serve the purpose of UPC bar codes. By reading all the tag IDs in the neighborhood and then consulting a backend database that provides a mapping between IDs and objects, the reader learns the existence of the corresponding objects in the neighborhood.

RFID tags can be either *active* or *passive* depending on whether they are powered by battery. Passive tags are prevalent in supply chain management as they do not need a battery to operate. This makes their lifetime large, and cost negligible (only few U.S. cents per tag). The power needed for passive tags to transmit their IDs to the interrogating reader is supplied by the reader itself. The reader "energizes" the tags in the vicinity with RF power continuously for the entire read operation, which consists of a *query* from the reader and followed by the tag *response*. For the tag response, part of RF power is transmitted back to the reader (using a process called *backscattering*) after appropriative modulation and coding via the tag's electronics [10, 36]. The electronics can also perform simple computations and has a small amount of memory.

In their basic form, RFID tags are useful as *identification and proximity sensors* – when a reader can access information on a tag, the reader is able to identify the tag (or, by association, the object bearing the tag) as well as infer that the tag is in close physical proximity of the reader. In addition, when augmented with other environmental sensors (such as temperature, motion, vibration, etc.), RFIDs can be turned into *wireless sensors*. Such technology has already started appearing in the marketplace [22, 30]. We will use the term *RFID sensor* to refer to such sensors. The term *RFID tag* will be generally used to refer to any RFID device, with or without a sensor.

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The sensing functionality, similar to the computation, can potentially be powered using the energy harnessed from the reader's transmission, if the sensing is done at the time of reading. See, for example, [30]. Alternatively, in order to make the RFID devices more capable, part of the functionality of an RFID device (e.g., logic or sensing) can optionally be powered by batteries. In particular, *semi-passive* tags use batteries to power the digital logic or sensor on the device; however, backscattering is still used for sending signals from the tags to the readers. Since energy harnessed from the reader's transmission is used by the tags only for communication, and not for driving the logic, the communication range with the semi-passive tags thus can be greater as compared to passive tags. *Active* tags use batteries to power the digital logic as well as transmissions. This allows an improvement in the communication range, at a higher complexity and cost [10, 36].

While the basic operating principles of modern RFID have been known for many years [39], popularity of RFIDs has been on the rise recently, due to the ability now to build RFID tags that are sufficiently small, and sufficiently reliable, at an adequately low cost. The trend is expected to continue enabling myriads of interesting applications that use RFIDs. However, research on efficient communication protocols for RFID-based systems has been rather limited – particularly in dense, networked tag/reader environments. These are environments where tags are numerous, potentially attached to *every* object in the environment, however small. There may also be a large number of readers to provide adequate coverage. Examples include various factory automation, warehousing, supply chain management systems, as well as new smart environments such as smart homes.

In our view, there is a need for fundamental research on protocols and algorithms that can improve performance of RFID-based systems significantly benefiting the emerging applications. In addition, there is also a significant opportunity for the RFID tag technology to evolve. Charting an evolution path is easier if clear performance advantages can be demonstrated. Our goal in this article is to outline a set of research issues that will challenge the mobile computing and networking community. We will focus on two basic issues. The first issue is related to multiplicity and diversity. We will explore various forms of multiplicity and diversity possible in the tags, readers, reader antennas and operating modes. The second issue is related to cross-layer cooperation to improve efficiency of information access, by developing lower-layer access algorithms and middleware that adapt to the higher-layer computational goals.

II. Preliminaries

II.A. Architectural Considerations

In many emerging applications, the physical space of interest will far exceed the tag-to-reader range, which is typically at most a few meters. Thus, multiple readers need to be distributed across the space of interest to provide coverage over all tags. We assume that the information gathered by the readers is to be used by an application executing on a central computer system to draw appropriate inferences. Thus, the readers should be provided a way for communicating with the central computer. Networking them together over a *wireless ad hoc network* (say, using IEEE 802.11 as a link layer protocol with appropriate network-layer addressing and routing support) is an option that will have a wide ranging applicability. This architecture makes the deployment of readers unconstrained from wiring needs; it also provides flexibility in the case when one or more readers may be mobile, or the network needs to be re-purposed on-the-fly and the readers re-positioned. We will refer to the network that connects the readers to each other and to the central computer as the *reader network*. In addition to simply relaying information to the central computer, the reader network also makes it possible to develop inter-reader cooperation techniques for efficiently accessing the RFID tags, and dealing with redundancy in tag data. Another efficiency issue that may arise is the energy usage. Readers may sometimes be battery-powered. Thus, their energy burden of reading tags and relaying this information to the central computer must be optimized carefully.

