Placement of Multiple RFID Reader Antennas to Alleviate the Negative Effect of Tag Orientation

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Abstract—One primary issue which hinders large-scale Radio Frequency Identification (RFID) applications is the imperfect read rate. According to Friis equation and experiments, we find that the dipole tag’s orientation plays a significant role in read performance both in theory and practice. In this paper, we consider how to deploy multiple reader antennas to alleviate the negative effect caused by uncontrollable tag orientations in item-level applications. Different from previous work, we expand the candidate antenna positions from the portal to real three dimensional space and establish two estimation functions based on sphere coverage models under different polarized environment. Meanwhile, we provide an improved enumeration scheme with leaping and layering search strategies based on sphere quadtree (SQT) model to find optimized deployment.

Keywords—RFID; deployment; reader antenna; tag orientation; polarization; sphere coverage; enumeration

I. INTRODUCTION

Radio Frequency Identification (RFID) technology has made substantial progress in recent years. Compared with traditional barcode, RFID has clear advantages, such as larger memory, much higher read efficiency, long distance and non line-of-sight communications and so on, which promote a great number of research and commercialization efforts. However, although it is referred to the next generation barcode, there are still some technical challenges to be resolved. One primary issue which hinders large scale RFID applications is that tags cannot be correctly read with 100% probability in real scene [1] due to various factors which lead to insufficient received power on a tag. In practical item-level application, one missed tag may cause great financial loss, so it’s an urgent issue to which many researchers have devoted their energy. Extended Friis equation [2][3] provides a mathematical analysis to describe the related factors which impact the power received by RFID tag from the reader antenna. Among these factors, we find that the tag orientation plays an important role in affecting tag’s received power even though other factors remain the same. Unfortunately, it is a tough nut to crack due to its uncertainty in practical scenario. For example, the tags attached to objects in a shopping cart are messy. To some extent, innovative tag antenna designs involving multiple dipoles or monopoles can overcome this problem [4]. However, considering the performance and cost, the dipole tag which is sensitive to orientation is the most common tag (such as Alien® ALN-9640 [5]) in industrial applications nowadays.

In order to improve the imperfect read rate (the term in this paper refers to the probability that a tag is correctly read by a reader) caused by the dipole tag’s orientation, multiple readers or one reader with multiple antennas are taken for the most common way. However, different from the previous work in [6][7][8][9], this paper focuses on discussing how to optimize the deployment of multiple antennas to increase read rate from the perspective of the tag orientation. We expand the candidate antenna positions from the portal to real three dimensional space and establish two estimation functions by converting the deployment problem into sphere coverage models under linearly (circularly) polarized antenna environment. Meanwhile, we provide an improved enumeration scheme with leaping and layering search strategies based on sphere quadtree (SQT) model to find optimized deployment. Our work provides a guideline for placement of multiple antennas.

The remainder of this paper is organized as follows. We review related work in Section II. Section III presents preliminaries about polarization and Friis equation. In Section IV, we formulate the problem. Then two sphere coverage models are introduced, followed by the enumeration scheme in Section V. Section VI shows the performance evaluation. Finally, we conclude our work in Section VII.

II. RELATED WORK

The present research involving the optimized reader antennas placement are divided into two categories, one of which is called the RFID network planning problem which selects reasonable reader antenna positions so that the wireless network can have the required coverage, ensuring that RFID systems can provide effective communication performance and capacity [10]. Unlike the antenna positioning in traditional cellular networks, uplink signal must be taken into account when dealing with the planning in the RFID networks [11]. Leong [12] explored antenna positioning in an RFID deployment zone and aimed to provide guidelines on safe distance between antennas in a dense reader environment. Guan [11] formulated the RFID networking planning problem into multi-objective optimization issues and mapped it into genetic algorithms. Bhattacharya [13] proposed an efficient algorithm based on particle swarm optimization technique to find out the minimal number of readers and their positions for maximum coverage of the tagged items.
The other type of work is to optimize placement of multiple reader antennas at the portal to increase read rate. Wang [6][7] is the first to explore this problem and enumerate possible reader antenna positions and tag directions to maximize the overall powering region by calculating the read accuracy based on extended Friis equation. Meanwhile, he discussed and selected a reasonable solution space to get the optimal deployment considering trade-offs between computational time and the solution precision. Shortly afterwards, biology-inspired approaches were introduced to resolve this issue. Lee [8] used the Genetic Algorithm (GA) to search the optimum solutions for the portal reader antennas placement problem, Kao [9] presented two methods with artificial immune systems which had excellent ability to attain the optimal deployment. The simulation results showed that, biology-inspired approaches could reduce execution time to some degree without losing too much solution precision. This paper concentrates on the latter placement problem from the perspective of the tag orientation.

