FINE: Frequency-divided Instantaneous Neighbors Estimation System in Vehicular Networks

Linghe Kong*, Xi Chen*, Xue Liu*, Lei Rao†
*McGill University, Canada †General Motors Research Lab, USA
*{linghe.kong@mail, xi.chen11@mail, xueliu@cs}.mcgill.ca †lei.rao@gm.com

***Abstract*—In this paper, we present a novel Frequency-divided Instantaneous Neighbors Estimation (FINE) system specifically designed for density estimation in Dedicated Short Range Communication (DSRC) based vehicular networks. A large amount of vehicular applications such as navigation, traffic control, and data dissemination substantially rely on the density information. Recent works pay great attention to obtain the real-time density information and reduce the occupation time of DSRC channel. The state-of-the-art approach is the Framed Slotted ALOHA (FSA) framework, which benefits from its fine-grained time division design. However, FSA considers only time resource and is unaware of the frequency resource in DSRC. For further accelerating the density acquisition, we propose a frequency-divided approach. The core idea of FINE is to resort fine-grained channel division for parallel neighbors counting. Extensive simulations are conducted to evaluate FINE. The results demonstrate that FINE significantly outperforms existing methods. In a typical dense scenario, FINE reduces the time cost from 2 ms (FSA) to 50 μs, while maintains the accuracy at the same level as FSA.**

I. Introduction

Vehicular networks [3, 8, 18] are promising on enhancing transportation safety, efficiency, and infotainment. Particularly, the licensed 5.9 GHz spectrum has been allocated to only support *Dedicated Short Range Communication* (DSRC) [1, 6], which is currently the fundamental communication standard in vehicular networks. In February 2014, U.S. Department of Transportation announced the regulation that requires all new light-duty vehicles to equip DSRC devices. The scale of DSRC vehicular network is poised to increase dramatically.

A great deal of applications have been envisioned in vehicular networks such as car navigation [19], congestion control [16], and data dissemination [12]. Most of these applications substantially rely on the density information (*i.e.*, the number of neighboring vehicles in a given range). It is desired that the density acquisition procedure is the quicker the better because of two reasons. First, the real-time density information is more useful than the historical one for vehicular applications [20]. Second, since lots of applications contend the DSRC channel [10] for data transmission, a quick density acquisition can reduce the channel occupation time and thus improve the time efficiency of DSRC. Hence, we focus on the quick density acquisition problem in this work.

Both academical and industrial communities have contributed some efforts on density acquisition approaches such as Google Map, routine messages in DSRC [1], and neighbor discovery [4]. Currently, the fastest one is the Framed Slotted ALOHA (FSA) [2], which benefits from its fine-grained time division design. However, FSA only considers the acceleration in time domain and is unaware of the frequency resource in DSRC, whose channel bandwidth is up to 10 MHz. This observation motivates us to consider the quick density acquisition problem from a new perspective: the frequency domain.

In this paper, we design a novel Frequency-divided Instantaneous Neighbors Estimation (FINE) system to further accelerate the density acquisition in DSRC. The core idea of FINE is to divide a 10 MHz DSRC channel into hundreds of subchannels and resort these fine-grained subchannels to achieve a parallel neighbors estimation. In FINE, an inquirer broadcasts the density acquisition request. Then, every neighbor randomly selects one subchannel to respond a short-duration subcarrier signal. At the end, the inquirer estimates the number of neighbors based on the number of empty/non-empty subchannels. Although the basic idea sounds straightforward, it is non-trivial to realize it in practice due to the following technical challenges. Along with the challenges, we briefly describe FINE solutions accordingly.

• It is non-trivial to determine the number of subchannels and the duration of response in FINE system. Naturally, more subchannels and shorter duration are expected for higher estimation accuracy and less time cost, respectively. However, many practical factors, such as the frequency offset of hardware and the different distance of neighboring vehicles, affect the parameter determination. To this end, we theoretically derive the relationship between the parameters and the practical factors according to Nyquist Shannon sampling theorem [5]. Based on the derived results, we design a quick request-response protocol between inquirer and neighbors in FINE.

