On the Design and Deployment of RFID Assisted Navigation Systems for VANETs

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Abstract—In this paper, we propose a systematic approach to designing and deploying a RFID Assisted Navigation System (RFID-ANS) for VANETs. RFID-ANS consists of passive tags deployed on roads to provide navigation information while the RFID readers attached to the center of the vehicle bumper query the tag when passing by to obtain the data for navigation guidance. We analyze the design criteria of RFID-ANS and present the design of the RFID reader in detail to support vehicles at high speeds. We also jointly consider the scheduling of the read attempts and the deployment of RFID tags based on the navigation requirements to support seamless navigations. The estimation of the vehicle position and its accuracy are also investigated.

Index Terms—RFID assisted navigation systems; Vehicle Networks; GPS; System design.

1 Introduction

Radio Frequency Identification (RFID) has attracted considerable attentions in recent years for its broad applications in ubiquitous computing. In this paper, we propose a RFID Assisted Navigation System (RFID-ANS) for VANETs. RFID-ANS consists of RFID readers installed on vehicles and passive RFID tags deployed on roads. As the maintenance for a passive tag is easy and its cost is less than a dollar, it is feasible to deploy a large number of passive tags for a relatively low cost over a broad area that is full of roadways.

Intuitively, RFID-ANS complements to the current GPS navigation system when GPS signals are not available (such as in tunnels) or if the GPS position is ambiguous to a vehicle (such as at cloverleaf intersections). But in practice, GPS does not provide sufficient information for navigation due to its low positioning accuracy (5 to 7 meters). Moreover, even combined with map-matching technologies, GPS still can not achieve lane level positioning and can not provide information regarding the traffic direction in the current lane. Nevertheless, these information are necessary to prevent vehicles from entering a wrong way when roads are under construction or lanes are temporarily borrowed by the traffic along a different direction. Our RFID-ANS is designed to address such problems. Its convenience and benefits give incentives for users to install RFID readers on their vehicles. Additionally, RFID-ANS can be configured to provide electrical traffic signs. It might be essential to future autonomous vehicle systems as this system can provide more precise real time road information for traffic scheduling. Note that the RFID reader attached at a vehicle is independent of the vehicle model, and it can be easily upgraded to guide driving. Therefore RFID-ANS could play an important role in the future complex driving environment that contains autonomous, semi-autonomous, and man-controlled vehicles.

RFID-ANS is a ground navigation system that is designed for lane level navigation. The issues relevant to a practical RFID-ANS in a complex vehicular environment have never been addressed before. To our knowledge, this is the first work that provides a systematic approach to designing a RFID-ANS. Our multi-faceted contributions are stated as follows.

- We provide an analysis on the design criteria of RFID-ANS. These criteria serve as guidelines for the design of the RFID readers and the deployment of the RFID tags. We present the relationships among these design criteria, and investigate how they should be used cooperatively to achieve the objectives of the navigation system. Based on these criteria, we identify the parameters that are important for the RFID-ANS design.
- We present the design of the RFID readers for RFID-ANS in detail. The ranges of the critical parameters for the RFID readers are derived according to the requirements of the navigation system and the tag deployment.

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- We jointly consider the design of the RFID reader's read interval and the deployment of the RFID tags, such that the cost and energy consumption can be optimized as long as the requirements of the navigation system are satisfied. The proposed methods for read attempt scheduling and tag deployment are robust and adaptable to dynamic road environments.
- We propose methods to estimate the vehicle position. The accuracy of the estimated position and the performance of the designed RFID-ANS are analyzed.

The rest of the paper is organized as follows. Section 2 summarizes the most related work to our research. In Section 3, our RFID-ANS model is presented. The design criteria and their relationships, and the set of important parameters for RFID-ANS design and deployment, are introduced in this section as well. We detail the design of the RFID reader in Section 4. The deployment strategy of the tags is proposed in Section 5. In Section 6, we introduce two vehicle position estimation methods. Section 7 illustrates an example RFID-ANS with practical settings. Finally, this paper is concluded in Section 9.

2 Related Work

A RFID system is composed of RFID tags and RFID readers. A RFID tag stores data, and a RFID reader accesses the tag to collect the data through wireless communications. There exist two types of RFID tags: *active tags*, which contain power modules to support wireless communications, and *passive tags*, which power their transmissions through the energy absorbed from the radio waves of the RFID readers. Compared to active RFID tags, passive RFID tags are easier to maintain as they do not need power, and their cost can be as low as several cents. Therefore, passive RFID tags are more appropriate for applications that require a large number of tags.

Traditionally RFID tags were designed for commercial applications to replace the bar codes for asset counting [1], [2] and identification [3]. One important challenge in such applications is how to handle the *read collision problem* that occurs when one or more RFID readers query multiple RFID tags roughly simultaneously in a small area. As a result, most existing research focuses on anti-collision protocol design to schedule the reader's read requests and the tag's responses [4]–[6]. In RFID-ANS, read collision is not possible as our design guarantees the one-to-one coupling of a RFID reader and a tag in a restricted area.

RFID systems have been deployed for VANETs, in which RFID tags are installed on vehicles while RFID readers are deployed on stationary infrastructures. For example, in a typical Electronic Toll Collection (ETC) system [7], automatic toll RFID readers are installed at the gate. A RFID tag (attached to the E-ZPass on a vehicle) is read by the reader when a vehicle passes by the gateway. The toll system identifies the vehicle through the data obtained from the RFID tag, and automatically charges to the vehicle's or the driver's account. A similar system is established for parking fee collection in [8]. Compared to these systems, RFID-ANS contains stationary tags on roads while readers move with vehicles at high speeds.

