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Distributed Receiving in RFID Systems

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***Abstract*—Many shortcomings in Radio Frequency Identification (RFID) systems stem from the underlying communication architecture; affecting performance, scalability and usability. This paper remedies such hindrance by introducing the novel paradigm of distributed receiving in RFID systems. The proposed scheme entails dispersing the routine functions of conventional readers onto spatially distributed entities, within the reader's interrogation zone, enabling formation of micro-zones. Such micro-zones facilitate the novel concept of multi-point communication in RFID systems. We also present a new breed of anti-collision algorithms – parallel singulation – exploiting the spatially isolated nature of micro-zones and the new multi-point communication architecture. Simulation analysis validates the distributed receiving system by demonstrating significant performance improvements, enhanced scalability and usability.**

I. Introduction

Radio Frequency IDentification (RFID), an emerging automated identification technology, turn objects into a mobile network of nodes, which can then be used to track objects, trigger events and to take certain actions. Energy scavenging and backscattering techniques are the foundation of low-cost identification solutions for RFIDs. Energy scavenging techniques harness incident radio waves to facilitate battery-less RFID tags (passive tags). Backscattering techniques reflect and modulate incident radio waves and facilitate transceiver-less RFID tags (passive and semi-passive tags). The performance of these two techniques – being wireless – significantly depend on the underlying communication architecture and affect the operation of RFID systems.

RFID systems are based on mono-static and multi-static communication architectures, with single antenna and multiple antenna configurations, respectively. However, a single reader, in both models, broadcasts the unmodulated signal and receives the backscattered modulated signal from the RFID tags. This single-assimilation point architecture, i.e., the centralized approach, constitutes a *forward-link* and a *backward-link*.

In the forward-link, the RFID reader broadcasts an unmodulated Carrier Wave (CW) signal and interrogation queries. Each passive tag, in response to the queries, would harvest its circuitry power from the CW signal incident on its antenna. The operational power requirement of a passive tag's circuitry, anywhere between $2.5\mu W - 100\mu W$ [1]–[4], along with CW signal attenuation, sets its operational range to a few meters. Thus, passive tags are bounded by the forward-link channel.

On the other hand, in the backward-link, passive and semi-passive tags communicate with the reader by reflecting and modulating the incident CW signal on their respective antennas. The reflected signal, overall, propagates double the distance between the tags and the reader. This leads to significant signal attenuation, hence setting the operational range of the semi-passive tags to a few tens of meters. Consequently, semi-passive tags are bounded by the backward-link channel. Furthermore, the centralized architecture and the tags' inability to sense the carrier channel creates collisions at the reader. Collisions are the most prominent hindrance to the performance of RFID systems; lowers reading rates, data rates and jeopardizes the system operational capacity.

Currently, numerous solutions have been proposed, both at the system-level and protocol-level, to attain maximal operational performance for the RFID systems. For instance, at the system-level, design of low-power circuits [1], higher gain antennas [3], directional antennas [4], etc. have been proposed. Similarly, at the protocol-level, energy-aware anti-collision protocols [5]–[7], energy-aware modulation schemes [8], [9], sophisticated anti-collision schemes [4], [10], [11], etc. have been proposed with promising outcomes. Nevertheless, the existing and related forthcoming solutions in literature are based on the underlying concept of centralized communication, hence inheriting its assumptions and suffering its limitations, such as the maximum possible reading rates [12]. Furthermore, these limitations place upper bounds on the reading range [4], bandwidth [3] and reading reliability [13] of RFID systems.

Impending RFID applications (e.g., intelligent transportation [14]), item-level object tagging [15] and mobility scenarios demand higher performance calibers from their underlying RFID systems. Promising CMOS technologies challenge the fundamental communication assumptions. For instance, emerging CMOS fabrication technologies promise significant reduction in the IC power requirement of tags by at least a factor of ten [3]. Consequently, the fundamental assumption of passive tags being forward-link constrained will no longer hold. Instead, they will become backward-link constrained. In addition, in an item-level tagging application, mobile tags (potentially in thousands) will prove impossible to interrogate using existing centralized systems.

Our contributions in this paper are as follows. Firstly, inspired by bistatic radar communication [16], we introduce a novel communication model for RFID systems, i.e., the concept of a distributed receiving architecture (Section II). In the proposed paradigm, the collection of modulated backscattered signals is dispersed to spatially distributed entities within the reader interrogation zone. Thus, this model, in addition to the regular RFID communication paradigms, supports multipoint-to-multipoint communication. The multipoint-to-multipoint

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paradigm in RFID eliminates redundant interrogation of same set of tags, by the overlapping RFID readers, hence, facilitating higher reading rates. Secondly, we introduce the concept of micro-zones of interrogation, by adjusting the reflectivity coefficients of tags (Section III). Micro-zones spatially isolate tags within the reader's interrogation zone, hence facilitating high bandwidth and data rates. Finally, by exploiting distributed receiving and micro-zones, we introduce parallel singulation algorithm to mitigate collisions (Section IV). We evaluate the proposed system, via comprehensive simulations, using our RFID implementation on the ns-2 simulator (Section V). The results validate that the proposed communication architecture, and the singulation algorithm, substantially improve system performance, usability and most importantly, enhance scalability under diverse distribution of (possibly mobile) tags.