II.B. Applications Considerations

To motivate the research topics outlined in this article, we discuss two example applications of RFID. These application drive the consideration of a large number of static or movable/mobile objects tagged with RFIDs in a wide geographical space.

Factory Automation and Supply Chain: Factory automation and supply chain are perhaps the most anticipated applications of RFID, with potential for widespread and dense deployment [34, 39]. The application requirements in these environments can be varied. For instance, the application may simply need to take an inventory of all objects. On a factory floor, or in a warehouse, it may be necessary to track the movement of objects on an assembly line, or a conveyer belt. Alternatively, the application may want to be aware of some environmental parameter, such as temperature [39], of the tagged objects.

In many such applications, the readers can collaborate to improve efficiency of data management. For instance, consider *read errors* that cause an object to "disappear" from its view intermittently. This is more likely due to noisy reads rather than real physical removal of the item [35]. While the central computer can identify the false alarms by analyzing data received from the readers, the readers themselves (or intelligent processors attached locally to the readers) can also locally perform preliminary data analysis to detect such false alarms. Local analysis can reduce the amount of data that must be transported to the central computers, and indeed the amount of data that must be gathered from the RFIDs in the first place, as elaborated in Section VIII. As additional examples, the application may need to know specific "high-level" events, such as "a new tag entering the location," "a tag removed permanently from view," "a tag in an unexpected location" etc. Rather than simply taking an inventory of all tags, a more efficient collaborative approach may be used by the readers to detect such events with greater efficiency [35].

Smart Environment: The motivation behind *smart environments* (such as a smart home) is to construct a living environment that can monitor the health and comfort of its occupants. The "smarts" added to the environment will enable automated detection of interesting events or higher-level "activities" (and response to such events and activities). Many researchers have previously proposed this concept [18, 37]. One key ingredient for the construction of a smart environment is the ability to monitor relevant status information (e.g., location, and environmental data such as temperature and motion) for the various objects in the environment – the kind of status information needed for each object may depend on the type of the object. However, one common requirement is the ability to communicate the information efficiently to the detection or inferencing system that analyzes the information.

In either application, not only a large number of (possibly mobile) tags must be read quickly and reliably, but also often queries will attempt to compute some function over an aggregation of tag data (e.g., "Does any package exceed the temperature threshold?" or "Did certain objects come in proximity to another object in a specific sequence?"), rather than asking for an enumeration of all tag reads. Instead of responding with a huge data set of all tag information read, it will be useful if the readers implement appropriate algorithms to determine answers to the queries efficiently.

II.C. Performance Metrics

Appropriate metrics need to be utilized to measure the efficacy of our approaches. We will consider three important classes of performance metrics, motivated by the potential applications of RFID tags and sensors. These three classes of metrics are related to speed, accuracy and energy efficiency, respectively.

- *Access Rate:* The precise definition of this metric, as well as the other metrics below, will depend on the specific application. In case of an inventory application, for instance, access rate will measure the number of tags that can reliably read per unit time on average. On the other hand, when using RFID temperature sensors, with an an application that desires to only know the the highest temperature over all RFID sensors, the access rate will determine the number of times the highest temperature can be accessed per unit time.

- *Accuracy (or Error):* The accuracy or error measures may also be different depending on the application. For example, when the requirement is to read all tags in the coverage area of a reader, an appropriate accuracy measure is the fraction of tags read reliably in a given duration of time. If the intent is simply to compute a statistic or a function of sensory data stored on RFID sensors (such as maximum temperature), the accuracy measure should capture how "close" the computed value is to the actual value. Note that there is often a trade-off between the access rate and accuracy. For example, protocols that allow "enough time" to resolve collisions among RFID tags, are likely to yield more accurate results, at the cost of a lower access rate.

- *Energy Usage:* The energy usage of interest here is that on the RFID tags/sensors, as well as on the readers. It is desirable to reduce both energy consumptions (note that semi-passive and active tags have a local energy source). Also, since the readers may themselves be wireless and battery-powered, reducing energy consumption of the readers can help prolong their battery life.