III. PRELIMINARIES

In this section, we introduce the important background information of the polarization and then the Friis equation which provides a mathematical description of the received power.

A. Polarization

An electromagnetic wave moves electrons in the plane perpendicular to the direction of propagation [14][15]. Polarization which is in general described by an ellipse is defined as the orientation of the electric field of an electromagnetic wave. Two special cases of elliptical polarization are linear polarization and circular polarization, as shown in Fig. 1. With linear polarization the electric field vector stays in the same plane all the time, just like the electric field in Fig. 1(a). The electric field of point \( O \) changes along the orange line (polarization direction). Because human beings are gravitationally challenged, it is most common to orient linearly polarized antennas either vertically or horizontally [14]. As shown in Fig. 1(b), the electric field vector of circular polarization appears to be rotating with circular motion about the direction of propagation, making one full turn for each RF cycle, and this rotation may be right hand or left hand [16].

The importance of polarization in RFID is simple to grasp. Most common tag antennas are long and thin and behave rather like a dipole (tags referred to in the rest of this paper are all dipole tags). If the electric field is directed along the tag orientation, it can act to push electrons back and forth from one end of the tag antenna to the other, inducing a voltage that is used to power the integrated circuit (IC) and allow the tag to reply. If the electric field is directed perpendicular to the wire axis, it merely moves electrons back and forth across the diameter of the wire, producing negligible current, no detectable voltage at the IC, and thus no power [14][15]. As a consequence, for linearly polarized reader antennas in Fig. 1(a), the best orientation of a tag located in point \( O \) is the same as the linearly polarized orientation (orange line in the blue plane). However, for circularly polarized reader antennas in Fig. 1(b), a dipole tag situated in point \( O \) can rotate at any angle within the blue plane perpendicular to the direction of propagation to obtain the maximum gain.

B. Friis Equation

The extended Friis equation provides a mathematical description of the power received by RFID tag from the reader antenna, which is shown below [2][3].

\[
P_R = \frac{P_T G_T(\theta_T, \phi_T)G_R(\theta_R, \phi_R)\lambda^2}{(4\pi r)^2} (1-|\Gamma_T|^2)(1-|\Gamma_R|^2)|\hat{P}_T \cdot \hat{P}_R|^2
\]

where, \( P_R \) is received power, \( P_T \) is transmit power, \( G_T(\theta_T, \phi_T) \) and \( G_R(\theta_R, \phi_R) \) denotes angular dependent receiver gain and angular dependent transmitter gain respectively, \( \Gamma_T \) indicates transmitter reflection coefficient, \( \Gamma_R \) indicates receiver reflection coefficient. \( \hat{P}_T \) is the reader polarization vector, \( \hat{P}_R \) is the tag polarization vector and \( |\hat{P}_T \cdot \hat{P}_R|^2 \) is the polarization loss factor (PLF). \( \lambda \) denotes the wavelength and \( r \) denotes the distance between the transmitter and receiver.

The value calculated by Friis equation is a theoretical value that can only be obtained in an anechoic chamber or free space, which is not suitable for the actual application due to various complex environment, but the Friis equation indicates the related factors that impact the received power. Among these factors, different tag orientations which are random and uncontrollable may cause huge changes of tags’ received power even other settings (the positions of reader antennas, the distance between a tag and an antenna and so on) are unchanged. Therefore, it’s meaningful for us to discuss the deployment of multiple RFID reader antennas from the perspective of the tag orientation.
IV. PROBLEM FORMULATION

**Definition 1 (antenna axis):** The antenna axis is defined as the polarized orientation for a linearly polarized antenna, while it is the direction perpendicular to the circularly polarized plane for a circularly polarized antenna.