• It is challenging to accurately recognize the empty/non-empty subchannels in frequency domain because of not only the noises but also the interferences. Especially, the sidelobe interference seriously affects the recognition. A duration-finite subcarrier signal generates a main peak at its corresponding subchannel and several smaller peaks at adjacent subchannels, which is so-called the sidelobe problem [11]. To deal with this problem, we exploit the sidelobe model derived in [11] to precisely recognize the main peaks. Then, we can identify the empty/non-empty subchannels with a low recognition error, which is $< 2\%$ shown in performance evaluation.

The major contributions of this work are summarized as follows. We design a novel FINE system, which is a distributed and instantaneous density estimation framework specially designed for DSRC vehicular networks. The design of FINE is based on frequency division, so it can fully exploit the frequency resource of DSRC channel and shorten the channel occupation time. Extensive simulations are conducted to evaluate the performance of FINE. Performance results demonstrate that FINE significantly outperforms existing approaches on time consumption and its accuracy is at the same level of the state-of-the-art approach.

II. Related Work

Plenty of methods have been studied to acquire the density in vehicular networks. We classify them into four categories.

Centralized density sharing: Several methods in this category have become commercial products so that people can use them nowadays. For example, Google Map is one typical application that provides coarse-grained density information in its traffic layout. However, methods in this category usually need infrastructures (*i.e.*, cameras, coils, or other sensors [17]) to collect the real-time traffic information. An inquirer has to link to the server through Internet to acquire the density. The drawback includes the demand of infrastructure, centralized server, and Internet. The time cost in this category is usually more than 1s due to establishing the connection to Internet.

Distributed density sharing: Getting ride of infrastructure, methods in this category require only on-vehicle wireless devices. Recently, there is a basic application in DSRC that every vehicle periodically broadcasts its routine message [1], which is a typical distributed density sharing method. Through counting the number of routine messages received in one period, an inquirer can obtain the density locally. The widely accepted broadcasting period in DSRC is 100 ms [1]. However, in a high density scenario, there will be too many broadcasting collisions, leading to an inaccurate density acquisition.

Neighbor discovery: In this category, an inquirer identifies its neighboring vehicles one-by-one and counts their IDs [4] via DSRC. Since this method needs to clearly decode all neighbors' ID packets, it costs much time on channel sensing and collision avoidance. The total time consumption of such methods is at several 10-ms level.

Framed Slotted ALOHA (FSA): The FSA framework is the most related work to this paper. In general, FSA is a one-return trial that an inquirer broadcasts request with a given number of time slots. Then, every neighbor randomly picks a slot to reply. Consequently, the inquirer receives a bit sequence of 0s and 1s, where 0 indicates a slot with no reply and 1 indicates a slot with one or more responses. In the end, the number of neighbors is estimated based on the bit sequence by the estimators such as UPE [7], LoF [13], and ART [15]. The FSA framework can complete the density acquisition about 2 ms. However, FSA falls in time domain design and does not take advantage of the frequency domain resource.

III. Preliminaries

We introduce the background of DSRC and density acquisition in vehicular networks, then we present our motivation to investigate the quick density acquisition problem.

A. DSRC Background

Dedicated short range communication (DSRC) [1, 6] technology is designed to support a variety of applications based on vehicular networks. It is envisioned that vehicles equipped with DSRC devices will increase dramatically. At the physical layer, DSRC utilizes IEEE 802.11p [6], which is an extended 802.11 protocol. In addition, since the licensed 5.9 GHz spectrum is exclusively allocated to DSRC, any DSRC transmission is free of the interference from the other wireless protocols. This dedicated spectrum is divided into seven channels and the bandwidth of every channel is 10 MHz.

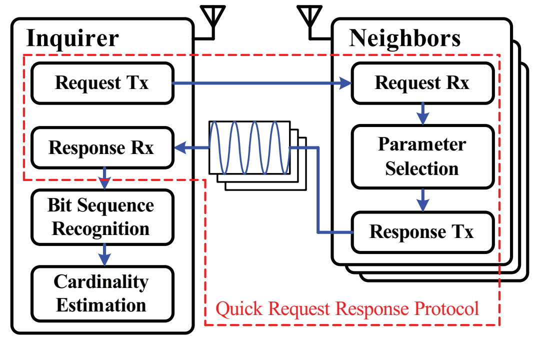


Fig. 1. The architecture of FINE system.