II. Distributed Receiving-based Approach

In current RFID systems, the reader is the single emanation and the single assimilation point. As the emanation point, it broadcasts the CW signal and interrogation queries. As the assimilation point, it receives the modulated backscattered signals from the tags. Therefore, it is the single-point entity for collection, processing and most importantly, collisions. The centralized model is the outcome of conceptually inheriting the mono-static model, from radar communication, by the RFID systems. This communication model concedes into RFID as master-slave architecture and is depicted in Fig. 1.

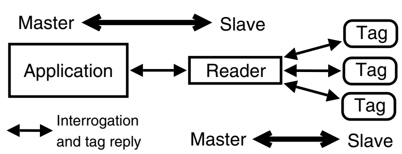


Fig. 1. Master-slave architecture of conventional RFID systems

To remedy such hindrance and inspired by the bistatic radar communication [16], we propose a novel communication paradigm in RFID. In the bistatic communication, the transmitter and the receiving antennas are spatially dispersed within the radar illumination range. Similarly, the basic idea behind the proposed architecture is to disintegrate the transmission and the receiving components of the existing RFID readers into spatially distributed entities. For this purpose a new component, named *fielder*, is introduced. The fielder tasks are collection, processing and relaying of the received information, from the tags, to the intended readers. The fielder, as shown in Fig. 2, in addition to the regular communication paradigms, initiates multipoint-to-multipoint communication in RFID. In the multipoint-to-multipoint paradigm, the tags' serial numbers received at a fielder are multicast to the subscribed reader(s), application(s) and other fielder(s). This subscription based data pushing eliminates the redundant interrogations of same set of tags, by the subscribed (with possible overlapping interrogation zones) readers. Purging the system from the overhead interrogations means fewer singulations and thus saving of the scare wireless resources. Furthermore, with the dispersed assimilation-point model, the collisions are reduced to tolerable levels.

The fielder is envisioned to be, similar to a wireless sensor node, a small-front, low-power, low-cost, and battery operated device and can be either stationary or mobile. The fielder adjusts its signal receiving threshold and receives reflected signals only from the spatially close tags. The fielder is deployed within the reader's interrogation zone in an adaptive manner. For instance, in a dense tags scenario, fielders maybe deployed in larger numbers to alleviate the collisions thus enabling a high reading rate. A multiplicity of deployment configurations are possible, e.g., stationary/mobile fielders with stationary/mobile readers. In this paper, however, we consider the stationary fielder(s) and the stationary reader(s) configuration.

In the rest of this section, we discuss the three RFID components, namely the reader, fielder and tag, and their comparatively discrete and novel features in the context of the proposed distributed receiving RFID systems.

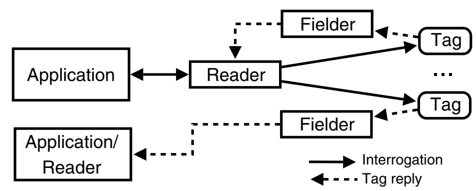


Fig. 2. Distributed receiving-based architecture in RFID systems

A. RFID Reader

In a conventional RFID system, the source of RF power, tag interrogation, processing of the reflected signal, collision resolution and relaying of data are all confined to single entity — the RFID reader. However, the distributed receiving RFID system disperses some of these routine tasks into the spatially distributed components of the system. The tasks include dispensation of the backscattered signals and data relaying. Therefore, to coupe with new functional modifications, the reader requires some operational changes.

Existing readers constantly broadcast the CW signal while receiving the reflected signal, on the same channel. On the other hand, in the proposed system, the reader broadcasts the CW signal on one channel and receives the data on a different channel. This is because the reflected signal will be collected and the processed data is relayed by the fielder to the reader using low-power communication protocol, e.g., Zigbee.

In existing systems, passive tags within the interrogation zones of multiple readers are illuminated, by each reader, individually in an autonomous manner. However, unlike existing systems, in the distributed receiving system the data processed by the fielders can be relayed to multiple readers without individual interrogations. This requires a reader to subscribe to certain fielders, e.g., a fielder within its interrogation zone. As a consequence, the reader can receive data without interrogations thus significantly reducing reader collisions.

