Received November 25, 2017, accepted December 17, 2017, date of publication December 20, 2017,
date of current version February 14, 2018.

Digital Object Identifier 10.1109/ACCESS.2017.2785443

Method to Improve the Positioning Accuracy of Vehicular Nodes Using IEEE 802.11p Protocol

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This work was supported in part by the National Nature Science Foundation of China under Grant 61671482, in part by the Fundamental Research Funds for the Central Universities under Grant 17CX02042A, Grant 16CX02046A, and Grant 14CX02212A, and in part by the the Nature Science Foundation of Shandong Province under Grant ZR2014FL014.

ABSTRACT Currently, vehicle incidence remains high, but the related research is mainly focused on single-vehicle collision warning, which is unable to notice the following multiple endangered vehicles in emergency. The main technical challenge of chain collision warning is accurate and seamless ranging or positioning of the neighboring multiple vehicles. Because of the non-line of sight (NLOS) environments, the traditional ultrasonic or laser method does not work. At the same time, the accuracy of global navigation satellite system (GNSS) is over 10 m, such as global positioning system (GPS) or BeiDou satellite positioning system (BDS), which is not efficient for the cooperative collision avoidance (CCA) system. Moreover, GNSS fails to operate in NLOS tunnels or downtown areas where blockage of satellite signals is frequent. Thus, in this paper, a seamless and high accuracy positioning method based-on three kind of multi-source information fusion is proposed, i.e., the high accuracy local positioning information is provided by IEEE 802.11p protocol, the dual-mode wide area differential positioning information provided by the fusion of BDS and GPS, the positioning information of dead reckoning provided by the fusion of on-board diagnostic (OBD) and micro-electro-mechanical system-inertial navigation system. In vehicle positioning system, the accurate time of arrival (TOA) estimation is very important, so in this paper, a two steps method for TOA estimation using the IEEE 802.11p short preamble is proposed. Simulations show that in both the international telecommunication union vehicular multipath channel and the additive white Gaussian noise channel, the proposed method provides better accuracy and is less time complex than some well-known methods. The estimated TOA fused with the GNSS and OBD information can be used for seamless and high accuracy positioning in the CCA system to avoid traffic accident.

INDEX TERMS vehicle positioning, ranging, timing estimation, IEEE 802.11p, cross-correlation

I. INTRODUCTION

"*Global status report on road safety* 2015" [1] by the world health organization (WHO) indicates that over 3400 people die on the world's roads every day, and the total number of road traffic deaths has plateaued at 1.25 million per year; Road traffic injuries are currently estimated to be the ninth leading cause of death across all age groups globally, and are predicted to become the seventh leading cause of death by 2030. The most effective way to mitigate traffic accident is the development and application of cooperative collision avoidance (CCA) or emergency warning message (EWM) systems that allow drivers to predict potential hazards and then take urgent steps to avoid collisions by receiving emergency warning message [2]. Studies show that about 60% roadway collisions could be avoided if the operator of the vehicle was provided warning at least one-half second prior to a collision [3].

The main technical challenge of CCA or EWM system is accurate and seamless ranging or positioning of the neighboring multiple vehicles [4]. However, currently available technologies [5], [6] like radar, camera or global positioning systems cannot meet most of the stringent requirements in terms of accuracy, reliability, update rate, and low outage probability imposed by this kind of applications [7]. Any single positioning technology has its own limitations [8]–[10]. For example, the existing Ultra Wide Band (UWB), Wireless Access in the Vehicular Environment (WAVE) or IEEE802.11p, Wi-Fi, infrared and ultrasonic radio positioning methods can achieve sub-meter level accuracy, but they are limited to a near area, so they are not suitable for vehicle positioning. Micro-electro-mechanical system -inertial navigation system (MEMS-INS) can estimate the vehicle moving parameters based on the inertial measurement unit, but due to the error accumulated with time, it alone can not achieve the high positioning accuracy for a long time. Under ideal conditions, the accuracy of global navigation satellite system (GNSS) is about 10 meters, so GPS or Beidou Positioning System (BDS) is widely used in vehicle positioning, but it is usable only in line of sight (LOS) environments. For vehicles, tunnels or downtown areas often appears, so GNSS fails to operate often, where blockage of satellite signals is frequent. Therefore, any single positioning technology has its own limitations, and can not meet the requirements of high dynamic, non-line of sight (NLOS), tunnels or downtown areas [11]–[13].

There are other sensors [14] used for vehicle detection, such as vision cameras, laser scanners, and radar and sonar sensors, but there are several disadvantages when using each sensor separately, so in [15], a novel infrastructure-based vehicle recognition system was proposed, where a laser scanner and a vision camera with time and environment synchronization are used in a multi-sensor fusion algorithm. Parker R. and Valaee S. presented a cooperative vehicle positioning estimation algorithm which uses signal-strength-based inter-vehicle-distance measurements, vehicle kinematics, and road maps to estimate the relative positions of vehicles in a cluster. Literature [16] presented a low-cost system for accurate positioning in challenging environments that uses the fusion of time-of-flight (ToF) wireless ranging and MEMS-INS. Literature [17] presented data fusion of three sensors INS, GPS and odometer for determining the correct location of a differential drive mobile robot [18]. China has developed a regional navigation satellite system called the Chinese area positioning system (CAPS). In order to improve CAPS location accuracy, in [19] UWB pseudo-satellite signals was used, which provides better performance than the GNSS system. However, none of these references are about the fusion positioning method of vehicles, so this paper presents a seamless and high accuracy positioning method for vehicle which is based-on three kind of multi-source information fusion.