B. Density Acquisition

This work concerns the density acquisition in vehicular networks. Specially, we mainly study the distributed density acquisition technique, which only leverages on-vehicle DSRC devices and does not require any extra infrastructures.

The goal of density acquisition is to obtain the number of vehicles within a given range. We first define the following three concepts: inquirer, effective distance, and neighbor. (i) The vehicle, who intents to acquire the density, is called *inquirer*. (ii) An inquirer is interested in the density information within an *effective distance*. The effective distance is usually 0-300 m [1] because the information from far-away vehicles is irrelevant to its immediate behavior. The transmission range of DSRC is up to 1000 m [6], which covers the effective distance requirement. (iii) The vehicles located within the effective distance of an inquirer are called *neighbors*. Then, the density is formulated as $N_v/\pi D_e^2$, where N_v presents the number of neighboring vehicles and D_e presents the effective distance. Since D_e is actively set by the inquirer, the density is obtained when the real-time N_v is acquired.

C. Motivation

There are two reasons inspiring us to focus on the *quick density acquisition problem*.

First, plenty of vehicular applications fundamentally depend on the real-time density information. For example, Rawat *et al.* [14] propose to control the DSRC transmission power according to density, so as to achieve a good tradeoff between coverage and communication quality. More examples of density based applications can be found in navigation [19], congestion control [16], and data dissemination [9].

Second, a quick density acquisition is valuable in DSRC vehicular networks. The contention of time resource in DSRC is drastic. Existing vehicular applications such as transportation safety, advertisement, navigation and infotainment applications have exclusively occupied a certain part of channel occupation time. The remaining time resource is rare. In order to avoid the channel saturation and transmission collisions, it is critical to utilize the DSRC channel efficiently and wisely.

In literature, the fastest approach is FSA, which achieves an accurate density estimation within 2 ms. Nevertheless, the time division based FSA is unaware of the frequency resource of DSRC channel. This observation motives us to design a frequency-divided approach to fully exploit the DSRC bandwidth and further accelerate the density estimation procedure.

IV. Design of FINE System

In this section, we present the explicit design of Frequency-divided Instantaneous Neighbors Estimation (FINE) system.

A. Design Overview

At inquirer side, the principal design of FINE is to evenly divide a channel into hundreds of subchannels in order to receive neighbors' responses simultaneously. At the neighbor side, every neighbor randomly selects one subchannel to respond a short-duration subcarrier signal. Thus, the inquirer can estimate the number of neighbors based on the number of empty and non-empty subchannels.

The architecture of FINE is illustrated in Fig. 1. Three key components in FINE are briefly described as follows.

Quick Request-Response Protocol (QRRP) is in charge of the transmission between an inquirer and its neighbors. The procedure of QRRP is a one-return transmission as shown in the dash line area in Fig. 1. First, an inquirer broadcasts its request. Once a neighbor receives the request, it randomly selects a subchannel and immediately responds a short-duration subcarrier signal at the selected subchannel. All neighbors respond independently, and thus their responses are simultaneously without any collision avoidance mechanism.

Bit Sequence Recognition translates the responses into a bit sequence. Although the responses are overlapped in time domain, they are distinguishable in frequency domain due to different subchannel selection. This component first operates Discrete Fourier Transform (DFT) on the signal and then scans every subchannel. An empty subchannel (no response) is considered as a bit 0 and a non-empty subchannel (one or more responses) is considered as a bit 1. The bit sequence is composed of these recognized bits.

Cardinality Estimation is responsible for estimating the number of neighboring vehicles based on the recognized bit sequence. The foundation of this estimation is that the larger number of neighbors, the more bit 1s and the less bit 0s. Existing FSA based estimators such as UPE [7] and ART [15] can be directly applied in this component.

