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A Novel Spatio-Temporal Data Redundancy Elimination Approach for RFID Systems with Multiple Readers

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Abstract. In this paper, we propose a Voronoi diagram based spatio-temporal data redundancy elimination approach for RFID systems having multiple readers so that every RFID tag will be read by only one reader depending on the distance between the tag and the center of the Minimum Enclosing Circle (MEC) of the Voronoi cell which the reader belongs to. Thus, the spatial redundancy in the gathered data is completely eliminated. Temporal redundancy is also minimized by reading the RFID tags at regular time intervals larger than an appropriately chosen threshold value. Existing methods of reducing data redundancy in RFID systems are often associated with loss of data, false positive errors and false negative errors. In contrast to this, our proposed technique is free from any false positive and false negative errors with no loss of data and every tag being read by only one single reader. Simulation of our proposed approach also establishes its superiority to the existing techniques in terms of these performance parameters.

Keywords: RFID systems, spatial redundancy, temporal redundancy, redundancy elimination, multiple readers

1 Introduction

Radio frequency identification (RFID) systems, mobile ad hoc networks (MANETs), wireless sensor networks (WSNs), vehicular ad hoc networks (VANETs), etc. are different interconnection technologies which play a pivotal role in the seamless integration of the physical world constituting, what is known as the Internet of Things (IoT) [1], [2]. RFID is an emerging technology for automatic object identification [3]. RFID systems are based on electromagnetic signals which have the advantages of low cost, simplicity in deployment and low energy consumption [4]. An RFID system consists of a set of readers and several objects, with each object being equipped with a small chip, called a tag [10]. RFID tags are used for the identification of the objects without using line-of-sight detection process which eliminates the limitations of barcode identification [12]. RFID is used in a wide range of application areas including agriculture, military, defense, health care, supply chain management, logistics, access control, IT access tracking, materials management, race timing, product tracking, payment, passenger identification in airport, postal tracking, near field communication (NFC) tag readers in smartphones, etc.[5, 9, 6–8].

RFID tags can be of two types, namely, active tags and passive tags. Active tags have their own power sources which are usually batteries. On the other hand, passive tags do not have any external power sources; they rely on the power transferred wirelessly from the readers to respond [13], [8]. RFID readers collect data by querying RFID tags and forward the received data to a back-end application or database server. This data transfer takes place through a middleware which is capable of filtering, aggregating, and transferring raw data. It also coordinates different reader activities. After receiving these data, the back-end server processes it to decide the appropriate actions to be taken.

For large scale RFID systems, it is necessary to deploy multiple readers with overlapped interrogation zones to fully cover an area and achieve a high accuracy in the estimation process [11], [12]. Consequently, a tag can be within the interrogation zone of several readers. The tags which are within the range of multiple readers may be identified multiple times by different readers [15] simultaneously, leading to spatial data redundancy. Fig. 1 shows a scenario with seven RFID readers $R_1, R_2, \cdots R_7$ with overlapping interrogation zones. In Fig. 1, individual interrogation zones of the RFID readers are shown by circles. Radius of the interrogation zones of RFID readers may vary depending upon the type of RFID tags that has been used. Table 1 shows different types of RFID tags and their maximum readable distances[14]. In Fig. 1, the overlapping areas of two adjacent RFID readers have been shown in dotted pattern. An RFID tag belonging to the dotted region can be identified by multiple readers. All the RFID readers collect data and send those to the server. Further, as the RFID data acquisition rate used for monitoring is often very high, a massive amount of temporally redundant data may also be generated. All these spatially and temporally redundant data not only increase the network latency, but also occupy more system storage space. If not properly filtered, these redundant data can even cause server overloading and failure to detect important tag information. To balance the accuracy and real-time performance of monitoring, it is necessary to identify and remove such redundant RFID data.