Future fifth generation (5G) communication systems will provide real-time device to device (D2D) communication ability which can be used for vehicle positioning [20]–[22]. Since 5G communication system study is in the early stages, there is a unique opportunity to study the mobile wireless positioning [23]. However, to date, there are no generally accepted 5G modulation and demodulation standards. Two of the most promising candidates are: orthogonal frequency division multiple (OFDM), and filter bank multicarrier/offset quadrature amplitude modulation (FBMC/OQAM).

Reference [24] studied the key communication technology of autonomous driving in 5G: Mitigating interference in OFDM-based vehicular communications. The OFDM-based communication standard is IEEE 802.11p [25], which is an approved amendment to the IEEE 802.11a standard [26] to add wireless access in vehicular environments (WAVE) to support intelligent transport system (ITS) applications [27]. This includes several modifications based on the IEEE 802.11a standard to provide robust connections and fast setup for moving vehicles. The IEEE 802.11p PHY layer is based onOFDM. Schmidl and Cox [28] developed a well-known timing estimation method (denoted as SC) for OFDM systems which is recommended in the IEEE802.11a standard [29]. However, the timing metric in [28] forms a plateau which leads to uncertainty in the timing estimation. In [30], Minn H., Zeng M. and Bhargava V.K developed a new timing estimation method (denoted as MZB) to reduce the uncertainty due to the plateau in SC method, but this method produces a parabolic shape so there is still uncertainty in the timing estimation. In [31] a more accurate timing metric was proposed, which is immune to carrier frequency offset (CFO) because the cross-correlation is employed rather than the auto-correlation in SC and MZB methods. However, this technique has high computational complexity. According to [31], Liu et al. presented a modified timing estimation method (denoted by Liu) in [32], where the computational complexity can be halved without performance degradation compared with [31], However, if Liu timing estimation method is used in IEEE 802.11p, there will be 10 identical peaks spaced 16 samples apart in ideal environment which may lead to uncertainty too. To improve the accuracy of the time delay estimation, or the short-range estimation for the multi-source information fusion vehicle positioning method, a correlate-sum method is proposed in this paper.

II. PROPOSED MULTI-SOURCE INFORMATION FUSION VEHICLE POSITIONING MODEL

Although the IEEE 802.11p-based positioning method can achieve sub-meter accuracy, the transmission distance is limited and can not achieve wide-area positioning for vehicles; although without wirelesses signal, MEMS-INS method can achieve good accuracy without external wireless signal, there is an inevitable time cumulative error; although GNSS method can achieve wide area positioning, the accuracy is limited, and it fails to operate in NLOS environment to the sky; although ODB can get the accurate speed, it can not get the acceleration and direction, so it can not realize dead reckoning as MEMS-INS. Therefore how to fuse these multi-source signals, make the best of their advantages and overcome their shortcomings is the key scientific problem of vehicle positioning. This paper intends to solve the fusion of multi-source data to achieve high accuracy, seamless vehicle positioning. The roadmap for multi-source information fusion is shown in Fig.1.

A. SHORT RANGE HIGH ACCURACY WIRELESS LOCATION BASED ON IEEE 802.11p

The details of IEEE 802.11p-based short range high accuracy wireless positioning is shown in Section 3, whose accuracy is about sub-meter. Thus, this method can be used in the area of crossroads or other areas need high accuracy positioning.

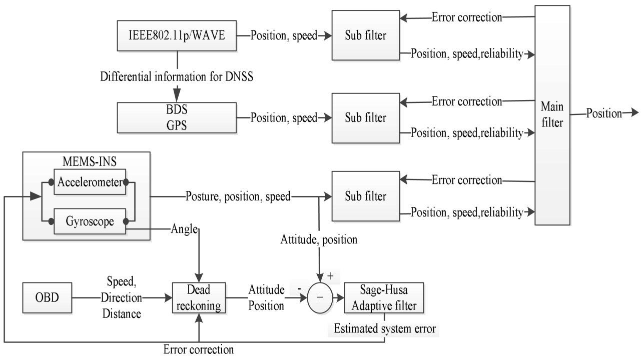

FIGURE 1. Roadmap for multi-source information fusion.

On the other hand, the GNSS differential information may be computed based on this high accuracy positioning information. With the help of vehicle-to-vehicle communication, the GNSS differential information will be transmitted to the neighbor vehicles to realize differential positioning and eliminate errors caused by ionosphere and atmosphere. The details of how differential positioning of GNSS works is shown in Fig. 2.