Benefiting from above design, the FINE system can instantaneously acquire density because of the advantages:

- Between inquirer and neighbors, there is only a simple one-return transmission. All neighbors respond simultaneously without any backoff or retransmission.
- The inquirer only needs to check whether there is a response in every subchannel instead of decoding responses. Hence, the response can be a short-duration subcarrier signal excluding any further information.
- The FINE system provides a fast and accurate estimation of neighbors only based on the recognized bit sequence.

Next we elaborate the details for each component.

B. Quick Request-Response Protocol

Before presenting the design of QRRP, two theorems about the number of subchannels and the duration of responses are introduced, which are the theoretical foundation of QRRP.

Theorem 1: In FINE system, the maximal number of subchannels is

$$\max(N_{sc}) = \lfloor \frac{B}{2f_c \times f_s} \rfloor, \qquad (1)$$

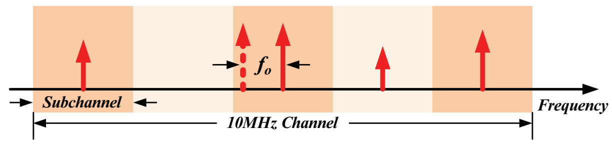


Fig. 2. The frequency offset usually exists in a commercial radio, which causes a slight shift f_o in the frequency domain. In order to ensure that the frequency of a response locates in the correct subchannel, the FINE system demands the bandwidth of a subchannel larger than $2f_o$ to tolerate the offset.

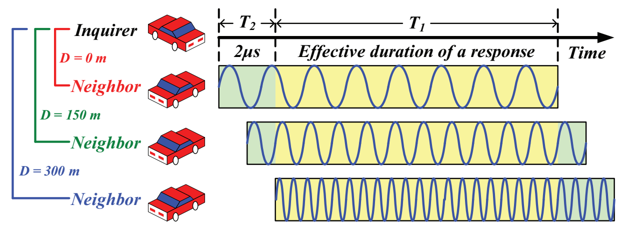


Fig. 3. The different distances between inquirer and neighboring vehicles lead to different propagation delay. In order to ensure that the overlapped duration of all responses is no less than T_1, FINE demands a segment of redundant duration T_2 on every response to eliminate the effect of different delay. In this example, the effective distance is $300m$, so $T_2 = \frac{300\times 2}{3\times 10^8} = 2\mu s$.

where N_{sc} is the number of subchannels, B is the bandwidth of a DSRC channel, f_c is the center frequency of the selected DSRC channel, and f_s is the frequency stability of a radio.

Proof: According to existing bit sequence based estimators [7, 15], we can easily summarize that the more subchannels lead to the higher estimation accuracy of FINE system. Hence, maximizing the number of subchannels in FINE is desired, which is constrained by the hardware. The major constraint is from the frequency offset of the Crystal Oscillator. The frequency offset $f_o = f_c \times f_s$, where f_c is the center frequency of the selected DSRC channel and f_s is the frequency stability of a radio, which is labelled on any radio device. The frequency stability f_s of the commercial radio devices are usually from 0.5 to 2.5 ppm. Typically, when $f_s = 2$ ppm and $f_c = 5.9$ GHz, the frequency offset is $f_o = 5.9$ GHz $\times$ 2 ppm $= 11.8$ KHz. Thus, the center frequency of a transmitted subcarrier may shift about up to ± 11.8 KHz in frequency domain as shown in Fig. 2. In order to maintain the peak (Since the response is a subcarrier signal, it shows a quasi-peak shape in frequency domain after DFT.) within the correct subchannel against the offset, the bandwidth of a subchannel should satisfy $B_{sc} > 2 \times f_o$, where B_{sc} is the bandwidth of a subchannel. Therefore, $N_{sc} = \lfloor B/B_{sc} \rfloor < \lfloor B/2f_o \rfloor = \lfloor \frac{B}{2f_c \times f_s} \rfloor$. Then, we have $\max(N_{sc}) = \lfloor \frac{B}{2f_c \times f_s} \rfloor$ and Theorem 1 is proved. ■

Theorem 2: In FINE system, the shortest duration of a response is

$$\min(T) = \frac{N_{sc}}{B} + \frac{2D_e}{C}, \qquad (2)$$

where T is the duration of a response, D_e is the effective distance, and $C = 3 \times 10^8$m/s is the propagation speed of electromagnetic wave.