III. Related Work

Most of the past work in communication or networking arena on RFID systems is related to link-layer protocols to inventory (or singulate) the tags in a "single reader" environment. The primary goal is to minimize the time needed to access all the tags that might be present in a single reader's coverage area. Several of these protocols use a *tree-walking* (sometimes also called *tree-splitting*) based approach [23, 17, 31]. Aloha based protocols have also been proposed for this purpose [13, 41]. Preliminary work on in-network computation in the context of sensors has recently been performed [11], however, this work assumes general sensor nodes; RFID devices, particularly passive RFIDs, have different characteristics than typical sensor nodes. Some preliminary ideas on using MIMO and adaptive array antennas to access RFID tags have been discussed in [24]. For active tags, access protocols have been explored to reduce the duty cycle to increase their lifetime [28, 5]. For passive tags, [42] shows that memoryless protocols consume less power. Understanding power consumption profile for various components within RFIDs will help us design more energy-efficient protocols.

The problem of interference in presence of multiple readers has been addressed in [9, 38]. Research on cooperation techniques between multiple readers has also started appearing recently [4]. There has been significant work in localization of wireless devices, including in the context of RFIDs [12, 8, 32, 27]. Application of RFIDs for the purpose of tracking users (relative to object locations) is also being explored by others [19].

IV. Exploiting Tag Multiplicity

Just as multiple copies of the same barcode are fixed on different sides of a large object for ease of scanning, multiple RFID tags can be used on the same object. We will refer to the tags attached to a given object, with the goal of improving the ease of access, as being each other's "mirrors" – this does not necessarily mean that the mirror tags contain identical state. The mirrors provide a form of diversity that can be beneficial to improve performance. We will explore two benefits of tag multiplicity, namely, improving accuracy and improving localization.

IV.A. Improving Accuracy

Consider the scenario illustrated in Figure 1(a). As shown, a box-shaped object is affixed two RFID tags,

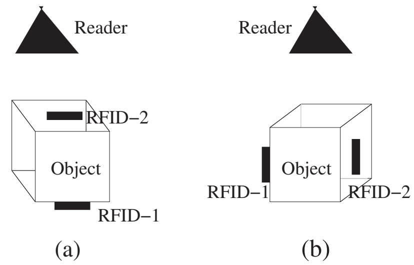

Figure 1: Example to illustrate benefit of RFID tag multiplicity.

and the object is close to the reader shown. However, due to the path loss due to materials within the box, the channel gain from the reader to RFID-1 is poor, whereas that to RFID-2 is good. Thus, in this case, the reader is able to access RFID-2, but not RFID-1. Being able to access any one RFID affixed to the box is sufficient to determine that the box is present in the vicinity of the reader. Of course, for this to work, the application will need to have enough information to determine that RFID-1 and RFID-2 are both affixed to the same object. Note that this method improves accuracy of object identification, rather than accuracy of individual tag reads. However, from an application's perspective, being able to identify objects is a desired goal. While tag multiplicity can provide the benefit illustrated above, two interesting issues arise as discussed below.

IV.A.1. Tag Naming

When multiple copies of a barcode are printed on a box, all the copies are identical. When multiple tags are affixed on the same object, should all these tags bear the same identifier? At the first glance, this may seem acceptable. However, with certain protocols (e.g., protocols based on tree-walking [23, 17, 31]) tags with the same identifier will always communicate with the reader simultaneously. To a reader, so long as the two tags transmit the same values, such simultaneous responses from the two tags may not necessarily be distinguishable from a single tag whose response is received along multiple paths (due to a multipath environment). If the reader is capable of operating correctly in a multipath environment, it may still be able to receive the transmission from the two tags correctly.

However, this is not adequate for correctness when protocols need to write information on the tags – since tags do provide writable memory, many protocols will make use of this memory. Consider that the reader issues a write command for a particular tag (specified using its identifier). Both tags having that identifier will be expected to complete the write reliably. However, in scenarios such as Figure 1(a), a write command from the reader may be executed successfully only by RFID-2. If, at a later time, the object is rotated, and becomes situated as shown in Figure 1(b), on a subsequent read operation, the tags will transmit different information back to the reader. Or, if an operation is to be performed as a function of stored information, the two tags may perform different actions, resulting in inconsistent states. This situation can lead to unresolvable ambiguity.

We suggest two distinct approaches to disambiguate reads from tags affixed to the same object. The first approach relies on *suitable selection of identifiers*. There are again two possibilities for this approach:

- *Explicit association:* Consider the example in Figure 1 again. With explicit association, the higher layer database will contain information to determine that RFID-1 and RFID-2 are affixed to (or "associated with") the same object. Thus, the identifiers of RFID-1 and RFID-2 can be arbitrary (but distinct), so long as the database stores the association information.