Our Contribution:

In this paper, we propose a Voronoi diagram based spatio-temporal data redundancy elimination approach for RFID systems with multiple readers. First the temporal redundancy is checked and reduced and then the spatial redundancy is checked and eliminated. Temporal redundancy is eliminated by reading the RFID tags at regular time intervals beyond an appropriately chosen threshold value. To resolve spatial redundancy, we consider that the total area of interrogation is a closed zone in an indoor environment. A Voronoi diagram partitions a plane into multiple non-overlapping regions based on some points [36], [28]. For each point there is a corresponding region called Voronoi cell. Two Voronoi cells meet along a Voronoi edge and three Voronoi cells meet at a Voronoi vertex. Our idea is to divide the total area into multiple non-overlapping Voronoi cells where each of them identifies the interrogation zone of one RFID reader. We assume that the coordinates of the RDIF readers $R_1, R_2, \cdots R_7$ are known *a priori*. Fig. 2 shows the Voronoi diagram drawn using the coordinates of the RFID readers $R_1, R_2, \cdots R_7$. Authors in [34] have proposed a Voronoi diagram based base station (BS) placement framework that can completely cover a given convex/non-convex region without generating any coverage hole. Their algorithm also minimizes the wastage of transmission power due to overlapped circles and out-of-region coverage. To start with, we assume that following this technique given in [34], n number of RFID readers are already placed to cover the whole region with minimum overlapped areas and without any coverage hole.

Type of RFID tags	Frequency range	Reading distance
Low Frequency (LF) Passive RFID Tags	125 to 134.3 kHz.	1 - 2 meters
High Frequency (HF) Passive RFID Tags	13.56 MHz.	1.5 meters
Ultra High Frequency (UHF) Passive RFID Tags	860 to 960 MHz.	1 meter or 3 feet
Ultra High Frequency (UHF) Active RFID Tags	433 MHz.	1 feet to over 3 kilometer (1.86 miles)
Super High Frequency (SHF) Active RFID Tags	2.45 GHz.	100 meter or 325 feet

Table 1: Different types of RFID tag and their maximum readable distance

Next, the location of each RFID tag is identified. Different approaches for wireless localization to estimate the location of an RFID tag has been studied in the literature. We use triangulation based localization algorithm to estimate the location of an RFID tag. Accordingly, a given RFID tag will be registered only to a particular RFID reader depending on the distance between the tag and the center of the Minimum Enclosing Circle(MEC) of the Voronoi cell in which the reader belongs to. Only the identified reader will read the corresponding tag and hence, the spatial redundancy can be completely eliminated. This is in contrast to other existing methods which show a higher compression rate at the cost of losing some relevant tag data. The temporal redundancy among data gathered from a given RFID tag at different time instants is eliminated by appropriately choosing the successive time instants of gathering data by a specific reader at sufficiently long intervals of time so that temporal redundancy is minimized without losing important information about the movement of the RFID tags in a dynamic environment.

Following the above technique, we propose an algorithm for removing spatial redundancy and minimizing temporal redundancy. This algorithm has a time complexity of $O(n^2)$, where n is the total number of RFID readers in the system. We simulate the proposed algorithm with random data sets. Experimental results show that our proposed method outperforms existing popular techniques in the sense that it is free from any false positive and false negative errors with no loss of data, so that every tag is read by only one single reader and all the active tags present in the system are identified.

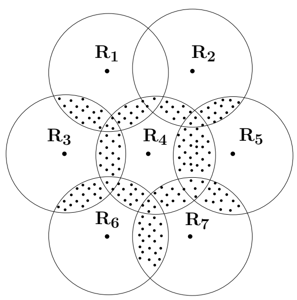

Fig. 1: An example scenario with multiple readers

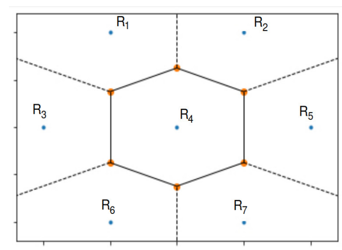

Fig. 2: Voronoi diagram of the RFID readers $R_1, R_2, \cdots R_7$ as shown in Fig. 1

2 Related Works

In traditional RFID systems, data from RFID tags read by the readers are stored in a data warehouse/database which is accessed by a query based system [17] depending on typical applications. In [16], a filtering approach has been proposed to eliminate data redundancy which is, however, not suitable for large scale data in meeting the real-time requirements. For such scenarios, window-based filtering methods are found to be more suitable [18]. Window-based methods work on only a small part of the data stream that fits into a particular window depending on several attributes. However, the effectiveness of such methods depends mostly on the selection of attribute fields and the size of the window [19].