B. RFID Fielder

The fielder, the novel entity of the proposed distributed receiving architecture, is responsible for processing of the tags' reflected signals and relaying of the processed data to the subscribed units. The fielder, along with the micro-zone formation, enables the reader to resolve the tag collisions.

The fielder, conceptually similar to a wireless sensor node, is a battery powered physical device based on off-the-shelf low-cost components. These components include IEEE 802.15.4 (Zigbee) transceiver, memory modules, microprocessor and RFID receiver. The fielder adjusts its receiving signal strength index (RSSI) threshold in order to create a virtual micro-zone, of a pre-defined area. The micro-zone is the confined area within the reader's interrogation zone and together, with the other micro-zones, covers the whole range. The fielders, mapped to the micro-zones in one-on-one manner, are responsible only for those tags that lie within its assigned zone.

Fielders can be in one of two states, namely *silent* and *forward*. In the silent state, no data is routed to the interrogating reader. The converse holds for the forward state. These states assist the reader in resolving collisions. For instance, in the case of reader collisions all fielders' state, with the exception of a randomly picked fielder, are set to silent. The intuition is to restrain multiple readers, with their overlapping reading zones, from interrogating the same set of tags, at one time. An overlapping reader not receiving any tag's reply – the silent fielder will not forward the data to their respective reader - avoids competing with others for singulation. Upon successful singulation, the data is then multi-cast, by the fielder, to the overlapping readers.

C. RFID Tag

The incident radio waves on the tag antenna facilitate two purposes. First is for the passive tag to harvest the DC power. Second is, for both passive and semi-passive tag, to communicate with the reader. The passive tag trades off the signal power between the rectifying and backscattering unit. Existing RFID tag, generally, splits the available power equally between the two units. In special cases, however, significant percentage of the power is set for the rectifying unit, i.e., tag's circuitry, at the expense of high-cost sensitive readers. On the contrary, the tag of the proposed distributed receiving system always distributes significant percentage of the available power to the circuitry unit, however, without the need of high-end sensitive readers. The micro-zone aids in minimizing the propagation distance of the reflected signal. Therefore, the signal integrity needs only to be valid within the micro-zone, i.e., up to the fielder which is spatially closer than the reader. Shortening of the backscattered path facilitates in longer reading range.

Existing tags backscatter the incident waves using an identical reflection co-efficient. The motive is to make the reflected signal, from all corners of the interrogation zone, strong enough to be successfully decoded at the reader. However, these reflected signals are also then strong enough to interfere with each other at the reader; the source of tag collisions. The tags in the proposed distributed receiving RFID system can dynamically adjust their reflectivity co-efficient. The co-efficient adjustments, i.e., reflection strength, are so that the signals can only be decoded successfully within the boundary of their respective zones. The reflected signal from a tag will not interfere with every tag within the reader interrogation zone, i.e., the tags from other micro-zones. This significantly reduces tag collisions and increases the bandwidth of the backward-link channel.

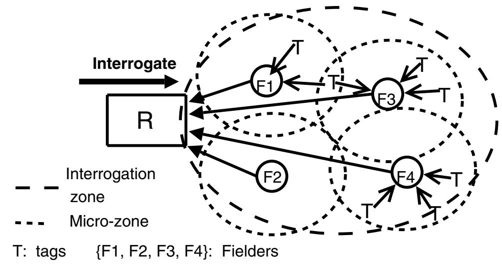


Fig. 3. Micro-interrogation zones in the distributed receiving RFID

III. Micro-Interrogation Zones

Tag collisions, in existing RFID systems, stem from the single-assimilation point model. Collisions take place when there is more than one tag within the reader's interrogation zone and the reflected signal from a tag is strong enough to interfere with others. To alleviate the situation, we introduce the concept of micro-zone interrogation within the reader's interrogation zone, as depicted in Fig. 3. The basic idea is to cluster the tags into micro-zones and interrogate these clusters in an autonomous manner. This reduces the number of tags that needs to be interrogated at one time. The micro-zones are formulated with assistance from the fielder and tag. The fielder adjusts its RSSI threshold such that the signal-to-noise ratio of the spatially close (within the pre-determined area) tags surpasses others. In addition, the tag also adjusts its reflection co-efficient, as per-reader request, such that the integrity of the reflected signal is only valid within the micro-zone. These adjustments lead to fewer simultaneous interrogations of tags and, hence fewer collisions. Furthermore, it improves the tags' reading rate and in turns the overall system throughput.

The micro-zone, conceptually similar to the cell in the cellular communication, does not interfere with its adjacent micro-zones, hence facilitating parallel interrogation. We address the dynamic reflectivity adjustment in rest of this section.

