Supplementary file related to the paper titled **On the Design and Deployment of RFID Assisted Navigation Systems for VANET**

1 Supplementary file related to Section 3: RFID Assisted Navigation System Model

Our RFID-ANS model is illustrated in Fig. 1(a).

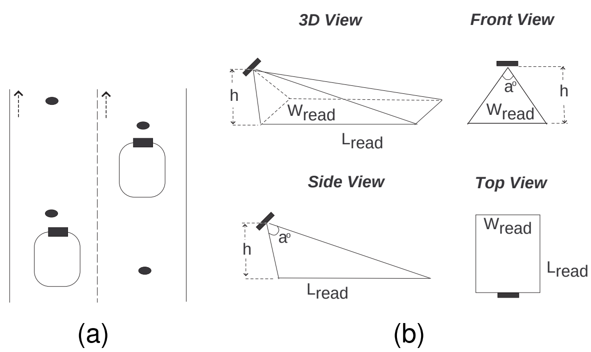

Fig. 1. (a) The RFID-ANS model, where the black ellipses, the white rounded rectangles, the black rectangles, and the dotted arrows represent RFID tags, vehicles, RFID readers' antennas, and the traffic directions, respectively. (b) The RFID reader's read area.

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.

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

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

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

2 Supplementary file related to Section 4: RFID Reader Design

2.1 RFID reader's read length

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).

$$L^T_{min} = \overline{V} \times T_{min} \tag{4}$$

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).

$$L_{min} = \frac{L^T_{min}}{\delta} \tag{5}$$

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).

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

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

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

2.2 RFID reader's read width

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

$$W_{read} > W_{lane} - W_{Vmin} \tag{8}$$

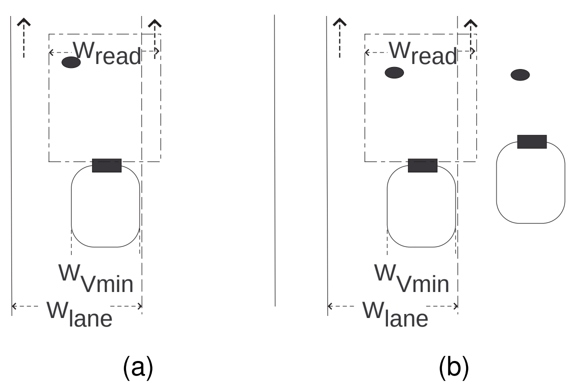

Fig. 2. (a) A vehicle should be able to read the RFID tag in the lane it presents. (b) A vehicle should not be able to read the RFID tags in other lanes.

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.

$$W_{read} < W_{lane} + W_{Vmin} \tag{9}$$

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).

$$W_{read} < W_{lane} \tag{10}$$

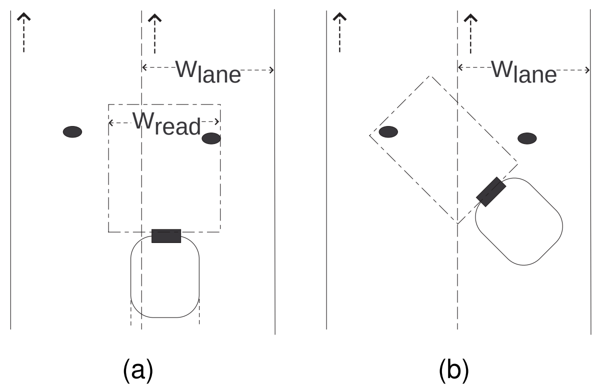

Fig. 3. (a) The vehicle should not be able to read the RFID tag that is deployed in the left lane. (b) The vehicle can read the RFID tag deployed in the lane that it is heading for.

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

$$W_{lane} - W_{Vmin} < W_{read} < W_{lane} \tag{11}$$

2.3 Considerations for lane changing

The $4th$ and $5th$ design criteria can be satisfied by Eq. (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.