Several redundancy removal algorithms specially designed to match the characteristics of RFID data streams are available in the literature. Authors in [20], proposed some redundancy processing framework based on pipelined data cleansing. Authors in [21] proposed a finite state machine based model for redundancy removal in RFID data. This approach divides the area of investigation into different states in the state machine models to avoid spatial redundancy. In the area of machine learning, several RFID data stream cleaning methods has been proposed which are mainly based on dynamic Bayesian networks (DBNs) [22]. Bloom filter-based approaches for filtering redundancy in RFID data have recently emerged.

Compared to the other approaches, as mentioned above, the Bloom filter-based approaches are more suitable for the dynamic data streams in real-time applications. Time Bloom Filter (TBF) [24], Time and Space Bloom Filter (TSBF) [25], Approximate Probability Synthesis Bloom Filter (PSBF) [26], Time-Distance Bloom Filter (TDBF) [12] etc. are the few Bloom Filter-based redundancy removal algorithms.

2.1 Methods for Localization

Most of the existing localization algorithms in a wireless network use parameters like time, angle, signal strength, etc. to estimate the location of an object [15], [27]. Combinations of such parameters may also be used to compute the location of an RFID tag [15]. Existing techniques which are very often used for localization, are briefly mentioned below.

Multilateration In this method, the coordinates of a tag are identified as the intersection point of three or more circles that are formed based on distance measurements between a tag and its neighboring RFID readers. In a two-dimensional space, the minimum number of readers needed to identify the position of a tag is three. A special case of multilateration is referred as trilateration where, only three readers are used to identify the position of a tag. However, we may achieve higher accuracy by increasing the number of readers [29], [30].

Triangulation As the measurement of distance could be erroneous in real life situations, we can use direction of the tags rather than measuring the actual distance between the RFID readers and the tags. This method uses trigonometric relationships to calculate the position of a tag based on the angle information of the tag from two neighboring reader nodes [30].

Bayesian inference In this approach coordinates of a tag are obtained by the use of probability and recursion on an appropriate parameter which is mainly signal strength in RFID system [31].

Nearest neighbor In the nearest neighbor method, a few reference tags are placed in a grid layout with known location information. Next, the position of a new tag is estimated by comparing its signal strength with those from the reference tags [32].

Kernel based learning In Kernel based learning, radio signal strengths are read at different training points along with their physical distances from the reader. This sample data is fed to the algorithm in the form of a vector and the algorithm gradually learns to determine the position of a new tag [33].