Proof: In order to achieve a quick neighbor estimation, the total duration of a response is desired to be minimized.

We derive $\min(T)$ in Theorem 2 by dividing the total duration into two parts $T = T_1 + T_2$, where T_1 is denoted as the effective duration for clear subcarrier recognition in frequency domain and T_2 is denoted as the redundant duration against different propagation delays from different neighbors. Next, we derive $T_1 \geq B/N_{sc}$ and $T_2 \geq 2D_e/C$, respectively.

Proof of $T_1 \geq N_{sc}/B$: According to Nyquist Shannon sampling theorem [5], in order to distinguish two different-frequency signals, the number of sampling points N_{sp} must satisfy $N_{sp} \geq S/\Delta f$, where S is the sampling rate and Δf is the frequency difference of two signals. Since the FINE system needs to distinguish peaks in adjacent subchannels and all subchannels are evenly divided, the frequency difference between two adjacent subchannels is the bandwidth of a subchannel, *i.e.*, $\Delta f = B_{sc} = B/N_{sc}$. In addition, the number of sampling points is equal to the sampling rate multiplying the sampling duration, *i.e.*, $N_{sp} = S \times T_1$. Then, we have $T_1 \geq 1/B_{sc} = N_{sc}/B$.

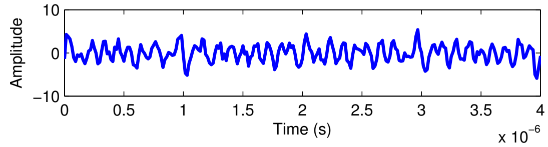
Proof of $T_2 \geq 2D_e/C$: Generally, the distances between the inquirer and different neighboring vehicles are different. If the effective distance D_e is set to 300 m, the closest neighbor to inquirer can be 0 m and the farthest neighbor to inquirer can be 300 m. Consider the propagation delay of the one-return request and response, the maximal delay difference between the closest and farthest vehicles is $2D_e/C$. In order to ensure that the overlapped duration of all responses is no less than T_1, the FINE system demands a segment of redundant duration T_2 on every responses against the effect of different propagation delay. Obviously, when $T_2 \geq 2D_e/C$ is added to the duration of every response, the overlapped duration of all responses larger than the effective duration T_1 can be guaranteed. In the example illustrated in Fig. 3, the effective distance is 300 m, so $T_2 = \frac{300\times 2}{3\times 10^8} = 2\ \mu$s.

Together with $T_1 \geq N_{sc}/B$ and $T_2 \geq 2D_e/C$, we have the result in Theorem 2 that $\min(T) = \frac{N_{sc}}{B} + \frac{2D_e}{C}$. ■

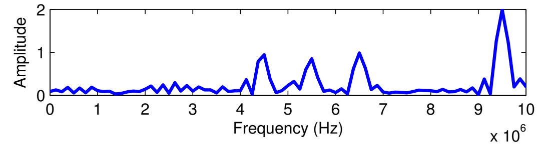
Based on the above two theorems, the detailed QRRP operates as follows.

• The inquirer broadcasts the request with an information tuple $<N_{sc}, f_c, L_i, D_e>$, where N_{sc} is the number of subchannels (determined by the inquirer, and its value should be smaller than $\max(N_{sc})$ derived in Theorem 1), f_c is the channel frequency (chosen from seven DSRC channels, 5.9 GHz by default), L_i is the location of inquirer (obtained from the on-vehicle GPS), and D_e is the effective distance (determined by the inquirer, and the recommended value is 300m [1]). The request is transmitted by a normal DSRC packet. After transmitting the request, the inquirer switches to the reception state.