The most related work to RFID-ANS are reported in [9]–[11]. Chon *et al.* [9] proposes the idea of using stationary RFID tags deployed on roads to localize vehicles when passing by. The feasibility of utilizing RFID tags for navigation when vehicles move at high speeds is investigated through an experiment in which a RFID reader reads the data in a tag when the tag is dropped down to the ground. Lee *et al.* [10] studies the relationship between the tag read latency and the vehicle's speed, and evaluates their results on a test road. These two works demonstrate the feasibility and practicality of applying commercial RFID tags and readers in the vehicular environment. But none of them considers critical issues such as tag deployment and read scheduling, which are important to the design of a practical RFID-ANS as they mainly focus on the concept and feasibility study. In the Road Beacon System proposed by [11], RFID tags serving as traffic signs are deployed in the pavement and vehicles get the road information through reading the tags. The technical details of this work are unavailable to our best knowledge.

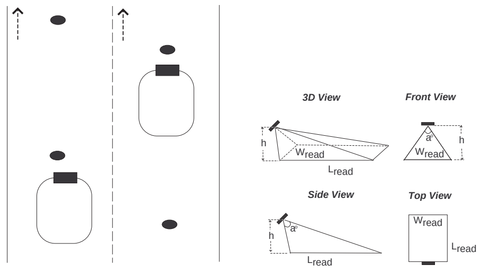
3 RFID Assisted Navigation System Model

In our RFID-ANS model as shown in Fig. 1(a), passive RFID tags are deployed at the centers of the lanes and a RFID reader's antenna is installed at the center of a vehicle's front bumper, since this position exhibits the minimum error rate [10].

We assume that a RFID tag can provide its physical position, the lane's current traffic direction, and the road's name, which can help the vehicle localize itself at a cloverleaf intersection or in a tunnel. A moving vehicle can obtain its current position through reading the tags when passing by. According to [10], a typical RFID reader's read area is a function of its antenna's hight, read angle, and pitch angle. A RFID reader's read area, in which the reader can communicate with a tag to obtain data, can be depicted as shown in Fig. 1(b), where h, α, L_{read} and W_{read}, are the antenna's hight, its read angle, the read area's length and width, respectively.

The length and width of the read area are calculated by Eq. (1) and Eq. (2), respectively.

$$L_{read} = h \times \left(\frac{1}{\tan(\frac{\pi-\alpha}{2}+\theta)} + \frac{1}{\tan(\frac{\pi-\alpha}{2}-\theta)}\right) \quad (1)$$



(a) (b)

Fig. 1. (a) The RFID-ANS model, where the black ellipses, the white rounded rectangles, the black rectangles, and the dotted arrows represent RFID tags, vehicles, RFID readers' antennas, and the traffic directions, respectively. (b) The RFID reader's read area.

where θ is the antenna's pitch angle, $-\frac{\pi-\alpha}{2} < \theta < \frac{\pi-\alpha}{2}$.

$$W_{read} = 2 \times h \times \tan(\frac{\alpha}{2}) \quad (2)$$

The design criteria of our RFID-ANS are explained as follows:

1) Each RFID tag should be covered by no more than one RFID reader's read area at any instant of time.
2) Each RFID reader's read area should cover no more than one tag at any instant of time.
3) If a vehicle is in a lane, the vehicle should be able to read tags that are deployed in the lane.
4) If a vehicle can read a tag, at least half of its body should be in the lane where the tag is deployed.
5) If less than half of a vehicle is in a lane, the vehicle should not be able to read any tag in the lane.
6) RFID tags should be deployed according to the road navigation requirements. In our study, navigation requirements are described by where and when a vehicle should successfully read tags.
7) A vehicle should schedule its read attempts such that the road navigation requirements can be satisfied and energy can be conserved.

Unlike traditional RFID applications, in which a RFID reader might encounter multiple tags at the same time, we require a one-to-one coupling of readers and tags at any instant of time in a RFID-ANS, as stated by the first two design criteria. In VANETs, any two moving vehicles can not stay at the same position simultaneously. Thus, any two vehicles should not contact the same RFID tag at the same time. This means that a RFID tag should only be read by at most one vehicle at any instant of time. On the other hand, a vehicle can not appear at two different positions at the same time. Therefore, a vehicle's read area should cover at most one tag at any instant of time. In RFID-ANS, this one-to-one coupling guarantees that transmission collisions can be avoided and the tag's random access time, which is employed to avoid collisions in traditional RFID applications, can be eliminated. As a result, the full theoretical RFID reader's read area, as calculated in [10], can be utilized by a vehicle to read tags. According to the experimental results in [10], a RFID reader's effective read length is about 60% of its theoretical value in VANETs due to the long random access time of its tags. As a result, the maximal vehicle's velocity for reliably reading a RFID tag is limited to 60mph (100kph) [9]. In our design, the first two criteria theoretically eliminate the necessity of the RFID tag's random access time. Therefore the effective read length can be maximized, and the read success rate can be improved for high speed VANETs.

L_{read}	The RFID reader's read length
W_{read}	The RFID reader's read width
W_{lane}	The lane width
L_{Vmin}	The minimum vehicle length
W_{Vmin}	The minimum vehicle width
$\overline{V}$	The road speed limit
D_{tag}	The distance between two consecutive RFID tags
S_{data}	The RFID tag's data size
R_{tag}	The RFID tag's data transmission rate

TABLE 1
The parameters for a RFID-ANS.

The $3rd$, $4th$, and $5th$ design criteria regulate the RFID reader's read width to achieve lane level navigation. These three criteria guarantee that a tag can be read by vehicles in the same lane, but not be read by vehicles at different lanes.

To satisfy the navigation requirements, the $6th$ design criterion is proposed to guide the deployment of RFID tags. To facilitate the cooperation among deployed tags, the $7th$ design criterion is proposed, which requires a RFID reader to smartly schedule its read attempts such that it can successfully read tags to support its navigation, and the energy can be saved from avoiding unnecessary read attempts.