The tag orientation significantly affects the read performance both in theory and practice. On the one hand, Fig. 2 presents that the read rate changes with \( \alpha \) (the included angle between a tag and the antenna axis under different polarized environment). Fig. 2(a) shows our real experiment scene, the reader’s (Alien\textsuperscript{®} ALR-9900+ [17]) transmit power is 2Watt, the tag (Alien\textsuperscript{®} ALN-9640 [5]) is placed 2m away from a fixed linearly polarized antenna with 7dBi gain and a fixed circularly polarized antenna with 6dBi gain respectively. Then, we rotate the tag orientation (shown as the top view in Fig. 2(b)) to measure the read rate under different Radio Frequency Attenuation (RFA). The experiment results are shown in Fig. 2(c) and 2(d). For the linearly polarized antenna in Fig. 2(c), we find that the read rate descends with the increase of \( \alpha \). Specifically, there exists a critical angle which causes the read rate to fall fast (for example, the critical angle is about 50\(^\circ\) when \( \text{RFA=4dB} \)). However, it’s contrary to circularly polarized antenna in practice. On the other hand, in accordance with Friis equation mentioned before, the tag orientation may greatly affect its received power even though other factors remain the same. Based on the above experiments and theory analysis, we consider that the tag orientation plays an important role in read performance. Consequently, it’s our major task to alleviate and even eliminate the negative effect caused by the tag orientation with multiple antennas in this paper. We assume that the tags are located in a small region, and then we discuss the optimized deployment of reader antennas from the perspective of tag orientations to increase the read rate based on the measured angle threshold (in general, it’s the critical angle like in Fig. 2(c) and 2(d)). We treat the small region as one point \( O \) in three-dimensional space and the tag whose orientation changes randomly is located in point \( O \). Though any points in three-dimensional space can be candidate positions for multiple reader antennas, the included angle between the tag and antenna axis is not relevant to the distance. Therefore, for simplicity, candidate positions are taken from the surface of a sphere whose center is the point \( O \) and once one position for an antenna is selected, we place the antenna over against the point \( O \) (like in Fig. 2(a)).

Now, our problem is how to deploy a minimum of antennas to ensure that there is at least one antenna which can read a tag with perfect read rate whatever its orientation. More specifically, suppose \( \alpha \) to be the included angle between the tag and antenna axis. As we can see from Fig. 2, for the linearly polarized antenna, the smaller \( \alpha \) is, the better. However, it’s contrary to the circularly polarized antenna. Therefore, we’d like to find an optimized deployment scheme with a minimum of reader antennas to make sure that there is at least one included angle between the tag orientation and one linearly/circularly polarized antenna’s antenna axis is less/greater than an angle threshold. Formulatively, that is:

**Given:** an angle threshold \( \psi (\psi \leq \pi/2) \)

**Find:** \( P_i (i = 1, 2, \ldots, N) \) which subjects to the followings:

for linearly polarized antennas:

\[
\max_{d \in D} \{ \min(\alpha_{d1}, \alpha_{d2}, \ldots, \alpha_{dN}) \} \leq \psi
\]

for circularly polarized antennas:

\[
\min_{d \in D} \{ \max(\alpha_{d1}, \alpha_{d2}, \ldots, \alpha_{dN}) \} \geq \psi
\]

**Objective:** minimize \( N \)

where, \( N \) is the number of reader antennas, \( d \) is the current tag orientation, \( D \) denotes the set of all orientations for the tag, \( P_i \) denotes \( i^{th} \) antenna’s position and \( \alpha_{di} \) indicates the included angle between the tag orientation \( d \) and the \( i^{th} \) antenna axis.

**Remark 1:** The pattern of co-working of multiple readers is also worth emphasizing: Before reading, all tags’ inventoried flags (see Gen-2 protocol [18]) are set to \( A \). Then the readers read tags sequentially till the last one and it’s the next reader’s turn when no more tags can be read by the previous reader. Once the tag is read by any reader during the process mentioned above, its inventoried flag is set to \( B \), which means one tag can only be read by one reader. The query mode above can avoid reader collision [19][20] and redundancy read problem, and the only additional overhead lies in the switching time among different readers compared to the read efficiency of one reader. Fortunately, it is a drop in the bucket for the whole reading access time.
V. PROBLEM SOLUTION

In this section, we provide two kinds of approaches to solve our problem, one is an approximate analytic solution based on two sphere coverage models and the other is enumeration scheme using leaping and layering search strategies based on SQT algorithm.