- *Implicit association:* In this case, the identifiers of RFIDs associated with a given object must bear some well-known relationship with each other. For instance, 2 bits in the RFID identifier may be reserved to distinguish between different tags associated with a given object (2 bits will allow at most 4 tags per object), while the remaining identifier bits among tags associated with the same object will have to be identical.

Implicit association has the advantage that no access to upper layer database is needed to determine that two tags are associated with a given object or not. However, it has the disadvantage that some bits in the identifier need to be reserved to distinguish between tags associated with the same object.

The second method is based on *timestamping*. The timestamping scheme may be used even when identifiers assigned to different tags associated with the same object are actually identical – in essence, timestamps will be used to implicitly differentiate between these tags. To understand the timestamping approach, again consider the problem with the write operation discussed above. Let us now assume that the readers are synchronized, and have a *common* notion of "time." The "time" need not be wall-clock time – the only property time needs to satisfy is that it should be monotonically increasing, and all readers need to use identical notions of time. Clearly, timestamps cannot keep increasing monotonically forever, particularly, since the amount of space we can devote for these on the tags is limited. However, even with a small number of bits used for this purpose, one can use the timestamp approach with suitable care taken when the timestamp rolls over – similar issues arise in many other contexts where finite counters are used [2]. Clock synchronization-like mechanisms can be employed to maintain timestamp synchronization among readers [2].

As before, assume the scenario in Figure 1(a), and that the reader performs a write operation on the tags, with the modification that the current "time" is also written to the tag. Now as before, subsequent to the initial write, the object turns, leading to the situation in Figure 1(b). When the reader issues a read command, in addition to using the tag identifier for accessing the tag, the reader also specifies a timestamp – in this case, the timestamp will be equal to that for the most recent write to that tag. This information can be stored in the higher layer database after writes to the tag, and used when reading the tags. Thus, only tags that contain a timestamp at least as large as that specified in the read command will respond to the command. This solves the problem with write operation discussed above. As should be clear from this example, the timestamp is implicitly used as an extension of the tag identifier.

The timestamps approach provides additional flexibility in accessing the tags, at the cost of requiring additional storage bits in the tags, and also more bits in the commands (although one can conceive ways in which the timestamp need not be specified in every command). In principle, the timestamp approach can be used in conjunction with implicit or explicit association as well.

For convenience, unless otherwise stated, in the rest of our discussion, let us assume that the explicit association approach is being used without any timestamps.

IV.A.2. Tag and Sensor Reading

When an object is affixed with multiple tags, to detect the object's presence, it is sufficient to be able to access any one of these tags. Similarly, if multiple sensors affixed to an object can provide the same sensory data, it may be enough to access one of these sensors. As seen before with respect to scenario in Figure 1(a), this redundancy can improve performance. However, in the scenario shown in Figure 1(b), the reader is able to access both the tags affixed on the box. Effectively, with tag multiplicity, the number of tags that compete for the reader's attention increases. This can have the adverse effect of reducing access rate, or increasing the time required to access tags affixed to all objects of interest. Thus, tag multiplicity can turn out to be detrimental to the performance of the RFID system.

Ideally, if the goal is to only access one tag per object, the reader should make no attempt to read the remaining tags after it has successfully read one. The actual mechanics of doing this will depend on the protocol used. For example, in a tree-walking [23, 17, 31] based protocol, the reader may simply not query for the redundant tags, thus increasing the speed of tree-walking. However, in a random access-based protocol such as framed Aloha, this technique is not sufficient, and additional mechanisms must be developed. In the case of active RFID tags, when coupled with implicit association, there is a potential for an RFID tag to learn that its "mirror" has already successfully communicated with the reader – knowing this, the tag may refrain from communicating with the reader in the same access cycle.

To summarize, while tag multiplicity can help improve accuracy, it can also increase the "load" since the number of tags increases. The challenge is to develop protocols that benefit from the improved accuracy, but prevent the increase in load from being detrimental to performance.

IV.B. Improving Localization

As mentioned before in Section II.B, it is useful to be able to estimate the location of objects. There is sufficient interest in localization of RFID tags such that a standard has been proposed to improve interoperability between software that uses location information and software that can estimate the locations [33]. As noted before, RFID tags can be viewed as proximity sensors – thus, if a reader can access a tag, then the object to which the tag is attached can be determined to be close to the reader. With multiple readers being able to access a tag, the location of the object can be determined as being within the intersection of coverage areas for those readers. Further improvements in accuracy of localization can be obtained by using signal-strength based triangulation methods [33], as also has been seen in wireless LAN environments [3]. Some early approaches are indeed being developed [25], where a single mobile RFID reader is used instead of multiple readers.