In summary, the $1st$, $2nd$, and $3rd$ criteria are proposed for the RFID read length design; the first five criteria join together to guide the design of the RFID read width; the $6th$ criterion is for RFID tag deployment; and the $1st$, $2nd$, and $7th$ criteria are needed to facilitate the cooperation between tag deployment and reader design.

The most significant parameters for a RFID-ANS are defined in Table 1. We analyze the relationship among these parameters and discuss the relevant issues in the following two sections.

4 RFID Reader Design

In this section, we analyze the settings of the critical parameters for RFID readers to meet the RFID-ANS design criteria.

4.1 RFID reader's read length

In RFID-ANS, the reader's read length should be carefully designed in order to successfully read the tags' information, as indicated by the first 3 design criteria.

The *necessary contact time* T_{min}, which defines the shortest time required to successfully obtain the data from a tag, is determined by the data size and data transmission rate as shown in Eq. (3).

$$T_{min} = \frac{S_{data}}{R_{tag}} \quad (3)$$

Let $\overline{V}$ be the upper bound of the vehicle speed. Then the theoretical minimum read length L^T_{min} to completely read the tag's data is defined by Eq. (4).

$$L^T_{min} = \overline{V} \times T_{min} \quad (4)$$

As mentioned in Section 3 of the paper, current RFID readers' effective read length is only about 60% of its theoretical value. Let δ be the read length loss ratio. Then the minimum read length L_{min} should be calculated by Eq. (5).

$$L_{min} = \frac{L^T_{min}}{\delta} \quad (5)$$

Note that the $2nd$ criterion indicates that the RFID reader's read length should be less than the distance between two consecutive tags such that the reader can communicate with at most one tag at any instant. Therefore D_{tag} is an upper bound for the reader's read length. According to the $1st$ criterion, two consecutive vehicles should not reach the same tag at the same time. Here we consider a conservative environment where a traffic jam could occur such that the distance between two vehicles can become very small. Then, to guarantee that there is no overlapping between the two vehicles' read areas, the read length should be less than the minimum vehicle length. Therefore, the maximum read length L_{max} can be expressed by Eq. (6).

$$L_{max} = \min\{D_{tag}, L_{Vmin}\} \quad (6)$$

According to Eqs. (3), (4), (5), and (6), we obtain Eq. (7) to bound the RFID reader's read length.

$$\frac{\overline{V} \times S_{data}}{R_{tag} \times \delta} < L_{read} < \min\{D_{tag}, L_{Vmin}\} \quad (7)$$

4.2 RFID reader's read width

As mentioned in Section 3, the RFID reader's read width should be designed to satisfy the first five design criteria. According to the $3rd$ criterion, the vehicle's read area should cover the tags that are deployed in the lane where the vehicle presents, as shown in Fig. 2(a). When the tag is deployed in the center of the lane, we have

$$W_{read} > W_{lane} - W_{Vmin} \quad (8)$$

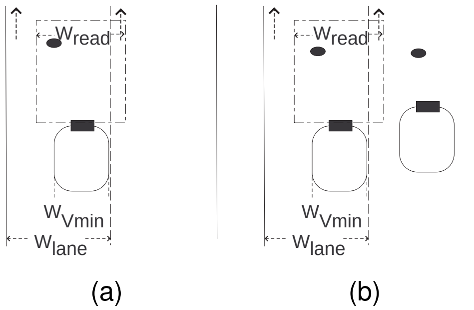


Fig. 2. (a) A vehicle should be able to read the RFID tag in the lane it presents. (b) A vehicle should not be able to read the RFID tags in other lanes.

According to the first two criteria and the lane level navigation requirement, a vehicle should not be able to read the tags deployed in other lanes where the vehicle is not present, as shown in Fig. 2(b). Then we have the following upper bound for the read width.

$$W_{read} < W_{lane} + W_{Vmin} \quad (9)$$

The first three design criteria define the vehicle's read capability when it stays in a lane. The $4th$ and $5th$ criteria regulate the read width when the vehicle is changing to a new lane. As shown in Fig. 3(a), the vehicle should not be able to read the tags in the left lane because most part of its body is in the right lane. As a result, we deduce Eq. (10).

$$W_{read} < W_{lane} \quad (10)$$

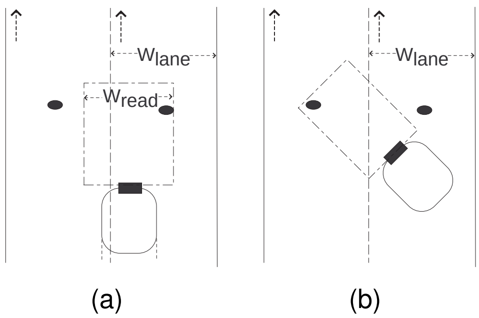


Fig. 3. (a) The vehicle should not be able to read the RFID tag that is deployed in the left lane. (b) The vehicle can read the RFID tag deployed in the lane that it is heading for.

Based on Eqs. (8), (9), and (10), we conclude with Eq. (11) to summarize the bounds of the RFID reader's read width.

$$W_{lane} - W_{Vmin} < W_{read} < W_{lane} \quad (11)$$

4.3 Considerations for lane change

The $4th$ and $5th$ design criteria can be satisfied by (11) when the vehicle changes its lane smoothly as shown in Fig. 3(a). Fig. 3(b) illustrates an example where the vehicle changes its lane sharply. When a vehicle changes its lane sharply, it could read the tag deployed in the target lane where less than half of its body is present. This phenomenon contradicts the $4th$ and $5th$ design criteria. However, as the target lane is the one that the vehicle is heading for and the vehicle will present shortly, we can tolerant such a reasonable exception in our RFID-ANS design. Then the problems that should be considered for the case of a sharp lane change include: $1)$ the vehicle should not be able to reach two tags simultaneously; $2)$ the vehicle should not be able to reach the tag deployed in the lane that it is leaving when most of its body has left the lane; and $3)$ a RFID tag should not be reached by more than one vehicle.