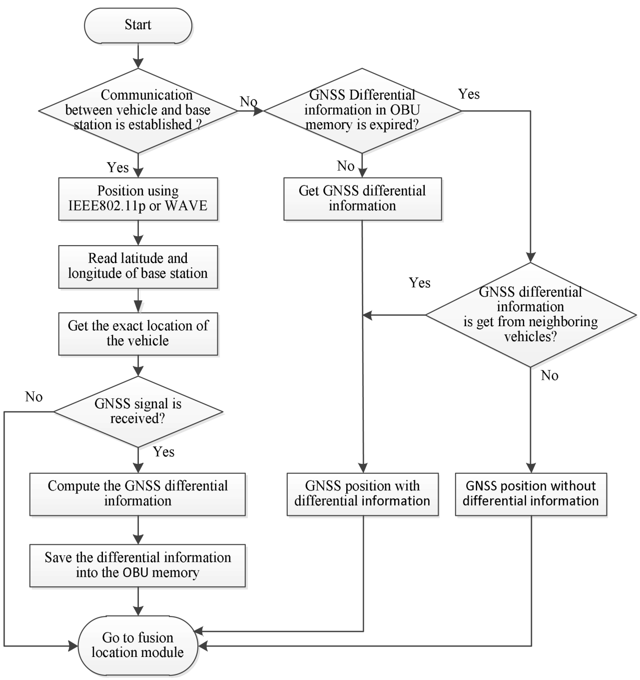

FIGURE 2. Workflow of GNSS differential information.

B. BDS + GPS DUAL-MODE AND DIFFERENTIAL LOCATION

In order to further improve the accuracy of GNSS positioning, particle filter is used to fuse BDS, GPS and IEEE 802.11p and then dual-mode and differential location is realized.

C. SPEED, STEERING WHEEL ANGLE AND OTHER INFORMATION OF OBD

OBD standard is used for vehicle diagnostics. During the 1970s and early 1980s manufacturers started using electronic means to control engine functions and diagnose engine problems. OBD-II is a new standard introduced in the mid-1990s, provides almost complete engine control and also monitors parts of the chassis, body and accessory devices, as well as the diagnostic control network of the car.

Speed and steering wheel angle from OBD bus will be integrated with MEMS-INS to improve the accuracy of inertial navigation.

D. MEMS-INS AND OBD FUSION TO ACHIEVE DEAD RECKONING

MEMS-INS is a quadratic integration based on the acceleration of the dead reckoning system, which can measure the acceleration, angular velocity, attitude and other information. In this paper, the gyroscope in the MEMS-INS system and the vehicle speed and steering wheel angle from OBD are used to compensate the MEMS-INS system by Sage-husa adaptive filtering, so as to improve the positioning accuracy.

When vehicle is moving, it will be affected by external environmental factors, so there exists large noise fluctuations in MEMS-INS and OBD measurement. The standard Kalman filter is no longer applicable, because it will lead to filtering divergence, so Sage-Husa adaptive filtering is used which is relatively robust to noise changes.

E. KALMAN FILTER TO ACHIEVE MULTI-SOURCE INFORMATION FUSION VEHICLE POSITIONING

The way of feedback correction is introduced as shown in Fig.1 to achieve the complete, accurate and continuous positioning of the vehicle. The simplified kalman filter is used to fuse the IEEE802.11p accurate positioning information, MEMS-INS + OBD dead reckoning positioning information and GPS + BDS satellite differential positioning information. Based on the idea of "first dispersed, then centralized post-processing", the filtering results of the three subsystems are uniformly calibrated on the spatiotemporal basis, and then the global optimal estimation is obtained by the fusion of the main filter, and the positioning accuracy is improved with lower complexity, as shown in Fig.1

III. WIRELESS ACCESS IN VEHICULAR ENVIRONMENTS

IEEE 802.11p [25] protocol is an amendment to the IEEE 802.11a standard to add wireless access ability in vehicular environments, e.g., at a high speed of up to 200 km/h, long range of range of 1000 m and multipath fading. A major difference in the PHY layers between IEEE 802.11p and 802.11a standards is the larger symbol duration. This results in a longer guard interval (GI) or cyclic prefix (CP) which provides tolerance to greater delay spreads and inter symbol interference (ISI) due to very high vehicular speeds. Thus, IEEE 802.11p can deal with the severe Doppler frequency shifts, rapidly changing multipath conditions, fast connection setup and reliable data exchange.

A. MODULATION IN IEEE 802.11p

OFDM is a frequency-division multiplexing (FDM) scheme used as a digital multi-carrier modulation method to mitigate the effects of fading. A large number of closely spaced orthogonal sub-carrier signals are used to carry data on several parallel data streams or channels. In the IEEE 802.11p standard, the inverse fast Fourier transform (IFFT) is used to generate the OFDM symbols. Each data symbol has 64 orthogonal subcarriers, 48 for data transmission, 4 for pilot signals, and 12 null subcarriers. The duration of each data symbol is $T_{\text{FFT}} = 6.4\ \mu$s, which is twice of IEEE 802.11a. The guard interval has a duration of 1.6 us.

In the IEEE 802.11p standard, the subcarrier channel bandwidth is 10 MHz and the carrier frequency is 5.9 GHz. Therefore, each subcarrier has a frequency spacing of $\Delta_F = 10/64 = 0.15625$ MHz. This is half of the channel bandwidth (or double the symbol duration), in the 802.11a standard.

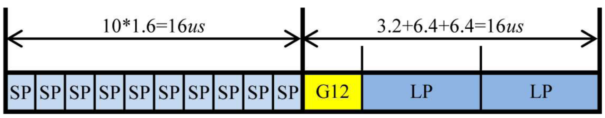

FIGURE 3. The IEEE 802.11p PHY preamble structure [25].