A. Variable Tag Reflectivity

An RFID tag, by design, maximally disperses the radio waves incident on its antenna. The purpose is that the signal, from any corner of the interrogation zone, should be strong enough to be successfully decoded at the central diverging point, i.e., at the RFID reader. However, the RFID system, based on the distributed receiving architecture, has multiple collection points, i.e., fielders, require the tags to reflect in such a way that the signal is confined within the micro-zone. To this end, tag reflectivity depends on the radar cross-sectional area σ and hence, can by modified by varying its impedance mismatch, i.e., introduction of a variable resistance R_{a2} in parallel with an already existing antenna resistance R_{a1} to create new variable antenna resistance R_a^{new}. The variable resistance is controlled by the data signal from the tag and is adjusted before execution of the anti-collision algorithm (section IV). In this paper, the details of the circuit design and their mathematical derivations are excluded due to space constraints. The modified radar cross-section σ_{new}, derived from Friss equation, radar cross section and basic electrical circuit, for the tag's antenna gain of G_t is

$$\sigma_{new} = \frac{\lambda^2}{4\pi}.{G_t}^2.\frac{4.R_a^{new}}{|R_a^{new}||Z_c|^2} \qquad (1)$$

Where λ is the radio signal frequency and $Z_c = R + jX$ is the imaginary part of the tag circuit.

The reader cluster the tags, by varying its antenna power level [10], based on their distance from it. The reader's interrogation range is divided into clusters, e.g., d, $d^{'}$ and $d^{''}$ at respective distance d, $d + \delta$ and $d + 2 * \delta$, from the reader. At any time, only tags from the same cluster will adjust their reflectivity co-efficient. The tag reflectivity co-efficient, i.e., its radar cross section, assignment algorithm is shown in Algorithm 1. In the first step, the intersection points P_k for each fielder's micro-zone f_k with the two boundaries of the current cluster, d and $(d - \delta)$, (δ is the stepping parameter) is calculated (lines 3-5). The set of intersection points P_k are determined for every fielder k which overlaps with the reader interrogation zone. The tag-fielder distance is the maximum Euclidian distance $\overline{fp}$, between the fielder f and its intersection points p, amongst all fielders (line 6). The new reflection coefficient σ_{new} is calculated, using (1), based on the minimum required power density of the reflected signal (calculating using Friis transmission equation for distance of $d(f, k)$) and is subsequently broadcast (line 7). Afterwards, the reader power-level is incremented, using technique from [10], and the aforementioned steps are repeated until the maximum interrogation is reached.

Algorithm 1 The reflectivity assignment algorithm

```
1: repeat
2:     // For the i^th cluster, (F is set of all fielders)
3:     for all  fielder f_k in {F} do
4:         {P}_k ← 4-intersection points with f_k, using
           d and (d - δ)
5:     end for
6:     d(f,t) ← max ( ∀ f ϵ {F} | max ( ∀ p ϵ {P}_f | overline(fp) ))
7:     Calculate σ_new using (1) and Send (Broadcast, σ_new)
8:     Increment reader's antenna power-level
9: until Maximum interrogation range is reached
```

B. Discussion

The distributed receiving is a new communication paradigm in RFID. The proposed system involves novel component, novel communication architecture and moreover, amends the functional and operation tasks of the existing tags and readers and be interoperable with existing systems. To accommodate, we propose multiple configurations, composed of mixture of the conventional and modified system components. Each of these configuration leads to distinct benefits.

Naturally, the mixed configuration will not result into maximal benefits — reading range, parallel singulation, higher reading rate and multipoint communication — as they would in the non-mix setting. For instance, using existing readers and tags, i.e., without any software and hardware upgrades, the operating range for the semi-passive and active tags can be increased. However, such a mix configuration will not yield higher reading rate. This is because, high reading rates are achieved using the micro-zones and parallel singulation, both of which depends on the availability of additional functionality at the readers and the tags (section II-A and section II-C). Similarly, using new readers with existing tags will enhance mobility support and will assist in multi-point communication. This is because the new reader may subscribe to the fielders and thus may receive tags data without singulation. However, such configuration will not assist in parallel singulation. This is because parallel singulation requires the tags to be able to adjust its reflectivity co-efficient and form the micro-zones.

IV. Parallel Singulation Algorithm - An Anti-collision Scheme

Existing anti-collision schemes are based on certain assumptions about the underlying system. First, tags within the interrogation zone are interrogated by the reader in a sequential manner. In other words, it is only after successful singulation of a tag that the subsequent singulation take place for the remaining tags. And second, all tags that lie within the interrogation zone, and due to the centralized architecture, will cause collisions at the reader.