3 Some Preliminaries

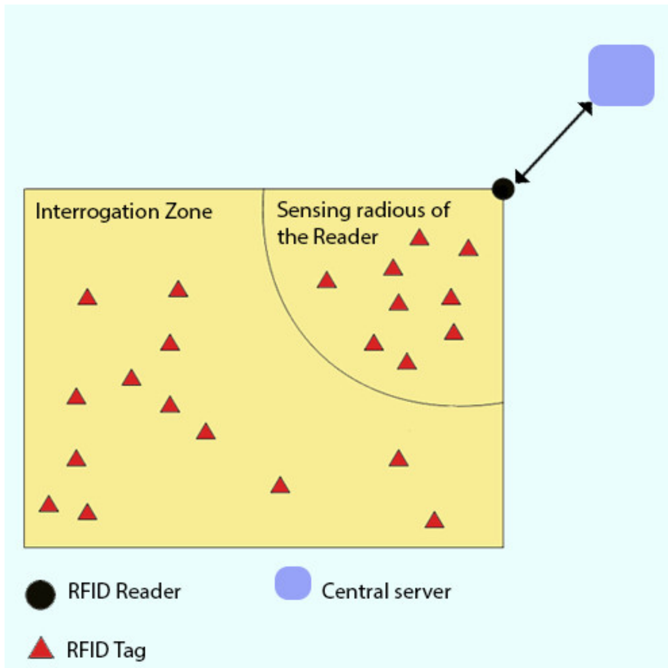

Fig. 3: RFID network architecture

Each RFID data is described as a four-tuple $< tag_{id}, reader_{id}, time, RSS >$, where tag_{id} stands for the ID of the captured tag that uniquely identifies the tag, $reader_{id}$ is the ID of the capturing reader, $time$ is the capturing time or the data acquisition time, and RSS is the received signal strength which is a function of the distance between the tag and the reader. We use D to denote a stream of RFID data, i.e., $D = d_1, d_2, \cdots, d_n$, where d_i denotes the i^{th} data (represented by the four-tuple $< tag_{id}, reader_{id}, time, RSS >$) in the data stream.

Redundancy in RFID data can be of two types - *temporal redundancy* and *spatial redundancy* [12]. In a given time window, a certain tag may be read multiple times by its assigned reader. Except the first reading in this window, all other data are considered to be redundant. This is referred to as temporal redundancy. On the other hand, a tag might lie within the sensing range of more than one readers and hence, could have been registered with multiple readers. This is referred to as spatial redundancy. Following the idea proposed in [12] we formally define temporal redundancy and spatial redundancy as follows,

Definition 1. Temporal redundancy *Let us set T as the time window in data stream D. If there are two tag data values $x \epsilon D, y \epsilon D$ in D, such that, $x.tag_{id} = y.tag_{id}$, $x.reader_{id} = y.reader_{id}$, $y.time$ - $x.time \leq \eta$, where η is a set time threshold, then data y is considered to be temporally redundant data. The tagged object is detected multiple times by a reader within the same time window. Therefore, only the earliest arriving data in the time window will be registered as non-redundant, while all others will be regarded as redundant.*

Definition 2. Spatial redundancy *Let us set T as the time window in data stream D. If there are two tag data $x \epsilon D, y \epsilon D$ in D, such that, $x.tag_{id} = y.tag_{id}$, $x.reader_{id} \neq y.reader_{id}$, $y.time$ - $x.time \leq \tau$, where τ is a set time threshold, then data y is considered to be spatially redundant data. The tagged object is detected by multiple readers almost simultaneously. Therefore, only one reader may register the tag according to the tag_{id} and for the other readers the data will be considered as redundant.*