A. Sphere Coverage Model

It’s hard to get an analytic solution directly from the above problem formulation. This subsection converts the problem into the sphere coverage model and respectively estimates the least number of antennas under linearly & circularly polarized antenna environment according to the measured angle threshold $\psi$.

1) Linearly Polarized Antenna Model: Once a linearly polarized antenna is fixed, the tag orientation can change in the range where $\alpha$ (the included angle between the tag orientation and the antenna axis) is less than $\psi$. As shown in Fig. 3(a), any orientation changes within the range of the circular cone can guarantee this constraint ($\alpha$ is less than $\psi$). Consider from the perspective of antennas, that is, one linearly polarized antenna can produce two circular cones within which the tag direction can alter randomly. Go a step further, it means that one linearly polarized antenna mapped two symmetrical spherical caps (the shadow in Fig. 3(a)) which are the portions of the sphere cut off by bases of the two cones. In order to meet the constraint in Section IV, our task turns to completely cover the sphere using spherical caps mapped by a minimum of linearly polarized antennas.

Definition 2 (cap angle): Given a sphere whose radius is $R$ and a spherical cap whose base radius is $r$, the cap angle is defined as the angle which is equal to $\arccos(r/R)$. For example, the cap angle of the shaded spherical cap is $\psi$ in Fig. 3(a).

We formulate this model as follows. Given a spherical cap whose cap angle is $\varphi$, how to completely cover the sphere with a minimum of this kind of caps. It’s a classic and incompletely solved covering problem which has been studied for decades. We follow BESTE’s [21] work and do some improvement according to our scenario. BESTE [21] established the relationship between the cap angle and the number of spherical caps when he designed the satellite constellations for optimal continuous coverage. For single coverage, he placed the caps with polar orbits, as shown in Fig. 3(b). Then we can get,

$$n(\varphi + \Delta) = \pi$$

where $n$ is the number of orbital planes, $\varphi$ is the cap angle, $\Delta = \arccos[\cos \varphi/(\cos \pi/m)]$, $m$ is the number of caps per orbital plane. It’s worth mentioning that our antennas are all static, so equation (1) is different from BESTE’s. Meanwhile, one linearly polarized antenna maps two symmetrical spherical caps in our scene, so $m$ is even. In fact, it’s a semi-sphere coverage problem, which means $N = nm/2$. Then we can calculate the area of spherical cap whose cap angle is $\varphi$,

$$\Omega = 2\pi R^2(1 - \cos \varphi)$$

Formula (3) describes the relationship between $\varphi$ and $N$ (the number of antennas). When given an angle threshold $\varphi$, we can approximately estimate the least of number of linearly polarized antennas by replacing $\varphi$ with $\psi$.

2) Circularly Polarized Antenna Model:

Definition 3 (spherical belt): Spherical belt is the remainder portion of a sphere cut off two symmetrical spherical caps, as shown by the shaded portion in Fig. 4(a).

Definition 4 (belt angle): Given a spherical belt generated by cutting off two symmetrical spherical caps whose cap angle are both $\varphi$, then we say that the belt angle of this spherical belt is $\varphi$.

Contrary to the linearly polarized antenna, once a circularly polarized antenna is fixed, the tag orientation is limited in the range where $\alpha$ is greater than $\psi$. As shown in Fig. 4(a), any orientation within the spherical belt whose belt angle is $\psi$ can meet the constraint ($\alpha$ is greater than $\psi$). That is, a circularly polarized antenna can map this spherical belt. Similar to linearly polarized antenna model, we formulate this model as follows. Given a spherical belt whose belt angle is $\varphi$, how to minimize $N$ (the number of this kind of belts) to cover the sphere completely. We propose a heuristic algorithm to solve this model and describe it based on the Fig. 4(b) which is the front view of a sphere, see Algorithm 1. Then, we establish the relationship between $N$ and the belt angle $\varphi$. Based on Algorithm 1, we can obtain the included angle ($\beta$)