The existing mechanisms for localization will work if we assume that each object of interest is associated with a single tag. They need to be extended when multiple tags are affixed to a single object. For the sake of illustration, consider the object in Figure 1(b). Clearly, we can independently estimate the locations of the two tags affixed to the object. However, the knowledge that the two tags are affixed on the same object provides an additional constraint by supplying certain bound(s) on the physical distance between the tags, or sometimes providing the actual distance. The latter is possible when the tags are always attached at fixed locations on the object, and the object is not deformable. These additional constraints will make it possible to improve on the location estimates.

V. Exploiting Reader Multiplicity

As noted in Section II.A, in many applications, multiple readers must be employed so that an entire region of interest is adequately covered. This multiplicity of readers can be exploited to improve performance of the RFID system. In fact, to improve tag access rate, one may decide to deliberately deploy a dense, possibly redundant network of readers in order to gain from concurrent reading. With falling prices for readers, this option is likely to provide an agreeable cost-performance trade-off in the future. In the following, we describe three issues that arise with such reader multiplicity.

V.A. Improving Tag Access Rates

Multiple readers provide concurrency and thus improve tag access rate so long as they do not conflict. We classify approaches for using multiple readers into two classes: *non-cooperative* and *cooperative*. In non-cooperative algorithms, the readers do not explicitly communicate with each other to improve access efficiency, wheres in cooperative algorithms readers do cooperate. Both forms of algorithms can potentially improve performance; cooperative approaches can possibly perform better, but at the cost of increased communication between readers.

Non-cooperative approach: In the the non-cooperative approach, the readers do not communicate with each other directly. However, implicit communication can still occur via the tags, if the tags are writable. For instance, if one reader stores some unique information (such as reader identifier) on an RFID tag when it is accessed, then another reader can avoid accessing that tag by limiting its access to tags that do not contain other readers' identifiers in a specified location in tag memory ("masking" those tags).

However, each write and read operation requires additional time, which increases with the amount of information written or read. The challenge here is to develop non-cooperative approaches that require minimal *indirect* communication between readers, thus, reducing the amount of information that is written to or read from RFID tags.

Cooperative approach: The readers can potentially communicate over the reader network (as explained in Section II.A) to cooperatively decide how to access the tag population. For instance, the readers can potentially estimate the tag population size using statistical methods [31], and then divide this population among themselves in some manner. With such a division, multiple readers can attempt to access different parts of the tag population simultaneously. Performance is improved in two ways. Since a smaller tag population needs to be accessed by each reader, the contention overhead can be decreased. Also, spatial reuse offered by geographically separated readers can further improve performance. Since the population estimates would change dynamically, because more information becomes available with time, or because of the dynamics of the environment (e.g., mobile objects), the readers can communicate on a continuing basis to revise the division of work.

V.B. Improving Energy Consumption

With multiple readers available to read a tag, it is not necessary for each reader to access every tag. This simply generates redundant information in the system. Ideally one would try to partition the space into readers' coverage areas. But this is hard to do, since the covered areas do not necessarily have nicely defined shape, and the coverage may be time-varying due to variations in the environment. Thus, we propose to investigate approaches to dynamically control reader coverages, which can help in reducing readers' energy consumption low as well as reduce redundancy. One approach to control a reader's coverage is to control its output power. Another potential alternative is to control the antenna beamform used by the reader. By using a directional beamform pointing in a certain direction, we can control the coverage of a reader.

For the purpose of the discussion here, consider power control. The goal with multiple readers would be to allow each reader to use minimum power such that the readers together can provide the necessary coverage, i.e., collectively all tags in the concerned environment should be accessed by at least one reader. The question is how to determine the optimal transmit power for each reader's transmission. (With multiple readers, there is potential for collisions due to multiple readers transmitting at the same time. We will discuss this issue later.)

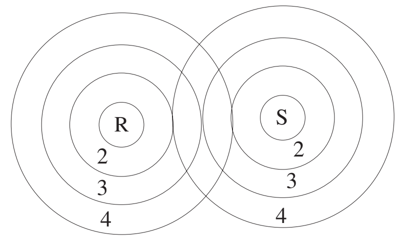

Figure 2: Demonstrating the *expanding horizon* approach.