As all the RFID tags are deployed in the center of a lane, the distance between any two tags in different lanes should be larger than the lane width. Therefore, to address the first problem, we should guarantee that the diagonal of the read area is less than the lane width as shown in Eq. (12). To prevent the case where the read area covers two tags in the same lane, the distance between two consecutive tags should be designed according to Eq. (13).

$$W_{lane}^2 > W_{read}^2 + L_{read}^2 \tag{12}$$

$$D_{tag}^2 > W_{read}^2 + L_{read}^2 \tag{13}$$

Since $D_{tag} > L_{read}$, the bounds of the read length defined by Eq. (7) should be rewritten as Eq. (14), according to Eq. (13).

$$\frac{\overline{V} \times S_{data}}{R_{tag} \times \delta} < L_{read} < L_{Vmin} \tag{14}$$

To address the second problem, we consider the example shown in Fig. 4(a), where K is the vehicle's turning angle with $0 < K < \frac{\pi}{2}$. Theorem 4.1 guarantees that the second problem can be solved based on the RFID reader design.

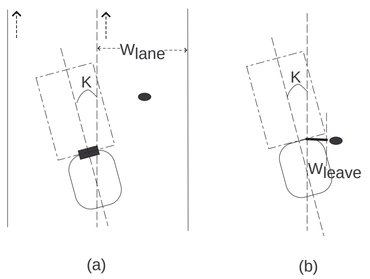


Fig. 4. The vehicle can not read a RFID tag deployed in the lane that most part of its body has left.

Theorem 4.1: The vehicle can not read a RFID tag deployed in the lane that the most part of its body has left.

Proof: We consider Fig. 4(b), where the bold solid line denotes the width of the RFID reader's partial read area that covers part of the lane that the vehicle is leaving. To support the theorem's claim, we need to prove that the width, denoted by W_{leave}, is less than half of the lane width as the tag is deployed in the center of the lane.

It is easy to verify that the vehicle's geometrical center must be in the left of the lane if most part of it has left the lane. Then, we can conclude that the RFID reader must be in the left of the lane, as it is installed at the center of the vehicle's front bumper. From Eq. (10), we obtain Eq. (15).

$$W_{leave} < \frac{W_{lane}}{2} \times \cos K - \frac{L_{Vmin}}{2} \times \sin K \tag{15}$$

Then we derive Eq. (16) to complete the proof.

$$W_{leave} < \frac{W_{lane}}{2} \tag{16}$$

□

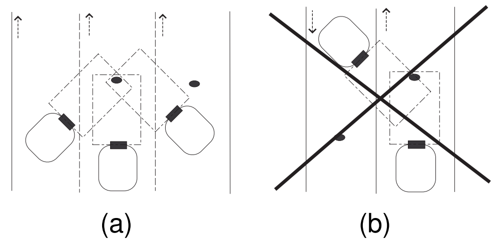


Fig. 5. (a) A RFID tag could be reached by more than one vehicle. (b) Two vehicles from different directions can not reach the same RFID tag.

Fig. 5(a) illustrates an example where a RFID tag might be reached by three vehicles in three different lanes. According to Eq. (14), the reader's read length should be less than the minimum vehicle length. Then the example in Fig. 5(a) is unusual as drivers usually won't cut into the lane when the open space is less than a vehicle's length for safety reasons. This scenario might happen when aggressive drivers change their lanes in heavy traffic jams where the average vehicle speed is almost zero. To address this problem, we simply require the reader to stop reading when the vehicle is fully stopped.

We have analyzed some example read collision problem. Fig. 5(b) shows that two vehicles from different directions must not reach the same RFID tag, as this is prohibited by both the law and the driver's consciousness.

Note that during a lane change, a vehicle might miss two tags when it makes an extreme sharp-turn. This read miss can be tolerable because extreme sharp-turns are abnormal and infrequent in reality. Moreover, one of the missed tags resides in the lane that the vehicle is leaving, and the vehicle will not miss the second tag in the lane that it is heading for.

4.4 Adaptive scheduling of the RFID reader's read attempts

In this section we propose approaches to adaptively scheduling a RFID reader's read attempts such that the vehicle can read the RFID tags with a high success rate. Assume that tags have been deployed based on the road navigation requirements. A straightforward and effective scheduling method is to keep sending read attempts. However, when tags are sparsely deployed, the drawbacks of this approach are obvious because of its low success rate and high energy waste resulted from unnecessary read attempts. Although the energy consumption of making read attempts is not comparable to that of the vehicle alternator, the accumulative power waste from failed readings of all vehicles could be a large value that should not be ignored. Moreover, in the scenario where multi vehicles are heading for the same lane or on a curved road, the probability of a read collision is large if all vehicles employ this straightforward method. Therefore, an ideal read scheduling method should be able to estimate the distance between two consecutive tags and be adaptable to different road segments where the distances between two tags might vary.

Generally speaking, read scheduling seeks to determine when RFID readers should send read attempts. According to Section 4.3, vehicles should not attempt to read tags when they are completely stopped. Moreover, they should reschedule their readings after they change lanes or enter new road segments. We assume that a lane change can be detected through monitoring wheel revolutions; and the system can be aware of the event via digital maps that a vehicle is entering a new road. Therefore, we focus on scheduling the read attempts when a vehicle stays in its lane. We start from a time at which a read attempt reaches a tag and results in a successful data read operation.