On the contrary, RFID systems based on distributed receiving have the following important characteristics. First, the interrogation zones are divided into multiple non-interfering micro-zones. Second, the reader only knows and is concerned with the intra micro-zone collisions. Finally, and most importantly, the singulation is not a sequential process. To elaborate, as only the intra micro-zone collisions are possible thus, each micro-zone can be interrogated independently. In sum, the existing anti-collision schemes need to be tailored for the RFID system based on the distributed receiving architecture. In this paper, we propose a parallel singulation algorithm where multiple instances of an existing anti-collision scheme are executed, for each micro-zone, in parallel and autonomous manner. We use a simple binary search tree anti-collision algorithm [4], [17], although any other scheme may also be used. Due to space constraints, we only briefly explain the algorithm. Details, along with delay analysis, can be found in our supplementary work [18].

The main goal of any RFID anti-collision protocol is to increase the singulation rate by reducing tag collisions. In the case of parallel singulation, this is achieved in two ways.

First, an execution of the binary search tree algorithm for each micro-zone in an autonomous manner. And second, synchronization between the reader and the fielders. Pseudocode for the parallel singulation algorithm is shown in Algorithm 2.

Algorithm 2 Parallel Singulation Algorithm

1: Set all fielders state s_x to **FORWARD**
2: Send (broadcast, RESET)
3: Set interrogation range to bare minimum
4: **while** Interrogation range $\neq R_r$ **do**
5: Execute Algorithm 1
6: Increment interrogation range by *step*
7: **end while**
8: Send (broadcast, $REQA_{0xffffffff}$)
9:
10: // Singulation process for the i^{th} interrogation cycle
11: **repeat**
12: **wait** until $REQA_{timeout}$
13: **for all** fielder f_k **do**
14: // Let j be the most-significant collision bit, if any.
15: **if** $(Collision)_{f_k}$ **then**
16: $REQA_{(i,k)} \leftarrow b_{n-1}...b_j = 0b_{j-1} = 1...b_0 = 1$
17: $Queue_k \leftarrow b_{n-1}...b_j = 1b_{j-1} = 1...b_0 = 1$
18: **else if** $(no - reply)_{f_k}$ **then**
19: $REQA_{(i,k)} \leftarrow$ Pop from $Queue_k$
20: **else if** $(no - collision)_{f_k}$ **then**
21: // Tag is successfully singulated
22: $REQA_{(i,k)} \leftarrow$ Pop from $Queue_k$
23: **end if**
24: **end for**
25: **for all** fielder f_k **do**
26: **if** $REQA_{(i,k)} \neq$ NULL and $REQA_{(i,k)}$ is Unique for i^{th} cycle **then**
27: $Send(f_k, REQA_{(i,k)})$
28: **else if** $REQA_{(i,k)}$ = NULL **then**
29: $Send(f_k, SILENT)$
30: $s_k \leftarrow$ **SILENT**
31: **end if**
32: **end for**
33: **until** $\exists k | s_k$ = **FORWARD**

The algorithm begins with housekeeping tasks (lines 1-8), i.e., adjustment of the tag reflectivity co-efficient using Algorithm 1, setting of all fielders state to *FORWARD*, broadcasting of the RESET and initial serial request (REQA) to all the tags within the reader's interrogation zone. The reader maintains, for each micro-zone, an independent instance of the collision tree and its associated data structures. The major data structure includes the broadcast request from the previous interrogation cycle, a queue and the sequence number. An instance of the anti-collision algorithm, runs for every micro-zone, as shown in lines 13-24 and is iteratively executed for each interrogation cycle. In a collision scenario between the tags of the k^{th} micro-zone, a new broadcast request $REQA_{(i,k)}$ is formed by replacing the most significant collision bit by 0 followed by trailing 1's. The broadcast request for the k^{th} micro-zone is then used for the subsequent interrogation cycle (line 16). The collision bit is also replaced by 1, followed by trailing 1's, and is queued on $Queue_k$ (line 17), which is de-queued under two scenarios. First, is when no response from the tags was received for the last request (line 19) and second, after successful tag singulation (line 22). As the requests broadcasted by the reader reaches all the fielders it may cause tags from other micro-zones to respond with their serial number. To overcome this, the fielders are kept in-sync with the reader as they filters out the irrelevant replies originating from their micro-zones (lines 25-32). The algorithm terminates with all fielders state being set to silent.

V. Performance Evaluation

In this section, we analyze and compare the performance of the distributed receiving system as oppose to the conventional systems. We use reading range, reading rate, reading reliability and mobility as performance metrics. We also compare the performance of the proposed RFID system with a multi-reader configuration of the conventional RFID system.