In a dynamic environment, where the RFID tags may move with time, or obstructions such as people or equipment may be mobile, it is not reasonable to expect that a static setting for the transmit power will remain optimal over time. A more dynamic approach is therefore required. We will consider a dynamic approach that we refer to as the *expanding horizon* approach.[1] In this approach, each reader will begin the process at a low output power level, and attempt to access the tags in its coverage at the low power level. In Figure 2, we assume that the coverage area is circular and the circle radius grows with output power level; thus, initial coverage area is depicted by the smallest circles around the two readers R and S as shown. When the tags within the initial small coverage area have all been accessed, they are marked as having been accessed in the current *access cycle* – thus, they will not respond to future access commands within the same access cycle.

After completing the access at the initial power level, each reader can increase its output power to the next level, expanding the coverage, and then repeat the access procedure (the different readers do not necessarily synchronize the power level increase). Since the tags that have already been accessed will be masked, the tags that will now respond will be within the ring labelled as 2 in Figure 2. Having accessed these tags, next the reader may access tags at yet higher power level (ring 3 in our example), and so on. Note that, depending on whether the readers synchronize the stepping up of power or not, different readers may make progress through the different power levels at different rates, depending on the density of the tags within their vicinity.

[1] This is motivated by the *expanding ring* mechanism used in some routing protocols for mobile ad hoc networks [29]. However, the realization of expanding horizons will have to account for the characteristics of the RFID devices and readers.

This approach can be used to reduce energy consumed by the readers significantly. In particular, if we synchronize the step up in power at the readers, then each reader will tend to read tags in its own vicinity. Tags that are within the coverage of two readers when operating at maximum power will typically be accessed by the closest reader. Effectively, when a reader attempts to access tags at a high power, very few "unmasked" tags are likely to be found, and the reader will not spend much time at these high power levels, reducing energy consumption.

Incidentally, the expanding horizons approach also has the potential to improve access rates. In particular, this can be achieved by *not* requiring that the readers step up their output power together. Thus, a reader that has a lower tag density in its vicinity can move up in power levels faster than a reader with a higher tag density. Also, the readers can potentially choose the *granularity* with which the power level is increased based on estimates of local tag density.

V.C. Solving the Reader Collision Problem

The possibility of using multiple readers in the same physical space gives rise to the problem that two readers may simultaneously try to read tags. Two problems can potentially arise. If the readers are in close vicinity they may interfere with each other directly. The transmitted RF power from one reader may "drown out" the tag response to another reader in the vicinity (*reader-tag collision*) [9] if they are on the same channel. Even when two readers on different channels, if there are tags within the coverage of these two readers, on receiving the two readers' signals simultaneously, the tags might not be able to respond to either reader's query reliably (*reader-reader collision*) [16]. Reader-tag collision can be resolved by using a different frequency for the interfering readers or having tag responses coming in a different channel than readers as in the EPC Global Gen2 standard for dense mode reading [1]. However, frequency coordination problem arises when number of frequencies is limited. Regulations in many countries prevent a centralized coordination of frequency hopping patterns [6].

As mentioned before, use of multiple frequencies still do not address the reader-reader collision. For this, tag reads must be separated in time. The problem is compounded by the fact that the tag to reader communication typically uses antenna patterns with a significant directionality, and the signal quality is much influenced by the the orientation of the tag with respect to reader's antenna, and so on. There are several articles that address reader-tag and reader-reader collisions using coordinated frequency and time slot assignments [38, 7, 15]. Carrier-sensing based approaches [20] could also be used for reader-tag collision; but again would be inadequate for reader-reader collision unless carrier sense ranges follow certain perfect relationships with the tag read ranges. Link-layer protocol development to address both reader collision problems in practical settings is an open area for research.

VI. Antenna Diversity

Antenna diversity refers to the availability of multiple antennas with different beamforms, possibly including directional beamforms. It is feasible to equip the readers with relatively low-cost directional antennas. In general, the reader may have the ability to switch between multiple such antennas. The different beamforms formed by different antennas give rise to different coverages for the reader. Even in an environments with just a single reader, antenna diversity can be beneficial. While there has been a significant research on using directional antennas for ad hoc networks (see, e.g., [21]) they are not directly applicable for RFID reader networks. The directional antennas in the RFID system enable the readers to communicate with the RFID tags, not the other readers.

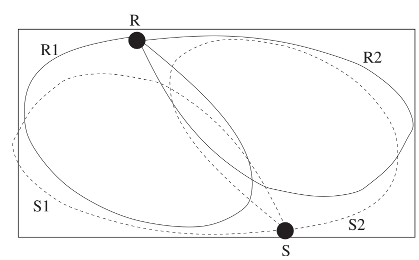

Figure 3: Example illustrating different antenna patterns. Dotted patterns for antennas are associated with reader S.