4 Proposed Method for Redundancy Elimination

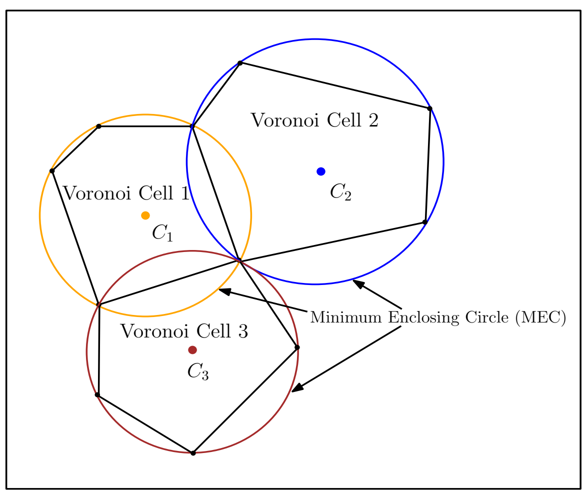

Fig. 4: Minimum Enclosing Circles (MEC) of different Voronoi cells

Let us consider a closed zone in an indoor environment as our area of interrogation. Following the Voronoi diagram based method proposed in [34], n number of RFID readers have been placed to cover the whole region under consideration without leaving any coverage hole and with no overlapped areas (in terms of the Voronoi cells of the readers). Once the whole interrogation zone has been partitioned into non-overlapping Voronoi cells, the Minimum Enclosing Circle(MEC) of each Voronoi cell is being identified using the method proposed by Welzl et. al. [37]. Partitioning of the interrogation zones into multiple Voronoi cells and finding their MECs has been done by the central server in $O(n^2)$ and $O(n)$ time, respectively. For n number of readers, we have n Voronoi cells and centers of the corresponding MECs has been identified as $C_1, C_2, \cdots, C_n$. The situation is shown in Fig. 4. We also place an RFID reader at the entry gate of the interrogation zone so that it can keep track of all the newly entered RFID tags. We assume that the RFID readers can communicate with each other as well as they are connected to a central server. The scenario is shown in Fig. 3. The server is supposed to have computational capability and storage space to store and process a global list of RFID tags and their relevant information. We further assume that the tags are dynamic and they continuously keeps changing their location with respect to time. We can remove both temporal and spatial redundancy from the RFID data by executing the following steps:

Step 1: When a new tag enters the interrogation zone it gets registered with the reader placed at the entry gate.

step 2: After a regular interval of time I, each RFID reader sends beacon signals to the RFID tags.

Step 3: At the time of registering the data, the RFID reader checks for temporal redundancy, i.e., if there are two tag data $x \epsilon D, y \epsilon D$ in D, such that, $x.tag_{id} = y.tag_{id}$, $x.reader_{id} = y.reader_{id}$ and $y.time \geq x.time$, then it is checked whether $y.time$ - $x.time \leq \tau$, where τ is a pre-assigned time threshold.
- If $y.time$ - $x.time \leq \tau$ then data y is considered to be temporally redundant data and is discarded.
- Otherwise, the data is temporally non-redundant. Next, we check for spatial redundancy.

Step 4: From the round-trip delay or from the RSS value from a tag, an RFID reader estimates the Euclidean distance between the tag and itself and then it sends this distance value to a central server.

Step 5: IF a tag is sensed by three or more RFID readers then the following events takes place,
- The positional coordinates of the tag are calculated by the central server by using multilateration technique.
- Depending on the calculated position of the RFID tag, distances between the tag and the center(C_i) of the MEC of the Voronoi cell in which the readers belongs to, has been calculate.
- The minimum distance has been identified by the central server and then the tag gets registered with the reader which belongs to that particular MEC.

Step 6: IF a tag is sensed by less than 3 RFID readers then, the RFID reader having lesser distance with the tag register the tag with itself.

Step 7: All the other RFID readers consider the data as redundant and discard it.

5 Proposed Algorithm

Algorithm 1: $Process\_RFID\_Data$

```
Input: RFID data x: x.tag_id, x.reader_id, x.time, x.RSS
Output: Updated list L of RFID data
Count_L = length(L) ;
for i = 1 to Count_L do
    if x.tag_id == L[i].tag_id then
        /*Check for temporal redundancy
        if (x.reader_id = L[i].reader_id) && (L[i].time - x.time ≤ η) then
            Discard RFID data x ;
            /* RFID data x is considered to be temporally redundant
        /*Check for spatial redundancy
        else if (x.reader_id ≠ L[i].reader_id) && (L[i].time - x.time ≤ τ) then
            Put x, L[i] in a seperate list K ;
            /*spatial redundancy identified
            Remove L[i] from L ;
            Execute Resolve_Spatial_Redundancy() /*Execute Algorithm 2;
    else
        Add x as a new entry in L ;
        /* RFID data x is considered to be non-redundant
```

The pseudocode representation of the above steps is given in Algorithm 1. Algorithm 1 is executed at the central server at a given regular interval of time. It takes the RFID data as input in the form of a four-tuple as described in Section 3 and checks it for redundancy. Redundancy is reduced in two steps - first the temporal redundancy is checked and reduced and then the spatial redundancy is checked and eliminated. After that it resolves the redundancy and updates a global list(L) of RFID data accordingly. As a part of pre-computation the whole interrogation zone has been partitioned into non-overlapping Voronoi cells and the minimum enclosing circle (MEC) of each Voronoi cell is being identified by the central server. Centers of the corresponding MECs have been identified as $C_1, C_2, \cdots, C_n$ and they are supplied as input to Algorithm 2. We assume that the execution time of the algorithm is very small so that during the execution of the algorithm, a tag does not change its position.