• A neighbor firstly decodes the information tuple immediately after receiving the request. Then, this neighbor prepares the response using its parameter selection module. This module has three steps: (i) Response decision: If the distance between this neighbor and the inquirer is within the effective distance (*i.e.*, $|L_n - L_i| \leq D_e$, where L_n is the location of this neighbor), this neighbor will respond; otherwise, it will not respond. (ii) Frequency selection: A neighbor randomly selects a subchannel from 1 to N_{sc}, *i.e.*, the selected subchannel $\theta_{sc} = \text{rand}(N_{sc})$. The center frequency of this subchannel can be computed by $f_{sc} = (\theta_{sc} - 0.5) \times \frac{B}{N_{sc}} + (f_c - \frac{B}{2})$. (iii) Duration determination: the duration is $T = \frac{N_{sc}}{B} + \frac{2D_e}{C}$ according to Theorem 2. All neighbors respond simultaneously.



(a) The effective signal (baseband) in time domain.



(b) The signal in frequency domain. We find that the 5-th, 6-th, 7-th, and 10-th subchannels are not empty. Hence, the bit sequence is 0000111001.

Fig. 4. Example of bit sequence recognition. Given 5 neighbors, the number of subchannels $N_{sc} = 10$, and the effective duration of responses $T_1 = 4\ \mu$s.

• The inquirer receives the responses from all neighbors. The total reception duration is $T_2 + T_1$ as shown in Fig. 3. After receiving the signal, the first step is to down-convert the signal from carrier to base band by removing the f_c, which is automatically executed by the radio front end. Then, the Analog-to-Digital Converter (ADC) transforms the analog base band signal to the digital signal by discrete sampling. The inquirer abstracts the last T_1-duration digital signal as the effective signal, which includes all responses' subcarriers, and delivers this signal to the next component.

C. Bit Sequence Recognition

This component first operates the Discrete Fourier Transform (DFT) to obtain the signal in frequency domain. Then, this component checks every subchannels and "translates" them into a bit sequence. The empty subchannel is considered as bit 0 and the non-empty one is considered as bit 1.

We use an example to show the basic idea of recognition procedure. In this example, we set that there are totally 5 neighboring vehicles; the 10 MHz DSRC channel is divided into $N_{sc} = 10$ subchannels; and the effective duration of responses is preset as $T_1 = 4\ \mu$s. The signal in time domain is shown in Fig. 4(a), which includes the response from 5 neighbors and Additive Gaussian White Noise (AGWN) as well. Operating DFT on the signal in Fig. 4(a), we have the signal in frequency domain as shown in Fig. 4(b). We find that the 5-th, 6-th, 7-th, and 10-th subchannels are not empty. Hence, the bit sequence is 0000111001.

To realize the basic idea, there are two practical problems.

Empty/non-empty judgement. It seems easy to set an amplitude threshold A_{th} for signal in frequency domain to identify an empty or a non-empty subchannel. If the peak value locating in a subchannel is larger than A_{th}, this subchannel is non-empty. Otherwise, it is an empty subchannel. But it is not easy to pre-determine a fix value of A_{th} because of the different background noise.

We design an adaptive A_{th} mechanism to deal with the dynamic noise amplitude. In this mechanism, the inquirer needs to sense every subchannel and obtain the real-time maximal value of noise before transmitting a request. Then, the dynamic threshold is set $A_{th} = \max(\text{Noise}) + \beta$ dB, where β is a constant. We set $\beta = 5$ dB in our experiment.

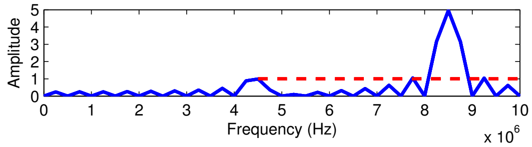


Fig. 5. An example of sidelobe problem. A large peak value in the 9-th subchannel accompanies large sidelobes in 8-th and 10-th subchannels, which have the same amplitude as the peak value in the 5-th subchannel. It is necessary to eliminate the sidelobe impact for correct bit recognition.

Sidelobe problem. A finite-duration and fixed-frequency subcarrier signal generates a main peak at its corresponding subchannel and several small peaks at adjacent subchannels, which is called the sidelobe problem [11]. On account of the different distances and powers of different neighbors, it is possible that the peak values of some sidelobes are larger than some values of main peaks. Hence, these sidelobes may affect the correctness of bit recognition. For example, in Fig. 5, the peak value (received power) in the 9-th subchannel is large. But this large main peak couples with several sidelobes in its adjacent subchannels such as the signals in the 8-th and 10-th subchannels. These sidelobes have the similar amplitude to the peak value in the 5-th subchannel, which may be falsely recognized as bit 1s.