A. Simulation Methodology

We have extended the ns-2 network simulator to support RFID. The major extension involves modification of the underlying simulator architecture to support the basic RFID functionality, the EPC class1-gen2 MAC protocol, multi-channel interfaces (RFID and IEEE 802.15.4) and non-EPC singulation protocols from the literature. Minor changes to the simulator include inheriting of the network node to serve as an RFID tag, reader, and fielder, single-hop communication model (backscattering modulation) between the tag and the reader, the reader's power control, etc. Unless otherwise specified, the simulations are performed using following parameters. In the setup, tags are uniformly distributed in a grid of $20 \times 20m$. A single reader is located at the center of the grid with an interrogation range of $15m$. The fielders are deployed in grid fashion, as configurations of 2, 4 and 16, covering the reader's interrogation zone with minimum possible overlapping. The tags randomly choose a 96-bit and a 32-bit serial number, latter is used for singulation. Simulations are made to run until all the tags are successfully identified. The performance metrics are averaged over twenty different experiments of different topologies.

B. Reading Range

Existing RFID systems use direct communication link between the tag and reader. This limits the reading range for both passive and semi-passive tags. A longer reading range means fewer readers to cover an area and longer tagged object visibility thus lower equipments manageability and monetary costs.

In the distributed receiving RFID system, the multi-hop, i.e., relaying of data through fielders, between the reader and tags, significantly increases the operating range of the semi-passive tags. The multi-hop link involves one or more wireless-hops, i.e., fielders, to transmit the data between the tag and the

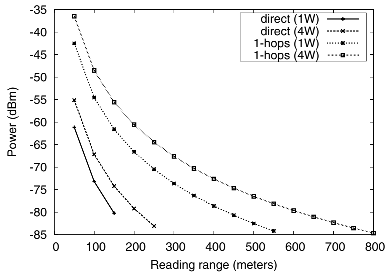
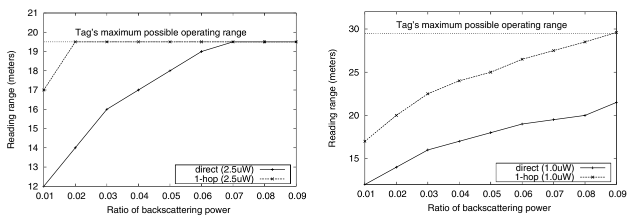


Fig. 4. Improvements in the reading range of the semi-passive tag



(a) Tag with min. IC of $2.5\mu W$ (b) Tag with min. IC of $1.0\mu W$

Fig. 5. Reading range of the passive tags

reader. Fig. 4 shows the reading range of a semi-passive for the reader's power level of 1W and 4W, for the direct (existing approach) and 1-hop (1-fielder per micro-zone configuration) system. The emitting power of 4W and 1W is the maximum allowable power that a reader may transmit according to the North American and European regulations, respectively. As expected, by using the distributed receiving architecture, the reading range for the semi-passive tag can be increased by an order of magnitude. For instance, for the 4W case, using 1-hop increases the reading range by a factor of 5. The reading range of the semi-passive tags can be potentially increased by using more than 1-hop.

The reading range of passive tags depends on several factors including minimum circuitry power requirement, efficiency of the rectifying unit and strength of backscattering signal. The reading range of a passive tag, with minimum circuitry power of $1.0\mu W$ and $2.5\mu W$ [1], is shown in Fig. 5. The horizontal dashed line in the graph shows the maximum possible reading range when using a rectifying module with an efficiency of 35%. The proposed system increases the passive tag's reading range under two scenarios. First, low-power circuitry and second, setting of the significant available power portion for the circuitry. For instance, in the case of $2.5\mu W$, the maximum possible operating range, in the proposed system, is achievable by using a very small ratio, 1% of the available power, for backscattering. On the contrary, to maintain similar range in the existing system, 7% of the available power must be available for backscattering. Using of any lower ratios adversely affect the reflected signal.

At low-power circuitry, the passive tag evolves into being a backward-link restraint. For instance, a tag with minimum power of $1.0\mu W$, has the maximum theoretical range of $29.5m$. The existing system, using up to 9% of available power available for backscattering, cannot go beyond the 21 meter mark. Diverting more power for backscattering, at the cost of lesser power for circuitry, is not helpful either as the tag, in such a situation, will not have enough power to operate. On the other hand, the proposed distributed receiving system achieves the maximal operating range.