B. PREAMBLE IN IEEE 802.11p

The IEEE 802.11p PHY frame structure has a preamble which contains 10 short preamble (SP) symbols and 2 long preamble (LP) symbols [25], as shown in Fig. 3. Each short preamble symbol consists of 12 nonzero subcarriers located at positions ± (4, 8, 12, 16, 20, and 24) which is shown as

$$S_{-26,26} = \sqrt{13/6}\{0, 0, +1+j, 0, 0, 0, -1-j, 0, 0, 0, +1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, +1+j, 0, 0, 0, 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, +1+j, 0, 0, 0, +1+j, 0, 0, 0, +1+j, 0, 0, 0, +1 +j, 0, 0\}.$$

The corresponding OFDM symbol is given as Equation (1),

$$s(t) = w(t) \sum_{k=-\frac{N}{2}}^{k=\frac{N}{2}} S_k \exp(j2\pi k \Delta_F t), \tag{1}$$

where $N = 52$ and $w(t)$ is the window function of the short preamble symbol. The factor $\sqrt{13/6}$ is used to normalize the power of the OFDM symbol as it uses only 12 subcarriers. S has nonzero values only for indices those are a multiple of 4, so the short preamble symbol duration is $T_{\text{FFT}}/4 = 1.6\ \mu$s. Thus, totally, the ten short preamble symbols have a duration of 16 μs.

Each long preamble symbol contains 12 null subcarriers and 52 nonzero subcarriers with a duration of 6.4 μs. Between the short preamble and the long preamble there are two guard interval (GI) symbols with a duration of 1.6 μs. Thus, the preamble of IEEE 802.11p has a duration of $10 \times 1.6\ \mu\text{s} + 2 \times 1.6\ \mu\text{s} + 2 \times 6.4\ \mu\text{s} = 32\ \mu$s.

The preamble is used for timing, ranging, frequency synchronization and channel estimation. The short preamble is typically used for coarse estimation while the long preamble is used for fine estimation. Coarse estimation is critical to the success of the subsequent fine estimation. Thus, a correlate-sum method based on the short preamble is proposed in this article to improve the coarse time estimation which can be used for the range or location estimation in Section 2.

C. CHANNEL MODEL FOR VEHICLE COMMUNICATION

To date, there is no generally accepted channel model [33] for IEEE 802.11p in vehicular communication. However, for a long time, the additive white Gaussian noise (AWGN) channel model has been used as a baseline for wireless communication systems, while the Rician model for LOS multipath channels and the Rayleigh model for NLOS multipath channels are commonly used. Nevertheless, these three models can not simulate the vehicle communication channel properly, because in an actual application environment, the sent IEEE 802.11p signals may be scattered, reflected, or diffracted by surrounding objects or vehicles, which may cause many different paths and channel attenuation. The international telecommunication union (ITU) has published a well-known channel model for vehicular test environment, which can be used to simulate the different path delays and channel gains. There are two different delay spread models specified in ITU documents, that is, low delay spread (A), and medium delay spread (B) and the former channel has six taps with power gains 0 dB, −1 dB, −9 dB, −10 dB, −15 dB, and −20 dB and relative delays 0 ns, 310 ns, 710 ns, 1090 ns, 1730 ns, and 2510 ns.. AWGN and Low delay spread of ITU (denoted as ITU-A) are used in this article for simulations.

The received OFDM signal in the time-domain is affected by phase noise $\Phi(t)$ and AWGN $w(t)$, so it can be expressed as

$$r(t) = x(t)\, exp\,(j\Phi(t)) + w(t). \tag{2}$$

IV. TIMING ESTIMATION METHODS

In the multi-source information fusion vehicle positioning model, among the methods of short range high accuracy wireless location based on IEEE 802.11p, BDS+GPS dual-mode and differential location, speed, steering wheel angle and other information from OBD, MEMS-INS and OBD fusion to achieve dead reckoning, the short range high accuracy wireless location based on IEEE802.11p is the most immature technology. Furthermore, the range or timing estimation is critical to the success of the subsequent location estimation, so this paper focuses on the timing estimation based on IEEE802.11p. Obviously, using longer preamble samples may perform better than using shorter preamble samples, yet it requires more computational load. Considering the fast moving speed, the vehicle requires rapid response, so this paper try to use 10 short preamble symbols to realize time estimation between multiple vehicles or vehicles and base station. Thus, using this estimated time offset the ranges between different vehicles may be calculated by multiplying the speed of electromagnetic wave. And then the inaccurate time offset may cause inaccurate vehicle ranging estimation.

A. EXISTING METHODS

If the purpose of OFDM system is just communication, the start point of ranging packet does not need estimated exactly and sometimes error is allowed if the whole channel is covered by the cyclic prefix. However, if the OFDM system is used for ranging, the offset estimation or the start point of ranging packet is very important, and more accurate time estimation is required, because the speed of electromagnetic wave is very fast. Of course, if all the short preamble samples are used in the ranging process, the better accuracy may be estimated than less short preamble samples are used, however more samples requires more computational load. To reduce the complexity and improve the time estimate result, several well-known techniques have been developed for OFDM-based coarse time estimation.