Consider the environment in Figure 3. As shown, there are two readers named R and S placed on two opposite sides of a room. Each reader has the choice of two antennas, whose beamforms are shown in the figure – antennas R_1 and R_2 can be connected to reader R, whereas antennas S_1 and S_2 can be connected to reader S. Clearly, if readers R and S were connected to antennas R_1 and S_1, respectively, then the union of their coverages will not include the entire room. On the other hand, if they were to connect to R_1 and S_2, respectively, then almost the entire room will be within their coverage. This simple example illustrates the need to coordinate the antenna beamforms used by the different readers.

Aside from improving coverage, a second potential benefit of antenna diversity is in increasing spatial reuse of the wireless channel, which, in turn, can help to increase tag access rates. Consider an application that requires *both* readers R and S to access all the tags in the room – this may possibly be for the purpose of localization. In this case, the interference between the two readers will be reduced if the antennas they use at a give time are chosen appropriately. In particular, when R uses R_1 if S uses S_2, and when R uses R_2 if S uses S_1, the interference will be lower, improving tag access efficiencies. The readers need to, however, determine the appropriate permutations of antenna patterns that are best-suited for this purpose. We foresee at least two categories of algorithms presently. One class of algorithms will periodically make statistical estimates on the coverage of each reader using each of its antennas, and use these estimates to determine the antenna permutations that are likely to induce least interference. The second class of algorithms will utilize flags stored on the RFID tags to pass information between the readers, that can be, in turn, used to deduce overlaps in their individual coverages.

VII. Diversity in Operating Modes

As mentioned earlier, RFID tags can be completely passive (no battery), semi-passive (battery used to drive logic and sensing, if any, but not transmission) or active (battery assists in transmissions as well for increased range). With sufficient battery power and design complexity, while an RFID tag can be equipped with a full-fledged processor and a radio transmitter (similar to a Berkeley mote [14]), such an approach is not likely to be practical for RFIDs due to cost and size considerations. However, with a plethora of tag technologies already available in the marketplace, one can imagine a continuum of tag designs, from no battery to batteries playing an increasingly important role, and a concomitant increase in the capability. One capability that is of interest would be to have some rudimentary processing power on the tags. For example, current generation of passive tags can interpret a limited number of reader supplied commands. With some battery assist, additional logic can be used to support a richer command set, or even a small instruction set with the microcodes supplied as commands from the tag. This makes them programmable on-the-fly with little on-board electronics. Obviously, more complex designs but short of a full-fledged processor-memory-radio system are possible with increasing power budget and cost. The on-the-fly programmability can provide support for new access protocols to enable efficient response to high-level queries. For example, a programmable tag can carry state information in the form of "tickets" through an assembly line, can upload data to only certain readers and not to others, respond to a reader only when certain conditions on its state are satisfied, or respond to complex range queries. These tasks can all be performed on the same tag (possibly at different times) while still maintaining low complexity, if the tags are made more programmable. To save energy, a design goal is to have a reader enable different functionalities on the tags only when necessary.

We envision that future RFID systems will carry a *heterogeneous* set of tags with varying capability and power budgets. However, one goal of a RFID system will be to access the needed information with minimal power consumption on the tags. This gives rise to a new concept of tags that can *adapt* their mode of operation, depending on the operational need. For example, the tag can start out being completely passive. But the reader can turn on more functionality in the tag on demand. Such adaptive tags can enable efficient access protocols. One example is tag-to-tag communication. This can solve the read asymmetry problem. This problem arises that often a powerful reader at a large distance can transmit with a power large enough to energize a passive tag; however, the backscattered power from the tag is not sufficient for the reader to read the tag data. Multihop relaying between tags, with readers' support, can address this problem (this problem differs from traditional sensor networks due to the possibility of the readers aiding in multi-hop relaying, by providing energy). Our hope is that success in such research will drive interest from industry to design and manufacture such tags and standardize their operations.

VIII. Improving Efficiency of Information Access

A RFID reader network can generate a vast quantity of data to be analyzed by a central computer system. To decrease energy usage and access efficiency, it is desirable if the amount of data communicated can be reduced without degrading the quality of decision-making. Fortunately, often the nature of the application requirements is such that all the available data is not needed to derive necessary information about the state of the system. If the readers can be endowed with additional intelligence to determine which data may be useful, then we can potentially improve efficiency of information access from the RFID network. In particular, we can reduce communication between tags and readers, as well as communication on the reader network, by exploiting application awareness, as elaborated below.