A vehicle is aware of it's RFID reader's setting, therefore it can calculate the length of a tag's *successful read area*, as illustrated by the shadowed area shown in Fig. 6(a). The vehicle can successfully obtain the data from a tag if it schedules its read attempt in the successful read area. The length of the successful read area, $L_{success}$, is calculated by (18), where L'_{min} is the minimum read length determined by the current vehicle speed.

As mentioned in Sec. 4, it takes at least T_{min} to successfully transmit a tag's data. T_{min} is determined by the data size and the data transmission rate, as shown in Eq. (3). Since a vehicle knows its current speed, it can calculate its current minimum read length L'_{min} based on Eq. (17), which is required to successfully read tags.

$$L'_{min} = \frac{V \times S_{data}}{R_{tag} \times \delta} \tag{17}$$

where V is the vehicle's current speed.

Note that L'_{min} increases with the vehicle's speed,

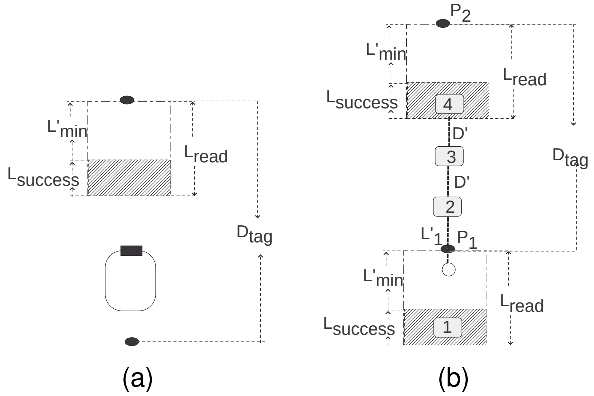


Fig. 6. (a) The successful read area to obtain a RFID tag's data. (b) The initial read attempt happens in the tag's successful read area. Here rounded rectangles are the positions at which the vehicle should send the read attempts, P_1 and P_2 are the tags' positions, and the white circle is the position at which the vehicle finishes its initial read attempt.

as a result $L_{success}$ becomes smaller if the vehicle is speeding up given L_{read}. Thus, it is believable that a speeding vehicle would slow down to get a larger chance of successfully utilizing the RFID-ANS service.

$$L_{success} = L_{read} - L'_{min} \tag{18}$$

In order to successfully obtain the data, we should consider how to schedule a vehicle's read attempts at the tag's successful read area. Generally speaking, the vehicle should send a read attempt when traveling a distance of D_{tag} after a successful read attempt. Then the key question is how can the vehicle obtain the distance between two consecutive tags. A straightforward method is for the tag to store the distance to the next tag. Obviously, this method is hard to implement and maintain. Furthermore, it is not necessary and is detrimental to RFID-ANS because the tag's increased data size results in a longer data transmission time and a smaller successful read area, according to (18). Therefore, in our RFID-ANS design, we assume that a tag does not have the distance information. Next, we focus on how vehicles should schedule their read attempts and how to obtain the D_{tag} value.

Note that a vehicle can measure the distance between any two positions it has passed as it knows its current speed and time. Also note that we assume that a lane change can be detected through monitoring wheel revolutions, and that the vehicle can detect whether it is entering a new road or not via digital maps. Then the vehicle should always initiate a read attempt when it starts, enters a new road, or changes its lane. Its initial read attempt falls into one of the following three possibilities.

1) Successfully obtains a tag's data.
2) Successfully reaches a tag, but fails to obtain the data.

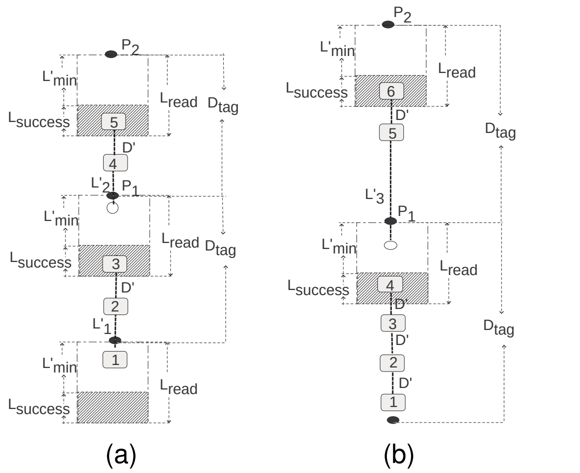


Fig. 7. (a) The initial read attempt happens in the tag's L'_{min} area. (b) The initial read attempt happens at the blank area.

3) Fails to reach a tag.

Case 1. If the initial read attempt obtains a tag's data, it happens in the tag's successful read area. Then the schedule of the following read attempts should follow Fig. 6(b), with $L'_1 = \sqrt{W_{read}^2 + L_{read}^2} - L_{read}$ and D' is close to but smaller than $L_{success}$. According to (13), $D_{tag} > L'_1 + L_{read}$. Then, after obtaining the position of the first tag P_1 at the white circle, the vehicle should send the second read attempt after a distance of L'_1. As the vehicle passes the white circle before P_1, the distance between the white circle and the next tag must be larger than $\sqrt{W_{read}^2 + L_{read}^2}$. Therefore it is impossible to miss the next tag if the second read attempt is scheduled after L'_1. After that, the following read attempts are scheduled for every distance D' until the next tag has been successfully read. Note that D' could be any number that is slightly smaller than $L_{success}$, which should be calculated based on the vehicle's current speed. As $D' <\approx L_{success}$, the scheduled read attempts must be able to read the tag P_2. Then, the distance between two consecutive tags can be estimated by $|P_2 - P_1|$.