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 revised 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 2.1 guarantees that the second problem can be solved based on the RFID reader design.

Theorem 2.1: The vehicle can not read a RFID tag deployed in the lane that 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

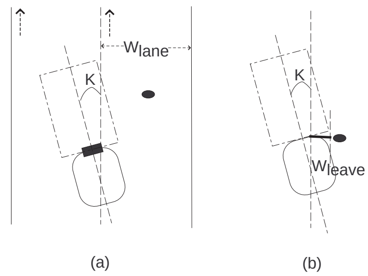

Fig. 4. The vehicle can not read a RFID tag deployed in the lane that most part of its body has left.

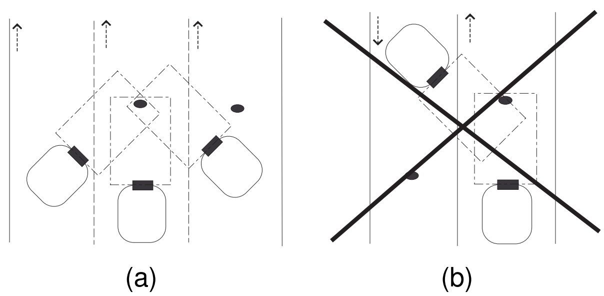

Fig. 5. (a) A RFID tag could be reached by more than one vehicle. (b) Two vehicles from different directions can not reach the same RFID tag.

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) 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.

2.4 Adaptive scheduling of the RFID reader's read attempts

As mentioned in Section 4.1, 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.

3 SUPPLEMENTARY FILE RELATED TO SECTION 6: VEHICLE POSITION ESTIMATION

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,

$$P_{vehicle} = |P_{tag} - \frac{L_{success}}{2}| \tag{18}$$

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

$$P_{vehicle} = |P_{tag} - L_{read} + \frac{L_{success}}{2} + D_m| \tag{19}$$

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. (18) and (19). 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. (18) simply because it has a simpler format.

4 SUPPLEMENTARY FILE RELATED TO SECTION 7: A RFID-ANS EXAMPLE

In this section, we use an example to illustrate how the parameters should be set in an experimental environment. 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), 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.

5 Supplementary file related to Section 8: Simulation

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. 6, 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. 6. The error is randomly selected from $(-Max_{error}, Max_{error})$, where Max_{error} is the maximum tag deployment error.

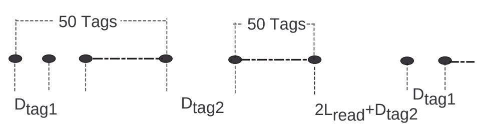

Fig. 6. The tag deployment map in the simulations

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 $D' = 0.9 \times L_{success}$.

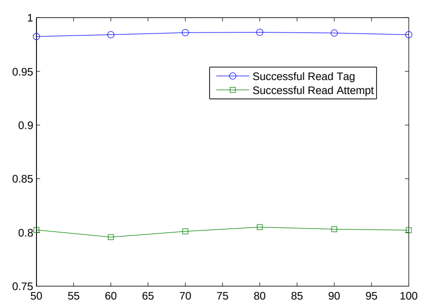

Fig. 7. The ratio of the successful read tags, and the ratio of the successful read attempts VS. Speed limit

Fig. 7 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. 8 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.

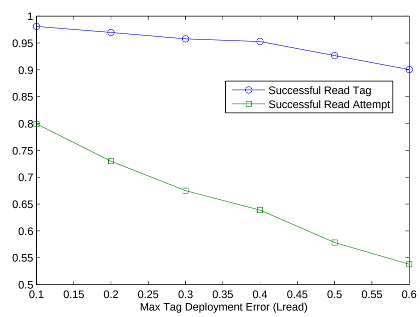

Fig. 8. The ratio of the successful read tags, and the ratio of the successful read attempts VS. Deployment Error