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
$n$ & $m$ & $\alpha$ & $mn\Omega/4\pi R^2$ \\
\hline
2 & 3 & 34.7 & 1.69 \\
3 & 4 & 46.5 & 1.87 \\
3 & 6 & 37.1 & 1.82 \\
4 & 6 & 32.3 & 1.86 \\
4 & 8 & 28.0 & 1.82 \\
5 & 8 & 24.9 & 1.86 \\
5 & 10 & 22.4 & 1.88 \\
6 & 10 & 20.3 & 1.86 \\
6 & 12 & 18.7 & 1.90 \\
\hline
\end{tabular}
\caption{Requirements for full coverage}
\end{table}
Algorithm 1: Full coverage with spherical belts

**Input**: the angle threshold \( \varphi \)  
**Output**: the number of antennas \( N \) & positions of antennas  

1. Place the 1\(^{st} \) antenna randomly, such as the \( \text{Ant1} \) in Fig. 4(b).  
2. \( A_iB_i \) and \( C_iD_i \) is the boundary of the spherical belt mapped by the \( i \)-th circularly polarized antenna. \( E_iF_i \) is through point \( O \) and parallel to \( A_iB_i \).  
3. \( i = 1 \). Draw a circle \( \Theta \) whose center is \( O \) and it is tangent with \( A_iB_i \) and \( C_iD_i \).  
4. If completely cover the sphere, \( N = i \) & stop.  
5. \( i = i + 1, A_i = C_{i-1}, D_i = B_{i-1} \)  
6. Draw the other tangent line of \( \Theta \) crossing point \( A_i \), and the tangent line intersects with the sphere on point \( B_i \).  
7. Draw the other tangent line of \( \Theta \) crossing point \( D_i \), and the tangent line intersects with the sphere on point \( C_i \).  
8. Place the \( i \)-th antenna on the intersection of vertical of \( E_iF_i \) and the sphere, such as the \( \text{Ant2} \) in Fig. 4(b).  

in Fig. 4(b)) between \( E_iF_i \) and \( E_{i+1}F_{i+1} \).

\[
\beta = \pi - 2\varphi \tag{4}
\]

In order to meet the full coverage, we need cover \( \pi \) with \( \beta \), that is,

\[
N \times \beta = \pi \tag{5}
\]

Based on formula (4) and (5), we can get,

\[
N = \pi / (\pi - 2\varphi) \tag{6}
\]

According to formula (6), once given an angle threshold \( \psi \), we can estimate the least number of circularly polarized antennas by replacing \( \varphi \) with \( \psi \).

**B. Enumeration Scheme**

Our problem was converted into two sphere coverage models in the above subsection, while an enumeration scheme will be presented in this subsection. On the one hand, it’s an accurate approach to deploy antennas when \( N \) (the number of antennas) is small. On the other hand, we can compare the performance of different solving methods we proposed. Although the enumeration scheme is an intuitive way, there are two important issues to be considered: 1) how to discretize candidate positions for reader antennas and tag orientations, 2) how to reduce the computational complexity.

Algorithm 2: SQT based on icosahedron

**Input**: The \( i\)-th subdivision \(<\text{vertices}_{i}, \text{faces}_{i}>\)  
**Output**: The \( i+1\)-th subdivision \(<\text{vertices}_{i+1}, \text{faces}_{i+1}>\)  

1: \( \text{vertices}_{i+1} \leftarrow \text{vertices}_{i}, \text{faces}_{i+1} \leftarrow \emptyset \)  
2: for each face \( F \) composed by triple \((N_1, N_2, N_3)\in\text{faces}_{i} \) do  
3:  for \( j = 1 \rightarrow 3 \) do  
4:  get the midpoint \( M \) of the \( j\)-th edge in \( F \)  
5:  get point \( V \) out to the sphere based on \( M \)  
6:  \( \text{vertices}_{i+1} \leftarrow \text{vertices}_{i+1} \cup V \)  
7:  \( V_j \leftarrow \) the array index of \( V \) in \( \text{vertices}_{i+1} \)  
8:  end for  
9:  add 4 faces composed by \((N_1, N_2, N_3, V_1, V_2, V_3)\) in \( \text{vertices}_{i+1} \) into \( \text{faces}_{i+1} \)  
10: end for
2) **Computational Complexity:** Suppose the candidate positions for reader antennas and tag orientations have been uniformly discretized into point set \( L \) and direction set \( D \) according to SQT model based on icosahedron. Now, we’d like to find the optimized deployment when \( N \) (the number of antennas) is given. As a result, for different \( N \), we can get best corresponding angle thresholds under the optimized deployment. Then, we compare the measured \( \psi \) with the best angle thresholds and choose the minimum \( N \). The enumeration scheme is presented as follows. For a determined \( N \), we have \( C^{N}_{\left| L \right|} \) kind of choices to place \( N \) antennas. Under one fixed deployment \( dp \) of \( C^{N}_{\left| L \right|} \) choices, we traverse every direction \( d \) in \( D \) to check whether there is at least one included angle between every \( d \) and one antenna axis is better than the current best threshold \( \varphi \). If yes, we update the \( \varphi \); otherwise, we pass this deployment to check the remainder choices. More formally,