In this case, as the second read attempt is scheduled after L'_1, it is possible that P_1 can be successfully read or reached by several read attempts when W_{read} is small and $L_{success}$ is large. We ignore the results of these read attempts because there is no tag between P_1 and P_2.

Case 2. If the initial read attempt successfully reaches a tag but fails to obtain the data because of insufficient contact time, the vehicle was in the tag's L'_{min} area when it sent the read attempt. Then the following read attempts can be scheduled as illustrated in Fig. 7(a).

The second read attempt is scheduled at L'_1 after the initial read attempt, where L'_1 is defined in case 1. As the position of the first tag is higher than the vehicle's first attempt position in Fig. 7(a), it is not necessary to schedule any read attempt for the tag P_1 before L'_1 for the same reason as in the first case. After the second read attempt, the following attempts are scheduled in every D' distance until the tag P_1 is successfully read. When P_1 is obtained at the white circle, the vehicle sends the next read attempt after a distance of L'_2, where $L'_2 = \max(D_{miss} - L'_{min}, D')$, and D_{miss} is the distance between the vehicle's first attempt position and the most recent attempt position at which it fails to reach the tag P_1. In this example, D_{miss} equals the distance between the vehicle's first and second attempt positions. Furthermore, it is not necessary to schedule a read attempt before L'_2 to read the tag P_2. After this attempt, the following read attempts are made for every distance D' until the tag P_2 is successfully read. When P_1 and P_2 are available, they can be used to estimate D_{tag}.

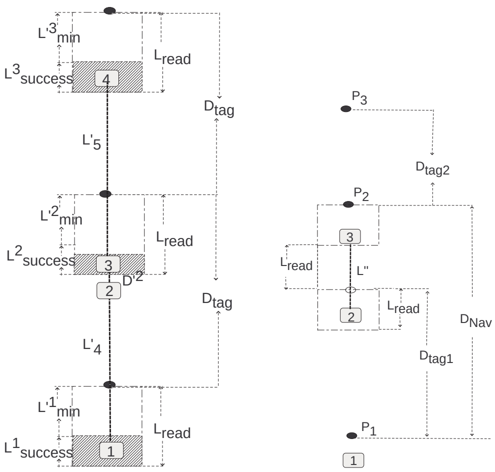
Case 3. If the initial read attempt fails to reach a tag, it happens in a blank area. The following read attempts are scheduled according to Fig. 7(b). At the beginning, the vehicle sends attempts every distance D' until the tag P_1 is successfully read. After obtaining the tag P_1's information at the white circle, the next read attempt is made after a distance of $L'_3 = D_{miss} + D'$, where D_{miss} is defined as before. In the example, L'_3 equals the distance from the vehicle's first attempt position to its fourth attempt position. As the vehicle's first attempt position is above the lowest tag, and the white circle is below P_1, it is not necessary to schedule any read attempt before L'_3. After this, the following read attempts are scheduled for every distance of D' until tag P_2 is successfully read. Note that the above three read schedulings for D_{tag} estimation are robust to the vehicle's velocity variation because D' is calculated based on the current speed.

As the vehicle's speed is not always constant, the boundary of the successful read area might vary. In addition, the vehicle does not know exactly when its front bumper passes a tag. Therefore, simply scheduling the read attempts for every D_{tag} might not result in a successful obtention of the data when the vehicle is accelerating. To address this challenge, the vehicle schedules its read attempts as illustrated by Fig. 8(a) after acquiring the distance between two consecutive tags, where $L'_4 = D_{tag} - L_{success}^1 + D'_2$, $L'_5 = D_{tag} - L_{success}^2 + D'_3$.

In summary, the vehicle should send the next read attempt after a distance L' from its most recent attempt position at which a success read attempt is made. L' is defined in (19),

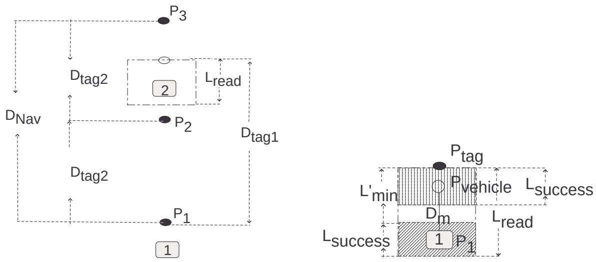
$$L' = D_{tag} - L_{success}^{previour} + D'_{current} \tag{19}$$

where $L_{success}^{previour}$ is the length of the successful read area of the vehicle's most recent successful read, and $D'_{current}$ is close to and smaller than the length of the current successful read area based on the vehicle's velocity. If this scheduled read attempt falls in the



(a) (b)

Fig. 8. (a) The scheduling of read attempts. (b) The deployment strategy of RFIF tags.



(a) (b)

Fig. 9. (a) The tag P_2 is missed by the vehicle. Here D_{tag1} is the old distance, D_{tag2} is the new distance, $D_{tag2} < D_{tag1}$, and the white ellipse is the estimated position for the tag P_2 based on D_{tag1}. (b) The vehicle's position estimation. Here P_1 is the vehicle's position at which it sends the read attempt, D_m is the distance measured from P_1 to the vehicle's current position, and the shaded area in the top half of the figure is the area where a success read could finish.

blank area, the vehicle keeps sending attempts every $D'_{current}$ until the next tag's information is obtained before it travels distance D_{tag}, as illustrated by Fig. 8(a). We present the read scheduling method to address the D_{tag}'s change in the next section.

5 RFID TAG DEPLOYMENT STRATEGY

Assume that the navigation system requires a vehicle to obtain its position through reading RFID tags once in every distance D_{ANS}. Note that this distance might vary with different road segments. For example, the distance required in urban areas might be much smaller than the one required for rural areas, and the distance required in the areas near intersections or exits should be smaller than the one required in normal road segments. Thus the tags' deployment is not a trivial task. The strategy for deploying RFID tags should satisfy different navigation requirements while guarantee that a vehicle can keep the required level of navigation running seamlessly.