To deal with the sidelobe problem, we adopt the mature sidelobe model in [11]. This model formulates the mathematical relationship among sidelobes, main peaks, channel bandwidth, and the total number of sampling points, and thus is able to identify whether a peak is a sidelobe or not. Exploiting this model, we can identify the sidelobes and remove them from the signal. Therefore, the sidelobe effect in bit recognition can be eliminated.

D. Cardinality Estimation

The goal of this component is to estimate the number of neighboring vehicles using the recognized bit sequence.

Bit sequence based cardinality estimators have been investigated such as UPE [7], LoF [13], and ART [15]. All of these estimators are compatible in FINE system. In current FINE system, we adopt ART estimator [15], which is the state-of-the-art estimator with a high estimation accuracy.

ART calculates the average run length of bit 1s and uses this information to generate a final estimation. A run of bit 1s is defined as a consecutive sequence of 1s. For example, given a bit sequence "11100111110", it have four runs, which are 111, 00, 11111, and 0 respectively. There are two run of bit 1s: 111 and 11111. The first run length of 1s is 3 and the second run length of 1s is 5. Hence, the average run length of bit 1s is $r_1 = (3 + 5)/2 = 4$. Leveraging the average run length r_1 and the total length of bit sequence N_{sc}, ART can estimates N_v according to Eq. (1)-(9) in [15].

V. Performance Evaluation

In this section, we evaluate the performance of FINE.

A. Evaluation Settings

Extensive simulations are conducted in the following scenario: An inquirer needs to acquire the density within the effective distance $D_e = 300$ m. The number of neighboring vehicles varies from 0 to 1000. Every vehicle is equipped with DSRC and GPS device. The transmission power is randomly selected from 10 dBm to 30 dBm.

We comparatively study two estimation methods.

- FSA+ART [15]: This method utilizes FSA to obtain the bit sequence. Then, the ART estimator leverages the average run length of 1s for neighbors estimation.
- FINE+ART: Our system obtain the bit sequence via the frequency-divided method. And the estimator ART is adopted for fair comparison.

The default settings of FINE include: the number of subchannels is $N_{sc} = 256$, the effective duration of response is $T_1 = 50$ μs, and the redundant duration of response is $T_2 = 2$ μs against the different propagation delay of neighbors.

B. Performance Result

Time cost. Time cost is one important metric concerned in this work. We compare FINE and FSA on this metric and plot their results in Fig. 6. Since the time cost of sending a request is the same for both methods, we only compare the time costs on their responding phase. We find that the time cost of FSA+ART is a quasi-linear curve. At the high density $N_v = 1000$, this time-division based methods require about 2 ms. On the contrary, the performance of FINE+ART is a constant 52 μs independent to the number of neighbors. The reason is that FINE exploits the frequency-divided subchannels to receive the responses.

Estimation accuracy. Estimation accuracy is another important metric for density acquisition. Since FINE utilizes 256 subchannels, we set 256 time slots in FSA+ART. We execute both methods 100 times per case at $N_v = 100, 200, \cdots, 1000$ respectively and show the average results in Fig. 7. Benefiting from the ART estimator, both methods provide satisfactory results. Their estimations are always close to the truth and their standard deviations are small compared to the total number.

C. Impact of Factors

In FINE, there are four factors: the recognition error, the effective duration T_1, the Signal Noise Ratio (SNR), and the sidelobe interference, significantly affect its performance. We evaluate the impact of factors as follows.

Impact of recognition error. The recognition error is defined as that an empty subchannel is falsely recognized as bit 1 and vice versa. A high recognition error ratio from *bit sequence recognition* component is undesired because it directly affects the estimation accuracy. In order to study the impact of recognition error, we artificially set 2%, 5%, and 10% bit errors and show the results of cardinality estimation in Fig. 8. We find that the lower bit recognition errors results the higher estimation accuracy.