5.1 Complexity analysis

In Algorithm 1, a newly received RFID data is checked for temporal redundancy and then Algorithm 2 is called to resolve spatial redundancy. In Algorithm 1, a global list L of RFID data is checked to reduce temporal redundancy. If we have n number of active tags in the system then the maximum possible length of L could be n. The time taken for reducing temporal redundancy is $O(n)$. Next, we call Algorithm 2 to eliminate spatial redundancy. In Algorithm 2, first we need to determine the coordinates of an RFID tag which takes constant time. If an RFID tag has been identified by z readers simultaneously and $z > 2$, then for all the

z readers we compute the distance between the RFID tag and the center of the MEC of each of the z Voronoi cells. It would take $O(z)$ time. Next, we compute the minimum of those z distances which again takes $O(z)$ time. For $z = 2$, the total computation takes place in constant time. Hence, the worst-case time complexity can be computed as, $O(n.(z + z)) = O(n.(2z)) \approx O(n^2)$.

Algorithm 2: *Resolve_Spatial_Redundancy*

```
Input: List K of RFID data with i^th data represented as
       < K[i].tag_id, K[i].reader_id, K[i].time, K[i].RSS >, Centers C_1, C_2, ··· , C_n of the MECs
       of the Voronoi cells
Output: Updated list L of RFID data after reducing redundancy
Count_K = length(K) ;
t_id = K[i].tag_id ;
Compute the coordinates of the RFID tag t_id by multilateration using all K[i].time, K[i].RSS
  values;
if Count_K > 2 then
    for i=1 to Count_K do
        Compute the distance v_i between RFID tag t_id and the center C_i of the MEC of the
          Voronoi cell in which reader K[i].reader_id belongs to ;
    /*Find the minimum v_i
    min_v = v_1 ;
    min_index = 1 ;
    for i=2 to Count_K do
        if min_v > v_i then
            min_v = v_i ;
            min_index = i ;
    /*Register the tag data with the identified reader
    m.tag_id = t_id ;
    m.reader_id = K[min_index].reader_id ;
    m.time = K[min_index].time ;
    m.RSS = K[min_index].RSS ;
    Add m to list L ;
else
    /*For Count_K = 2 case,
    for i=1 to Count_K do
        Calculate distance d_i between RDIF tag t_id and reader K[i].reader_id using K[i].time
          and K[i].RSS;
    if d_1 > d_2 then
        m.tag_id = t_id ;
        m.reader_id = K[2].reader_id ;
        m.time = K[2].time ;
        m.RSS = K[2].RSS ;
    else
        m.tag_id = t_id ;
        m.reader_id = K[1].reader_id ;
        m.time = K[1].time ;
        m.RSS = K[1].RSS ;
    Add m to list L ;
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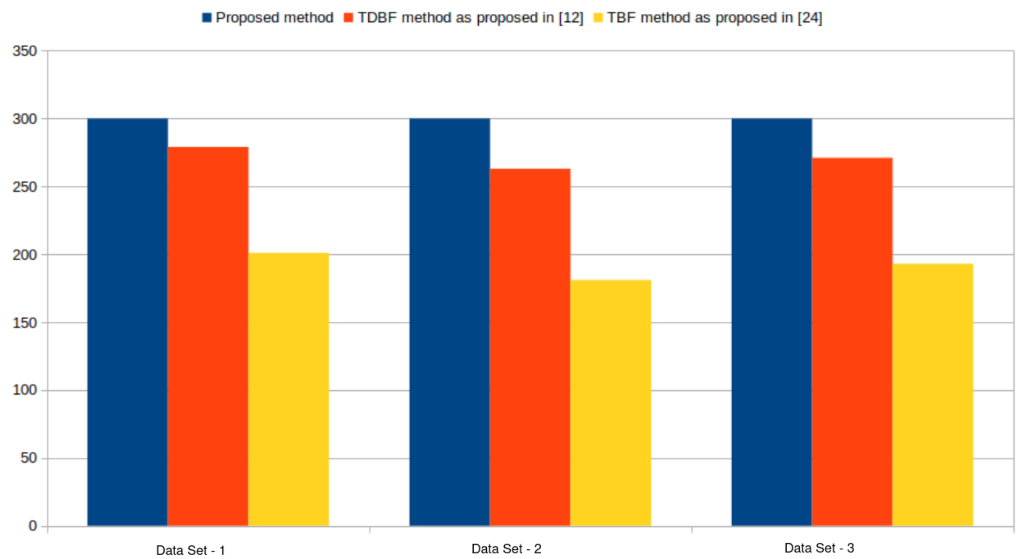

Fig. 5: Experimental results showing detected number of active tags

6 Experimental Results