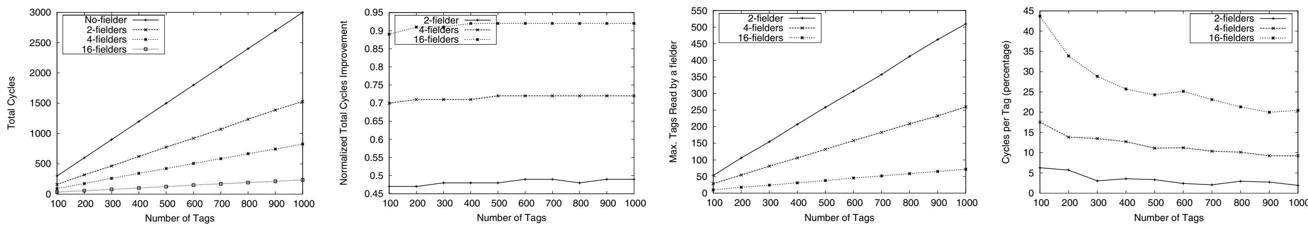
C. Reading Rate

The tag singulation rate is a product of the total number of interrogation cycles and the individual cycle intervals. High reading rates imply that more tags can be singulated by a reader thus supporting item-level tagging. The total singulation (reading) cycles, normalized cycle improvements and the average singulation cycles per tag for various tag enumerations, using the conventional and the parallel singulation schemes, with configuration of 2, 4 and 16 fielders, are shown in Fig. 6. The number of singulation cycles for the proposed approach is many-fold lower in comparison to the number of cycles required by the conventional approach. For instance, using 2, 4 and 16 fielders, decrease the total reading cycles by 45%, 70% and well over 90%, respectively (Fig 6-b). Furthermore, the total reading cycle, when using the 16-fielder configuration is almost linear, as is shown in Fig 6-a. Hence, the RFID system based on the parallel singulation has the potential to support higher volumes and dense tag distributions.

Due to the nature of parallel singulation, the micro-zone with the highest tag enumeration determines the total number of singulation cycles. As an illustration, Fig. 6-c shows maximum number of tags singulated, among all micro-zone, using 2, 4 and 16 fielders. As expected, more clusters translate into fewer tags in each of them thus potentially fewer collisions. For instance, with a total of 1000 tags in the reader's interrogation zone, using a configuration of 16-fielders, the maximum tags read by any given cluster are always less then 100. However, under a similar setting, using a configuration of 2-fielders, the numbers are almost five to six times high. In short, the 2-fielders case will require more cycles resulting in lower reading rates compared with the 16-fielders' configuration. On the other hand, an increase in the number of fielders also increases the probability of the overlapping regions. Overlapping imbalances the tag distribution and creates idle cycles. Fig. 6-d shows the average cycles per tag normalized to the best case. As the ratio of the overlapping area of the 16-fielders is high, so is its divergence, e.g., by 25% from its best case. Whereas, minimal diverges is observed for the fewer fielders scenario. For instance, divergence of only 3% is observed for the 2-clusters configuration. To summarize, there exists a trade off between the reading rate and the cluster configurations.

D. Reading Reliability

Reading reliability is the probability a tag is readable regardless of reader and tag antenna orientations. Having high



(a) Total Cycles (b) Normalized Cycles (c) Max tags read amongst the fielders (d) Normalized Cycles

Fig. 6. Total cycles, average cycles per tag and normalized cycles comparison between conventional and distributed RFID system

reading reliability is of utmost importance for certain applications. For instance, self-checkout counter at a departmental store – a miss-read tag is lost revenue.

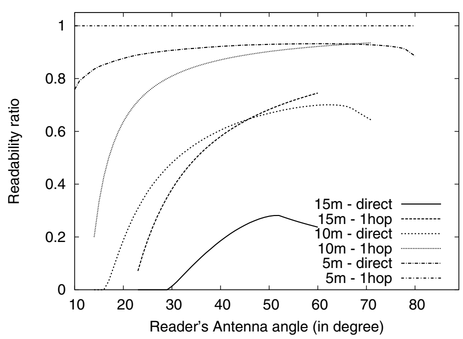


Fig. 7. Reliability ratio for the conventional and distributed receiving reader

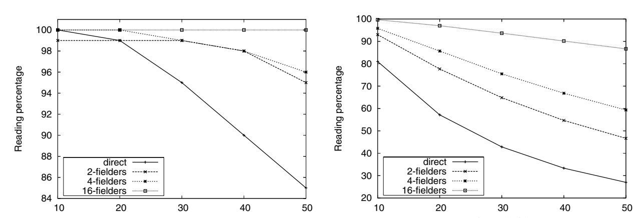
The antenna gain, a function of the azimuth and the tilt angle, affects the power delivered by the antenna. For instance, the tag receives minimal and maximal power when its antenna orientation is parallel and perpendicular to the reader's, respectively. The readability ratio of a tag, in the conventional (direct-hop) and the proposed (1-hop) system, using single antenna configuration, at various distance from the reader is shown in Fig. 7. Each point in the graph is an average of successful tag read, using orientations between 10° and 180°. The readability of the distributed receiving system, at long distances, is almost three times higher than the conventional system. Note that 100% readability is achievable at short distances. Such significant improvements are partly due to tag setting considerable portion of the available power for its circuitry. Therefore, even under harsh settings, majority of available power is used for tag operations. As well, the integrity of the backscattered signal is to be valid only inside its micro-zone. In other words, the tag of the distributed receiving system is capable of operating under diverse antenna's orientations, i.e., diverse range of power, thus meeting the challenges of futuristic applications, e.g., item-level tagging.