VIII.A. Optimizing Communication between Tags and Readers

The goal here is to reduce the communication between tags and readers while retaining acceptable quality for desired information about the RFID environment. In particular, often the desired information, such a statistic, can be computed, possibly approximately, only by reading a subset of the tags. For example, the tag to reader communication often uses frame-based slotted Aloha protocol, where the reader announces a contention window cw and the tags pick a random slot within cw to respond. By suitable choice of cw relative to the size of the tag population, collisions are avoided using this randomization. Such protocols can be easily modified for RFID sensor applications, where only a statistic on the tag values are desired, and not individual tag values. For example, suppose the minimum of tag values is to be determined. The reader can ask the tags to pick a slot number that is proportional to their values. The reader now only has to read the first tag announcement. This greatly optimizes delay as well as energy usage. Further improvements may be obtained by trading off accuracy of the estimate within limits of acceptability.

The collision problem still remains when multiple tags have the same value. Ordinarily, they will respond in the same slot. Randomization can be used to avoid collision, for example, by appropriately choosing cw, the proportionality constant α (to determine the slot number) and then adding/subtracting a small random number to avoid multiple tags with the same value responding in the same slot. Domain knowledge about ranges of sensor values will influence choice of cw and α so that delay and energy can be minimized.

Other statistic, such as the median, can also be computed more efficiently by implementing suitable algorithms in the readers, as opposed to reading all data and letting the application compute the median. In particular, one simple way to estimate the median is to access half of the sensor population in the increasing order of their sensory readings (this can be accomplished analogous to reading the minimum value). This, however, requires knowledge of the tag population size, which may either be known from a prior inventory operation, or can can also be estimated using approximate methods, such as random sampling. For instance, one possibility is for the reader to communicate a probability p to the tags, and the tags then respond only with this probability, The number of tags responding can then be used to estimate the total population size. The appropriate sample size (i.e., value of p) can be determined by performing statistical analysis on the gathered data (for example, by determining the confidence intervals with iterative sampling with increasing p, and stopping when the desired interval size is reached).

VIII.B. Optimizing Communication on the Reader Network

As noted earlier, it is difficult to ensure non-overlapping coverage for the different readers. Thus, the readers are likely to collect some redundant data from the RFID devices. It is clearly unnecessary to propagate all this data to the central computer. Instead, if the readers can cooperate with other readers in their vicinity, and filter the redundant data, the communication costs on the ad hoc reader network, as well as energy consumption at the readers can be reduced. Mechanisms need to be developed to identify the redundant data at the various readers. This is similar to aggregation in sensor networks [40]. Note that although the traditional sensor networks also need to avoid propagating redundant data, the RFID system differs in that we now have the flexibility of embedding intelligence in the tags as well as readers. Also, the readers are usually more capable compute platforms than sensor motes. Research in this direction can benefit from *data stream processing* algorithms [26]. Work in this area has considered the possibility of obtaining statistical estimates of certain aspect of data while only requiring small amount of storage. An interesting research issue here is the trade-off between processing required at the readers, and the communication cost in the reader network.

Duplicate data is the simplest form of redundancy, and perhaps easiest to identify. However, in general, the redundant data itself depends on the information desired by the application, thus application-awareness can help improve efficiency further. The application needs can vary. For instance, the application may be interested only in certain activities, e.g., "a particular tag not observed for a while," "searching for missing items", etc. [35]. Efficient querying techniques will develop *filters* at the readers such that only minimal information is propagated to the central computer.

These filtering algorithms should use local communication among nearby readers, and also attempt to reduce computing burden on the readers.

IX. Conclusions

In this paper, we have articulated a research agenda for RFID-based networks. We have focused particularly on performance issues in dense environments, such as those that can arise in factory automation, supply chain and various smart environments. The paper discusses an architecture with multiple RFID readers forming a collaborative network to perform RFID tag reads and analysis. The goal of this paper is to challenge the mobile networking and computing community to address the issues discussed here so that RFID networks become more efficient, enabling large scale deployments. We argue that performance measures such as accuracy, access rate and energy usage can be improved by exploiting diversity and redundancy in tags, readers, antennas, and operating modes. The paper also articulates how reader coordination can be utilized for improving performance. We hope that this paper will serve to encourage the research community to pursue issues related to performance of RFID-based networks.

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