As mentioned in Section 4.4, vehicles in RFID-ANS always reschedule their read requests by initiating a read attempt when they have changed lanes or entered new road segments. Note that we label a road segment as new when the vehicle passes an intersection or takes an exit. Then, we focus on the deployment strategy of RFID tags in continuous road segments where the navigation requirements vary. In continuous road segments, we require that a vehicle reschedule its read attempts when it has failed to contact the tag at an estimated position or failed to obtain the tag's data.

Generally speaking, the change of the navigation requirements falls into one of the following two categories:

1) The required distance changes to a smaller value.
2) The required distance changes to a larger value.

Category 1. If the tag is simply deployed according to the changed distance as shown in Fig. 9(a), the vehicle might miss P_2. As the vehicle schedules its read attempts based on the previous estimated distance D_{tag1} from (19), the distance between two scheduled consecutive read attempts is larger than D_{tag2}. As a result, the vehicle passes the tag P_2 without reading it. Then, after the vehicle obtains the next tag P_3's data, the distance between two success reads is $D_{Nav} = 2 \times D_{tag2}$, which is larger than any of D_{tag2} and D_{tag1}. Therefore, the navigation requirements might not be satisfied between P_1 and P_3.

Note that D_{Nav} determines the system's realtime navigation accuracy. We give it a special name *navigation precision* in this paper. To achieve seamless navigation when the required distance is decreasing, we propose the following deployment strategy as illustrated in Fig. 8(b): The distance between P_1 and P_2 is $D_{Nav} = D_{tag1} + 2 \times L_{read}$, and $L'' = L_{read} + L_{success}$ is the distance after which the vehicle should re-initiate read attempts since it notices that the next tag is not at the estimated position after traveling distance D_{tag1} without reaching any tag.

It can be verified that the vehicle can obtain the data of the tag P_2 using the deployment strategy mentioned above. Then, to guarantee seamless navigation, we require $D_{Nav} < D_{ANS}$. This results in a general deployment requirement shown in (20).

$$D_{tag} < D_{ANS} - 2 \times L_{read} \quad (20)$$

According to (13), (14), and (20), we obtain (21).

$$\sqrt{W_{read}^2 + L_{read}^2} < D_{tag} < D_{ANS} - 2 \times L_{Vmin} \quad (21)$$

Category 2. For the second category, we need to simply increase D_{tag} between two consecutively deployed tags. As the vehicle automatically reschedules its read attempts after L'' if it fails to read or reach the next tag, in order to guarantee that the vehicle can obtain the next tag's data, we require that the difference between the old, short deployment distance and the new, long deployment distance be larger than $2 \times L_{Vmin}$. Then, the vehicle should not miss any deployed tags. As a result, the vehicle can obtain the required level of seamless navigation.

Based on the tag deployment strategy presented above, a vehicle can smoothly adapt to varied navigation requirements without a bitch. As a result, the real time navigation precision of the designed RFID-ANS is bounded by the minimum navigation requirements. According to (8), the minimum D_{ANS}, is $3 \times L_{Vmin} + W_{lane}$, while $W_{lane} > W_{read}$ and $L_{Vmin} > L_{read}$.

6 Vehicle Position Estimation

We assume that a vehicle can estimate its position as soon as it successfully reads a tag. As mentioned above, the vehicle does not know the exact time at which its front bumper passes a tag even if it can obtain the tag's position P_{tag}. Therefore, as shown in Fig. 9(b), the vehicle should not simply use P_{tag} as its current position $P_{vehicle}$.

There exist two methods to estimate the vehicle's current position according to Fig.4(b).

1) Use the center of the column strip area as the vehicle's current position. As a result,

$$P_{vehicle} = |P_{tag} - \frac{L_{success}}{2}| \tag{22}$$

2) Use the center of the successful read area as P_1. Then, estimate the vehicle's current position by

$$P_{vehicle} = |P_{tag} - L_{read} + \frac{L_{success}}{2} + D_m| \tag{23}$$

Assume that D_m is accurate. Note that P_{tag} and L_{read} can be treated as constants. Thus the accuracy of the estimated position is related to $L_{success}$ only as shown in Eqs. (22) and (23). Therefore, the two position estimation methods are equivalent in terms of position accuracy. The position error is bounded by $\frac{L_{success}}{2}$. As $L_{success}$ is determined by the read length, the vehicle's speed, the tag's data size, the tag's transmission rate, and the read loss ratio, different system setup will have different location accuracy. Generally, the position error is bounded by half of the lane width because $L_{success} < L_{read} < W_{lane}$. Therefore, RFID-ANS can achieve lane level navigation. We prefer to use Eq. (22) simply because it has a simpler format.

7 A RFID-ANS Example

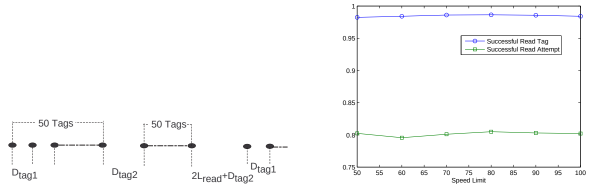
We setup an example RFID-ANS according to the standard for interstate highways in the United States. As depicted in Section 3, the lane width, the minimum vehicle length and width, the tag's data size and transmission rate, and the speed limit should all be constants in the design. According to the standard for interstate highways in the United States, the minimum lane width is 12 feet (3.66m), and the maximum vehicle speed is 75mph (121 km/h) in rural areas. To our knowledge, the *Smart Car* is probably the smallest car on the market that can run on U.S. highways. Thus, we use its dimensions, a length of 8.8 feet (2.68m) and a width of 5.1 feet (1.55m), as the minimum vehicle length and width, respectively. As the GPS coordinates are represented by $xxx - xx.xxx$ in decimal, 50 bits are sufficient to store the tag's horizontal and vertical coordinates. We use 3 bits and 11 bits to represent the lane direction and road name, respectively. Accordingly the RFID tag's data size is set to 64 bits. We assume that the tag has a data transmission rate of 256 kbps (EM4222 chip) [10], and that the navigation system requires the vehicle to successfully read a RFID tag once every 60 feet (18.29m). Accordingly, we have