Impact of the effective duration. A too shorter effective duration T_1 leads to the confusion of signals (in frequency domain) in adjacent subchannels, which further leads to bit errors. The impact of the effective duration is shown in Fig. 9. It can be found that 256 channels demand at least 50μs, otherwise the recognition error ratio is more than 10%. And 12.5μs is adequate for 64 channels with a negligible error ratio. We recommend an available setting combination of 256 subchannels and 50 μs in current FINE because of the performance in Fig. 6 and 7.

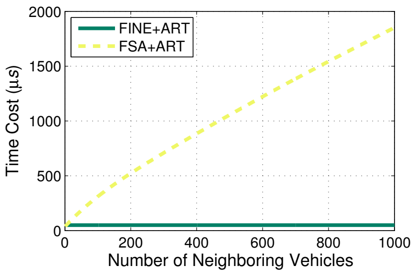


Fig. 6. Time cost comparison.

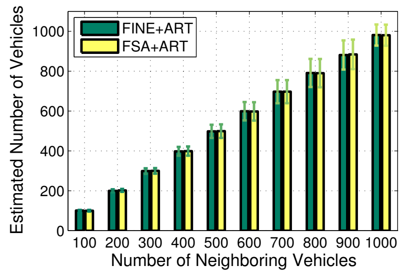


Fig. 7. Estimation accuracy comparison.

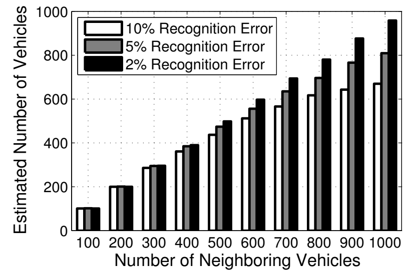


Fig. 8. Impact of recognition error.

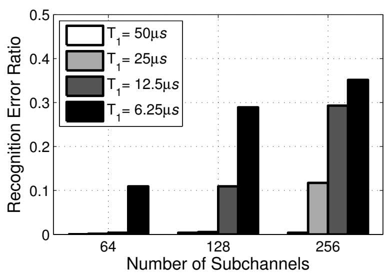


Fig. 9. Impact of the effective duration.

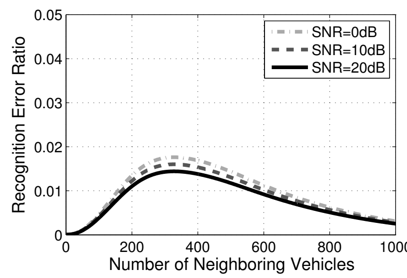


Fig. 10. Impact of SNR.

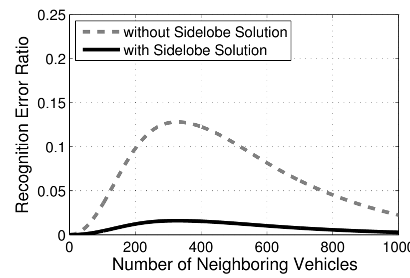


Fig. 11. Impact of sidelobe solution.

Impact of SNR. Noise universally exists in practical wireless communications. We study the noise impact on FINE through setting different SNRs. The results of SNR=20 dB, 10 dB, and 0 dB are presented in Fig. 10. The FINE system shows a high anti-noise. Even when SNR=0 dB, the recognition error ratio is still less than 2%.

Impact of sidelobe. In bit sequence recognition, we designed the solution to address the sidelobe problem. Its benefit is revealed in Fig. 11. The maximal recognition error ratio would be 13% if there is no sidelobe solution. When we apply the sidelobe solution, the maximal ratio is reduced to 2%.

VI. Conclusion

We present a novel FINE system to accelerate the density acquisition in DSRC vehicular networks. Different from current time division systems, FINE estimates the number of neighboring vehicles via frequency division, and thus exploits the bandwidth to reduce the time cost. In addition, FINE is fully distributed, which does not require any roadside infrastructure. We address several practical design issues including frequency offset, propagation delay, and sidelobe in our design. The FINE system achieves a 50 μs-level density acquisition with high accuracy, which significantly reduces the time consumption and improves the spectrum efficiency.

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