1) SC METHOD

Schmidl and Cox developed a well-known timing estimation method (denoted as SC) [28] based on OFDM, which is recommended in the IEEE802.11a standard. In the SC method, the preamble pattern in the time-domain is [GI A A]3, where GI is the guard interval symbols, so that after the GI, the symbol in the first half is the same as that in the second half. The GI is the same as the last part of symbol. The SC method uses the following timing metric

$$M\left(d\right)=\frac{|P(d)|^2}{R^2(d)}, \tag{3}$$

where $P(d)$ is the auto-correlation of the received samples and $R(d)$ is the received signal energy, given by

$$P\left(d\right)=\sum\nolimits_{m=00}^{L-1} r^*\left(d+m\right)\cdot r\left(d+m+L\right), \tag{4}$$

$$R\left(d\right)=\sum\nolimits_{m=00}^{L-1} |r(d+m+L)|^2, \tag{5}$$

where r is the received signal, L is the length of A, d is the time index corresponding to the received samples and $*$ denotes complex conjugate. Thus there are $N=2L$ training samples.

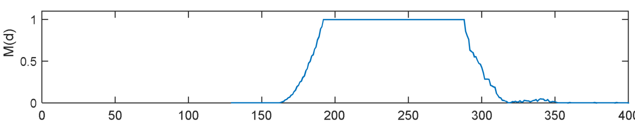

FIGURE 4. Timing metric for the SC-32 method in an ideal environment.

Fig. 4 presents timing metric $M(d)$ with $L=32$ (denoted as SC-32) for an ideal signal channel without noise and multi-path, and the time delay is 191 samples. For the IEEE802.11p physical layer structure as shown in Fig.3, there are 160 samples for the short preamble, so the first $160-2L=N_g=96$ samples should be considered as the guard interval symbols GI. Fig. 4 shows that the timing metric forms a plateau whose length equal to the length of the GI ($N_g=96$ samples) minus the length of the channel delay spread. In an AWGN channel, there is no delay spread, so the length of the plateau is 96 samples.

Obviously, in real vehicle communication environment the signal may be affected by some noise, so the plateau of timing metric with the SC method in Fig. 4 may results in uncertainty in the timing estimation.

As the length of the short preambles is 160 samples, if interval symbols GI is reduced to 0 samples ($N_g=0$), there will be no plateau, and now the value of L should be 80, that is, $N_g=160-2L=160-80\times 2=0$ samples. Now, this method for $L=80$ is denoted as SC-80 compared with $L=32$ (SC-32). The SC-80 performance is presented in Fig.5 for an ideal environment with a time delay of 191 samples, and this indicates that there is no plateau, but the number of values required for the correlation operation is over twice that of SC-32 method, so the computational complexity is higher.

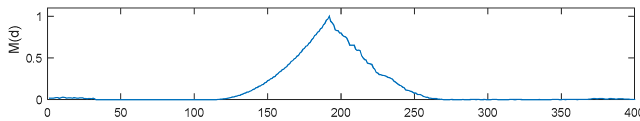

FIGURE 5. Timing metric for the SC-80 method in an ideal environment.

2) MZB METHOD

In order to overcome the uncertainty leaded by the plateau in SC method, Minn, Zeng and Bhargava proposed a new timing metric $M_1(d)$ in [30] (denoted as MZB), which is averaged over a window of length N_g+1 samples and is given by

$$M_1\left(d\right)=\frac{1}{N_g+1}\sum_{k=-N_g}^{00} M(d+k), \tag{6}$$

where N_g is the length of the interval symbols GI, $M(d)$ is the same as Equation (3) in SC method. The $P(d)$ in Equation (3) is the same as (4), while the $R(d)$ in (3) is given by

$$R\left(d\right)=\frac{1}{2}\sum_{m=00}^{N-1}|r(d+m)|^2, \tag{7}$$

where N is the number of training samples and $N=2L$. Fig. 6 shows the timing metric $M_1(d)$ for the MZB method with $N_g=96$, $N=64$, and $L=32$ in an ideal channel with a time delay of 191 samples. Compared to Fig. 4, there is no plateau, but the peak is parabolic and is not very sharp, so there is still uncertainty in the timing estimation.

3) LIU METHOD

Both SC method and MZB method are auto-correlation based methods, which are always immune to CFO, but their timing

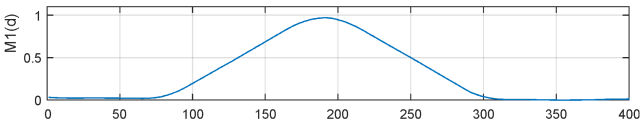

FIGURE 6. Timing metric M1(d) for the MZB method in ideal environment.

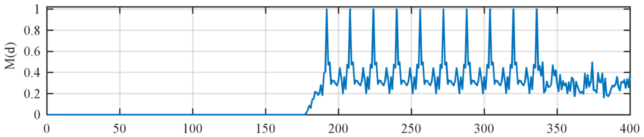

FIGURE 7. M(d) for the Liu method in ideal environment.

metrics are not sharp enough. Cross-correlation based methods have impulse-like timing metrics, but their performance is sensitive to CFO. In [32], Yun *et al.* proposed an auto-correlation and cross-correlation based timing method which has both advantages of the first two approaches. Fig. 7 shows the timing metric $M(d)$ for the Liu method in an ideal channel with a time delay of 191 samples. Because of the 10 identical short preamble symbols in IEEE 802.11p, there will be 10 same peaks spaced 16 samples apart in ideal environment.