**Given:** \( N \) (the number of reader antennas)

**Find:** \( P_i \) \((i = 1, 2, ..., N)\)

**Objective:**

for the deployment of linearly polarized antennas:

\[
\min_{dp \in C^{N}_{\left| L \right|}} \left\{ \max \{ \min (\alpha_{d1}, \alpha_{d2}, ..., \alpha_{dN}) \} \right\}
\]

for the deployment of circularly polarized antennas:

\[
\max_{dp \in C^{N}_{\left| L \right|}} \left\{ \min \{ \max (\alpha_{d1}, \alpha_{d2}, ..., \alpha_{dN}) \} \right\}
\]

In general, there are at most \( C^{N}_{\left| L \right|} \times |D| \) enumerations for a given \( N \). Theoretically, the optimal deployment can always be found, however, the computational complexity increases substantially with the increase in search space, \( N \), \( |L| \) and \( |D| \) are all critical factors determining computational effort. Among these three factors, \( N \) indirectly depends on \( \psi \), \( |L| \) is subject to the practical deployment space and the physical size of the antennas, so it is not very large, while \( D \) can be selected freely. In this case, we propose leap search and layering search strategies to improve the enumeration.

a) **Leaping Search:** Intuitively, the vectors (the tag orientation or antenna axis) comprised of points in adjacent region and point \( O \) (the center of a sphere) are similar. Therefore, we’d like to traverse leapingly when searching the solution space, that is, after choosing or checking one point, we traverse another point which is far away from the previous point. As a consequence, for antennas, it’s possible to find a better deployment more quickly, and for tag’s orientation, leap search may find a direction faster, which makes the included angles between all antenna axes and itself are all worse than current best threshold \( \varphi \), then there is no need to check the remainder orientations. The SQT based on icosahedron does provide the way we need. For the \( i^{th} \) subdivision space, the top \( n \) points are all points in \( i-1^{st} \) subdivision space and so on until the \( 0^{th} \) subdivision space. That gives us a natural leap searching space, which is one of major causes for us to choose SQT to discretize a sphere.

b) **Layering Search:** Although \( L \) (candidate positions for antennas) limited by practical scene is not very big set, while \( C^{N}_{\left| L \right|} \) increases quickly with the increase of \( N \). In this case, we have to decrease \( L \) to reduce computational effort, which may lead to losing much solution accuracy. Here we propose an layering search strategy to alleviate this problem. The concrete method is as follows. If the search space produced by \( i^{th} \) subdivision is too big for computing, we obtain an optimum deployment from \( i-1^{th} \) subdivision space, then the neighbor points of these best deployment points found in \( i^{th} \) subdivision space are used for launching a new search to get better deployment. Layering search aim to reduce execution time without losing too much solution accuracy when the search space is too big.

VI. PERFORMANCE EVALUATION

Two estimation functions based on sphere coverage models and an improved enumeration scheme have been presented in the above section. In Fig. 6, we analyse the performance of leaping and layering search strategies used in enumeration and compare the results resolved by different solution approaches.

A. The Gain of Leaping Search

Fig. 6(a) and 6(b) contrast the efficiency between leaping search and gradual search for finding the best deployment under three linearly (circularly) polarized antennas. In this simulation, the antenna positions are taken from the second subdivision space in Algorithm 2 (162 points, which is enough for antenna candidate positions in practice). Then, we compare the execution time of gradual search (Step), leap search for antennas (LeapAnt), leap search for tag directions (LeapDir) and leap searching for both antennas and tag directions (LeapBoth) under different candidate tag orientations. Due to the huge difference of execution efficiency, we take natural logarithm to the time \( t (ln(t)) \) to make the curves show clearly. As shown in Fig. 6(a) and 6(b), we find that LeapBoth is the most efficient, LeapAnt and LeapDir are more efficient than gradual search. For linearly polarized antennas in Fig. 6(a), LeapDir is faster than Step more than 10 times and LeapBoth is even faster than Step more than 100 times when \( i \geq 5 \). For circularly polarized antennas in Fig. 6(b), LeapAnt is slightly more efficient than Step, LeapDir is faster than Step more than 10 times and LeapBoth is faster than Step more than 40 times when \( i \geq 5 \). As a consequence, the gain of the leap search strategy in enumeration is great, which can tremendously reduce the running time.