$$\begin{aligned} 6.9 < W_{read} < 12 \\ 0.046 < L_{read} < 8.8 \\ W_{read}^2 + L_{read}^2 < 144 \\ \sqrt{W_{read}^2 + L_{read}^2} < D_{tag} < 22.4 \end{aligned}$$

Next, based on Eqs. (1) and (2), we can set the parameters h, α and θ accordingly such that the read length can be maximized and the above conditions can be satisfied. This example RFID-ANS has a navigation accuracy of 38.4 feet (11.7m), which satisfies the navigation system requirements.

8 Simulation

In this section, we report our simulation results obtained from the example RFID-ANS mentioned in Sec. 7. Matlab is used in the simulation. We wrote a program to simulate the vehicle running and tag reading. In the simulations, we assume the read error caused by wireless communication can be represented by the read length loss ratio δ. We set $\delta = 1\%$ in the simulations. Following the parameters introduced by Ref. [2], we set the antenna's hight $h = 1.23$ feet, its read angle $\alpha = 141.3^o$, and its pitch angle $\theta = 6.7^o$. As a result we have $W_{read} = 7$ feet, $L_{read} = 8$ feet, and 10.7 feet $< D_{tag} < 42.4$ feet according to the design analysis in Section 7. We use two settings for D_{tag}, with $D_{tag1} = 18$ feet and $D_{tag2} = 36$ feet, respectively. We place 1000 tags in a straight line as shown in Fig. 10(a), where D_{tag} is changed alternatively once every 50 tags. The line length is roughly 5 miles. We add a tag deployment error to each tag, which represents the shift from the tag's real position to its expected position shown in Fig. 10(a). The error is randomly selected from $(-Max_{error}, Max_{error})$, where Max_{error} is the maximum tag deployment error.



(a) (b)

Fig. 10. (a) The tag deployment map in the simulations. (b) The ratio of the successful read tags, and the ratio of the successful read attempts VS. Speed limit

A virtual vehicle is employed in our simulation study to test the performances of the proposed RFIF-ANS in terms of the ratio of the successful read tags, the ratio of the successful read attempts, and the position error. These parameters are examined under different speed limits $(50 - 100$ mph), and different maximum tag deployment errors $(10\% - 60\%) \times L_{read}$. The vehicle uniformly selects its starting point at the line between $(0, 18)$ feet. And it changes its speed every 1 ms by an acceleration uniformly selected from $(-20, 20)$ mph/s. The simulation has been run for 100 times. Although we focus on single lane scheduling in this paper, the results can also show RFID-ANS's performance in multi-lanes environments because vehicles will always initial read attempts when they entered new roads or changing lanes. In the simulation, we set $D' = 0.9 \times L_{success}$.

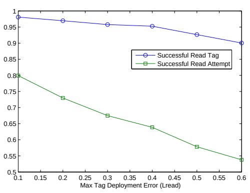


Fig. 11. The ratio of the successful read tags, and the ratio of the successful read attempts VS. Deployment Error

Fig. 10(b) reports the ratio of the successful read tags and the ratio of the successful read attempts when the maximum tag deployment error is set to be $10\% \times L_{read}$. The results indicate that more than 97% of the deployed tags can be successfully read by vehicles, and that almost 80% of the scheduled read attempts can yield successful reads. Fig. 11 reports the same two ratios under different maximum tag deployment errors when the speed limit is set to 70 mph. Although the deployment error significantly affect the performances, 90% of the tags still can be successfully read. Additionally, the position error is always upper bounded by 2 feet through the whole simulation process.

9 Conclusion

We summarize our investigation on the design of RFID-ANS in this section. The proposed RFID-ANS can achieve a navigation precision of $3 \times L_{Vmin} + W_{lane}$ and the accuracy of the vehicle's estimated position is $L_{success}$. An ideal RFID tag for RFID-ANS should have a near zero access time. The important parameters for the design of the RFID reader and the deployment of the RFID tags should satisfy the following conditions.

$$W_{lane} - W_{Vmin} < W_{read} < W_{lane}$$
$$W_{read}^2 + L_{read}^2 < W_{lane}^2$$
$$\frac{\overline{V} \times S_{data}}{R_{tag} \times \delta} < L_{read} < L_{Vmin}$$
$$\sqrt{W_{read}^2 + L_{read}^2} < D_{tag} < D_{ANS} - 2 \times L_{Vmin}$$

Note that in the above conditions, the effect of the read noise and that of the communication delays are modeled by the read length loss ratio δ. In our future research, we will treat the two negative effects separately. The communication delay will be controlled by tag design and reader design. The effect of the read noise will be estimated through modeling and analysis. We will also focus on studying multi-lane tag co-development strategies and the corresponding read scheduling methods such that the system's performance can be improved in complex environments.

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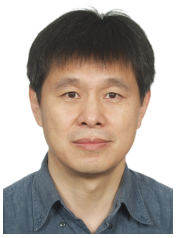

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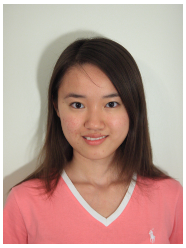

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