E. Mobility

In existing RFID systems, a mobile tag may be miss-read in two scenarios. First, if it moves out of the reader's zone before being interrogated. Second, being interrogated, however dense tag environments and thus immense collisions, prevents it to be singulated in time. Both scenarios lead to miss-read tags. The effect of mobility on tag reading, using single reader configuration for the conventional and proposed system, for 100 and 600 tags is shown in Fig. 8. To be fair in comparison, we have not entertained the long reading range and the multipoint paradigm of the proposed system, for this experiment.

The reading rate of the mobile tags, for the conventional system, degrades under two cases: first, in high-speed mobile tags and second, in dense-tag environments. At high speed, conventional systems' low reading rates, cannot singulate the tag on time, before it moves out of the interrogation zone. Similarly, in the dense environments, immense collisions prolong the duration of interrogation process. For instance, both at high speeds and dense distributions, the reading ratio falls well under 30%.

The distributed receiving system, on the other hand, can handle high-speed and dense-tag environments. The micro-zones facilitate potentially fewer collisions, whereas parallel singulation algorithm support fast reading rates. Fewer collisions and fast reading rates assists in singulating mobile tags at high speed and in dense environments. Furthermore, more the number of micro-zone better is the system's ability to tackle high speed mobility. For instance, using 16-fielders, the reading percentage is an order of magnitude higher than the use of 2-fielders, reading rates of over 90% is maintainable, regardless of tags speed and density.



(a) 100 mobile tags (b) 600 mobile tags

Fig. 8. Mobility effect on tags reading

F. Multi-reader Configuration

Micro-zones may be mimicked by using a set of readers, equal in number and interrogation area, deployed at the same locations as the fielders. The motive behind such an experiment is to compare the performance of multiple readers to the distributed receiving system with multiple fielders. The total number of reading cycles, with multiple standalone readers and the fielders, is shown in Fig. 9. Interestingly, the total cycles for the multi-standalone system are only marginally lower than the proposed system. For instance, the difference between two and four multi-standalone readers to that of a single distributed reader aided by 2-fielders and 4-fielders is at most 4% and 11%, respectively.

The minor performance difference between the two configurations is because of the micro-zones' overlapping effect. In the case of multiple standalone readers, the tags within the overlapping region are singulated as many times as there are the overlapping readers. However, in the distributed receiving system, each tag in the overlapping zone is singulated only once, hence causing idle cycles for other zones' singulation trees. These overlapping micro-zones, and hence their potential negative effects, can be alleviated using an optimal placement scheme for the fielders. Nevertheless, the distributed receiving system seems an attractive and low-cost solution over the high monetary costs associated with using multiple readers, for minimal performance gains.

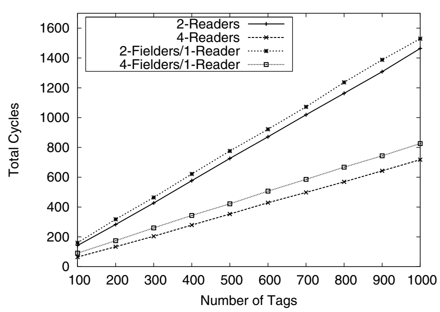


Fig. 9. Comparison of total number of cycles for the multi-readers and fielders configurations

VI. Concluding Remarks

The existing RFID architecture is the underlying root cause of the shortcomings in performance, scalability and usability. In this paper, we introduce the distributed receiving system in which collection of the modulated backscattered signal from the tags is dispersed to spatially isolated entities. These entities, named fielders, are low-cost and battery operated devices, deployed within the reader's interrogation zone. Each fielder, along with adjustments in the tags' reflectivity coefficient, creates zones, coined as the micro interrogation zone, conceptually isolates the tags within its own region from the tags of other micro-zones. A parallel singulation algorithm, exploiting the localization and distributed nature of these micro-zones, interrogates each zone in a parallel and autonomous fashion. This new architecture leads to significant performance improvements in achieving high reading rates, low collisions, longer reading range for semi-passive tags and more bandwidth.

The novel architecture initiates a new research direction in RFID, for example, the proposed parallel singulation algorithm. Optimized fielder deployment techniques and formation of the micro-zones with minimal overlap need to be developed as they promise to further boost system performance. Novel MAC protocols, for both fielder and reader, need to be developed in a distributed context. Other possible research areas include the design of distributed backscattering modulation schemes, mix configurations using stationary/mobile fielders and readers, reader load balancing using micro-zones and so forth. New initiatives, for instance, 3D localization, subscription based e-tracking etc. are just some of the possible future applications for the distributed receiving RFID system.

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