In order to improve the timing estimation error, a modified method (denoted as Liu) is proposed base-on the Liu method, that is, a threshold (= 0.7× maximum peak) is used to choose the peaks group. If the number of peaks exceeding the threshold and spaced 16 apart is not less than 5, thus the maximum number of group is deemed as the first arrival signal. If none of peaks group is found, the maximum peak is deemed as the first arrival signal.

B. PROPOSED METHOD

The SC and MZB methods both use the auto-correlation of the received signal. In the proposed method, the cross-correlation between the received signal and the known short preamble symbol given in (1) is employed. The timing metric $M(d)$ is the same with the SC method in Equation (3), but P(d) and R(d) are defined as

$$P(d) = \sum_{m=00}^{T-1} r(d+m) \cdot t^{*}(1+m), \quad (8)$$

$$R(d) = \sum_{m=00}^{T-1} |r(d+m)|^{2}, \quad (9)$$

where $t(1+\mathrm{m})$ is a short preamble symbol, i.e. the reference template, with length $T = 16$.

Shown in Fig. 8, the timing metrics $M(d)$ are considered with a time delay of 191 samples and SNRs $E_b/N_0 = 0$ dB, and 30 dB respectively. In these cases, the first peak should be located at the $L_{first} = 191 + 16/2 + 1 = 200^{th}$ signal sample. Fig. 8 shows that when $E_b/N_0 = 30$ dB, all the 9 peaks are very sharp, and the first maximum signal appears at the 200^{th} sample, as expected, so the first maximum signal should be considered as the timing offset estimated. However as Eb/N0 decreases, the 9 peaks will become more and more different, and sometime the first maximum signal may not be the exact timing offset to be estimated. For example, when

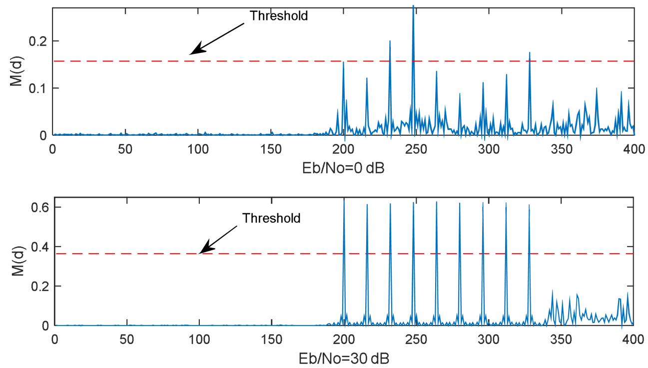

FIGURE 8. M(d) for the correlate-sum method with Eb/N0 = 0 dB and 30 dB.

$E_b/N_0 = 0$ dB, the strength of the 9 peaks are not the same, some are very low, and some are very high, so the timing offset cannot be estimated accurately using the maximum signal. As an example, consider a threshold

$$Threshold = 0.6 \times \text{maximum}, \quad (10)$$

there are only 2 peaks that exceed the threshold, and the first signal exceed the threshold is not at the 200^{th} sample. If the threshold is set to $0.5\times$ maximum, it can catch the correct sample at 200^{th}. Therefore, when E_b/N_0 is very low, the noise can affect the number of peaks that exceed the threshold, so it is difficult to determine the optimal threshold value, that is to say it is very hard to determine which one is the first arrived signal.

As shown in Fig. 8, in an ideal environment, $M(d)$ will have 9 peak signals, and the space between each of them is 16 samples. Thus, the sums of these 9 values of $M(d)$ spaced $T = 16$ samples apart is

$$G(t) = \sum_{d=1}^{9} M(t + (d-1) * T), \quad (11)$$

and the time delay ($\hat{D}_{est}$) estimate is obtained as

$$\hat{D}_{est} = \text{argmax}(G(t)) - \left(\frac{T}{2} + 1\right). \quad (12)$$

Now, $G(t)$ in an ideal environment is shown in Fig. 9 with a time delay of 191 samples. Thus, there are 17 peaks located symmetrically around the maximum peak at the 191+ 16/2+ $1 = 200^{th}$ sample. In this case, the maximum signal is just the time offset, and this method is denoted as Proposed-1.

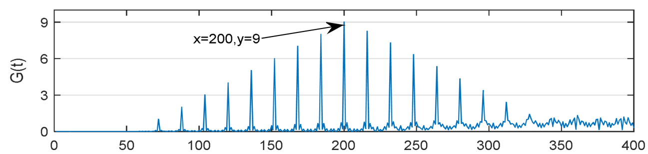

FIGURE 9. G(t) in an ideal environment.

For example, $G(t)$ with $E_b/N_0 = -5$ dB and a time delay of 191 samples, shown in Fig.10, the 9 peaks of $M(d)$ are difficult to identify, but the maximum of $G(t)$ is very clear,

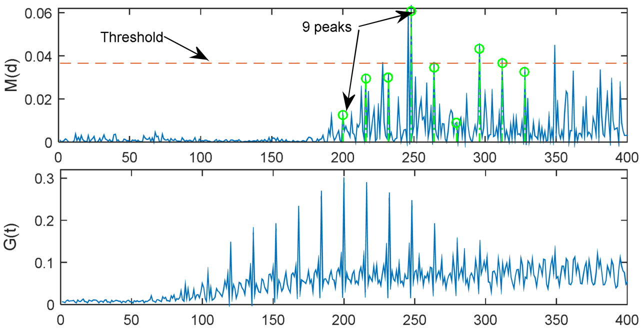

FIGURE 10. M(d) and G(t) with Eb/N0 = −5 dB.

and appears at sample 200, so the time delay $\hat{D}_{est}$ is correct and Proposed-1 method can perform well.