We evaluate the performance of our proposed algorithm in terms of the three parameters - compression ratio, false positive rate and false negative rate. The data compression ratio is the ratio of the total number of tags collected per minute, divided by the number of tags actually registered after redundancy removal. Higher compression ratio implies that more data have been identified as redundant and filtered out by the algorithm. However, an excessive data compression may lead to loss of some important information. False positive refers to the false identification of an RFID tag data as redundant. Thus, false positive implies loss of some useful data. On the other hand, if a redundant RFID tag data is mistaken as a non-redundant data then it is called false negative which is also undesirable so far as system overhead is concerned. A dynamic situation has been considered as our experimental environment to measure the performance of our algorithm with respect to the above parameters.

For our experiment we have used synthetic random data sets which are generated by using COOJA simulator[35]. We assume that there are 300 active tags. Three sets of 10000 different data values have been generated to represent random movement of the dynamic tags. The values of the respective RFID data fields are created by using a pseudo random number generation algorithm. The algorithm has been executed with each of these three random data sets as inputs and the corresponding performances have been compared with those of the TBF [24] and TDBF

[12] algorithms. Fig. 5 shows the experimental results which indicate that both TBF and TDBF filter have a lower compression rate than our proposed method, but it is associated with loss of some relevant data which may lead to a situation that some valid RFID tags will not be identified. In contrast, our proposed algorithm has successfully identified all the 300 active tags for each of the data sets which implies that it is free from false positive errors. No false negative errors have been detected either, and each tag has been read by only one reader, leading to complete elimination of spatial redundancy.

7 Conclusion

We have proposed a Voronoi diagram based spatio-temporal data redundancy elimination approach for RFID systems having multiple readers. Redundancy elimination has been done in two steps - first the temporal redundancy is checked and reduced and then the spatial redundancy is checked and completely eliminated. Temporal redundancy has been reduced by reading the RFID tags at regular time intervals above an appropriately chosen threshold value. To eliminate spatial redundancy, we have presented a Voronoi diagram based technique that partitions the area of interrogation into multiple non-overlapping regions. The RFID tag which is within the sensing range of multiple readers, gets registered with only a single reader depending on the distance between the tag and the center of the MEC of the corresponding Voronoi cell which the reader belongs to. We have proposed an algorithm implementing the above technique which has a time complexity of $O(n^2)$, n being the total number of RFID readers in the system. The algorithm has been simulated with random datasets. Simulation results show that our proposed approach outperforms other existing popular methods in the sense that it is free from false positive and false negative errors with each tag being read by only one single reader leading to complete elimination of spatial redundancy, and yet capable of identifying all the active tags present in the system.

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