B. The Effect of Layering Search

We evaluate the effect of layering search for the optimal placement under different polarized scenarios in Fig. 6(c) and 6(d), which select the fifth subdivision space based on SQT (10242 points, which is much greater than \( M=1916 \) in [6][7]) as the set of tag orientations. We search the optimal deployment and get the best corresponding angle threshold \( \varphi \) for linearly (circularly) polarized antennas from the first subdivision space (1st Subdivision) and second subdivision...
space (2nd Subdivision). Then, based on the points of optimized placement got by traversing first subdivision space, we find their neighbor points in second subdivision space, after that, we launch a new round of search according to these points and their neighbor points to get the best placement (LayerSearch). As can be seen from Fig. 6(c), the best angle threshold \( \varphi \) of 2nd Subdivision is better than 1st Subdivision’s especially when there are 3 or 5 linearly polarized antennas, but the execution time of 2nd Subdivision is more than 1st Subdivision’s about \( 4^N \) times (\( N \) is the number of antennas). However, the \( \varphi \) of LayerSearch is close to 2nd Subdivision’s and the running time of LayerSearch is less than double 1st Subdivision’s. Similarly, LayerSearch for circularly polarized antennas in Fig. 6(d) also can improve the deployment although not as well as the former one. Therefore, considering that if the computational complexity of searching from \( i^{th} \) subdivision space is too high, we can adopt the layering search strategy based on \( i-1^{th} \) subdivision space to reduce execution time substantially without losing too much solution accuracy.

C. Result Comparison

In Fig. 6(e) and 6(f), we compare the best angle threshold \( \varphi \) solved by two estimation functions based on sphere coverage models and the enumeration scheme under different number of antennas. During the enumeration, the set of tag orientations are fixed to fifth subdivision space, and the candidate antenna positions are taken from second subdivision space when \( N \leq 6 \), however, due to the high computational complexity when \( N > 6 \), we adopt the layering search strategy based on first subdivision space. Fig. 6(e) shows the result of estimation function (formula (3)) based on spherical caps model (SphericalCap) and enumeration scheme (Enumeration) for linearly polarized antennas. It’s obvious that the solution of Enumeration is better than SphericalCap’s, which attributes to much redundant coverage near the polar region caused by placing the caps with polar orbits in spherical cap model. Meanwhile, we find that the two curves are close to each other when \( N \geq 10 \). Two reasons to be considered, one is the curves originally tend to be gentle with the increase of the \( N \), the other is that our search space for antenna candidate positions is not enough for providing a good deployment with the increase of \( N \). Therefore, for linearly polarized antennas, we’d better use enumeration scheme when \( \varphi \geq 30^\circ \), on the contrary, we evaluate the result with spherical cap model. In Fig. 6(f), we show the solution of estimation function (formula (6)) based on spherical belt model (SphericalBelt) and enumeration scheme (Enumeration). As can be seen from the figure, the solution of Enumeration is almost the same as SphericalBelt’s when \( N \leq 6 \), which indicates Algorithm 1 based on the spherical belt model is an excellent deployment scheme for circularly polarized antennas. In a word, SphericalBelt is better than Enumeration according to Fig. 6(f).
VII. CONCLUSION

In this paper, we have discussed how to deploy multiple reader antennas to alleviate the negative effect caused by uncontrollable tag orientations in item-level applications. For this antenna placement problem under different polarized environment, we present an improved enumeration scheme and two estimation functions based on sphere coverage models, which play a guiding role in deployment of reader antennas in practice. According to the simulation, we conclude that the enumeration scheme is considered first when the number of linearly polarized antennas is small, while for circularly polarized antennas, the spherical belt model is superior to enumeration.

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