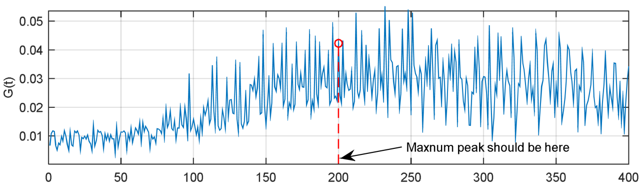

FIGURE 11. G(t) with Eb/N0 = −10 dB.

However, as E_b/N_0 decreases more and more, the first arrived signal will become more difficult to be identified by the maximum signal. As shown in Fig. 11, when $E_b/N_0 = -10$ dB, the maximum of $G(t)$ is located at the 232th sample, so it is very hard to locate in the proper sample index (200th). That is to say, the maximum of $G(t)$ is not the first arrived signal.

In [34] we have proposed a correlation-summing-skewness analysis method, which uses a dynamic threshold based on the skewness analysis of values of $G(t)$, where a polynomial with degree 3 was fitted to the best threshold ξ for each value of skewness by using the method of least-squares. The least-squares fitting result is shown in Equation (13)

$$\xi = 0.016085S^3 - 0.088866S^2 + 0.17697S + 0.82368. \tag{13}$$

Thus a specific skewness value is corresponding to a specific dynamic threshold. However, in this method, the fitting result is closely related to the specific prior vehicle channel, which means different vehicle channel needs different fitting result. At the same time, because of the compute of skewness, the computational complexity is high.

Therefore, in this paper we proposed another threshold to determine the proper first arrived signal, which is the proper timing offset. In idea environment, shown in Fig.9, the maximum peak is 5.4 and the second maximum value is about 5.2, so the threshold is selected as

$$Threshold = 5.2/5.4 \times \text{maximum}, \tag{14}$$

which is denoted as Proposed-2.

V. PERFORMANCE RESULTS AND DISCUSSION

In this section, the performance and computational complexity of the proposed methods are examined in AWGN channels and ITU-A vehicular channel. The used performance metrics are mean absolute errors (MAE) and $P(x)$,

$$MAE = \frac{1}{K}\sum_{n=1}^{K}\left|D_n - \widehat{D}_n\right|, \tag{15}$$

where D_n is the sample index corresponding to the n^{th} actual time delay, $\widehat{D}_n$ is the sample index corresponding to the n^{th} estimated time delay, and $K = 2000$ is the number of simulation iterations;

$$P(x) = \frac{1}{K} CountIF(\left|\hat{D}_n - D_n\right| \le x), \tag{16}$$

where $CountIF$ is the number of iterations that the estimated sample index error is not larger than a given value x. For example, $P(0)$ is the average number of iterations that the estimated sample index error is 0. At the same time, Doppler shift is given by

$$F_d = v \times f_c/c, \tag{17}$$

where v is the relative moving speed which is typically set to $v = 100$ km/h, $f_c = 5.9$ GHz is the center frequency of the transmitted signal, and c is the speed of electromagnetic wave. Carrier frequency offset is unavoidable in practical vehicle environment and hence it is considered in the following simulation.

In the remainder of this paper, six methods are simulated and compared, that is, the proposed two correlate-sum methods Proposed-1 and Proposed-2 as well as the other 4 existing methods: Liu method, MZB method, SC-80 method and SC-32 method.

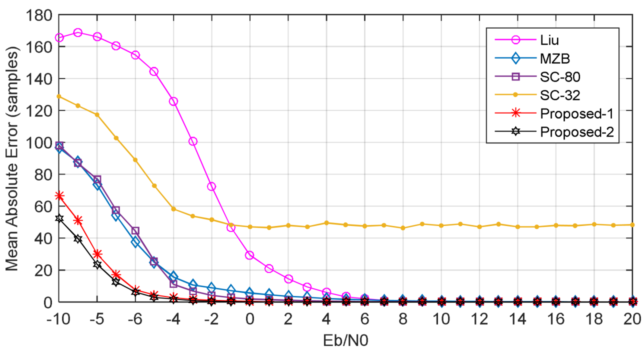

FIGURE 12. MAE of different methods.

A. AWGN CHANNEL PERFORMANCE

The performance in AWGN channel was simulated for different E_b/N_0 from −10 dB to 30 dB. Figure 12 presents MAE for the six methods. These results show that the Proposed-2 method provides the best performance, and then the Proposed-1 method particularly at low E_b/N_0 values less than −4 dB. For example, when $E_b/N_0 = -10$ dB, the MAE of the Proposed-2 method is 52 samples and 66 for Proposed-1 method, while MAE are only 166 samples for the Liu method, 129 samples for the SC-32 method, 98 samples for the SC-80 method and 97 samples for the MZB method. The MAE of the SC-80 method is almost the same as the MZB method among all the different values of E_b/N_0.

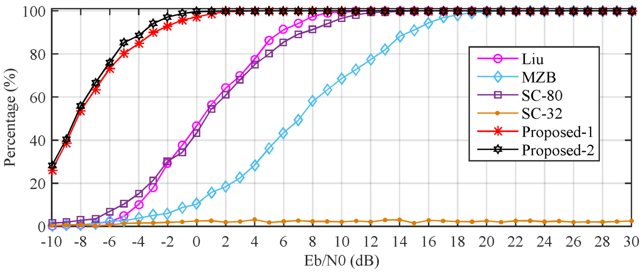

FIGURE 13. **Probability that the timing error is zero in an AWGN channel.**

Fig. 13 presents $P(0)$ for the 6 methods. These results show that the proposed two approaches provide the best performance, but the Proposed-2 method is better than the Proposed-1 method, particularly at low to medium SNRs. For example, when $E_b/N_0 = -5$ dB, the Proposed-2 method provides the correct percentage result is 85.4% and 80.3 for Proposed-1 method, while the other methods are only 10.45%, 4.85%, 2.65%, and 1.35% for the methods of SC-80, Liu, MZB, SC-32 respectively. For $E_b/N_0 = 0$ dB, the percentage of the Proposed-2 method is about 100%, and Proposed-1 method is over 97%, whereas for the same percentage the Liu method E_b/N_0 should be greater than 8 dB, with SC-80 greater than 11 dB, and with MZB greater than 18 dB. For the SC-32 method, $P(0)$ is never greater than 3.2%.

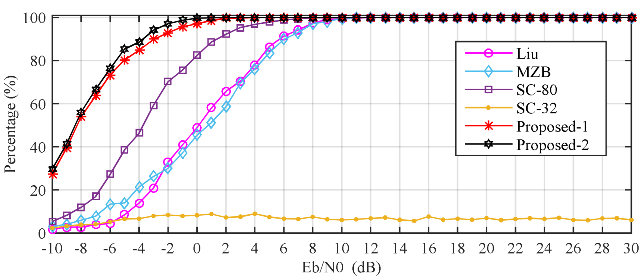

FIGURE 14. **Probability that the timing error is less than 3% in an AWGN channel.**

Fig. 14 presents $P(3)$ for the 6 methods. This shows that the proposed method again has the best performance. Further, the results for the proposed method in Figs. 13 and 14 are almost the same, but differ significantly for the SC-80 and MZB methods. When $E_b/N_0 = 0$ dB, $P(3)$ with the proposed-2 method is about 100% and 97% of proposed-1 method, but for the same percentage with SC-80, E_b/N_0 should be greater than 5 dB, and with the Liu and MZB methods E_b/N_0 should exceed 9 dB. For the SC-32 method, $P(3)$ is never greater than 10%. The results in Figs. 13 and 14 indicate that the performance with the SC-32 method is very poor, and so this technique is not suitable for vehicular ranging.

B. RICIAN CHANNEL WITH ITU-A VEHICULAR CHANNEL PARAMETERS

The Rician channel with ITU-A vehicular channel parameters were simulated for values of E_b/N_0 from -10 dB to 30 dB. There are 6 paths, with the gains and delays given in Section 3.

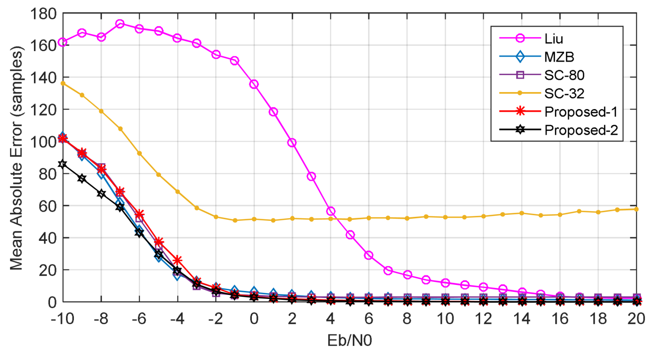

FIGURE 15. **MAE of different methods.**

Figure 15 presents MAE for the six methods. Just as shown in Fig 12, the Proposed-2 method is the best, and then the Proposed-1 method. For example, when $E_b/N_0 = -10$ dB, the MAE of the Proposed-2 method is 85.8 samples, while MAE are only 101.5 for Proposed-1 method, 101.6 for SC-80 method, 102.6 samples for the MZB method, 136.2 samples for the SC-32 method, and 162.1 samples for the Liu method. The MAE of the Proposed-1 method, SC-80 method and the MZB method are almost the same among all the different values of E_b/N_0.

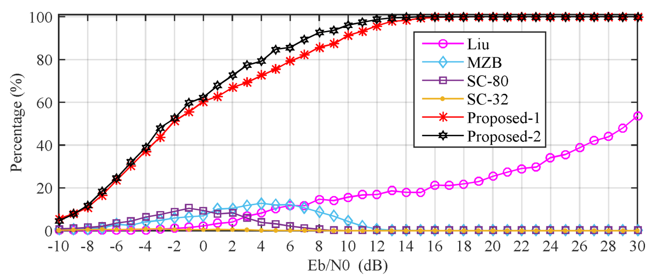

FIGURE 16. **Probability that the timing error is zero in the ITU-A channel.**

Fig. 16 presents $P(0)$ for the five methods. This shows that only the proposed two methods can provide adequate performance, and then the Liu method. For the other three methods, $P(0)$ increases at first as E_b/N_0 increases, and then decreases to a values near 0. The reason for the behavior is the multipath of ITU-A channel.

Fig. 17 presents $P(3)$ for the 6 methods in the ITU-A multipath channel. This shows that when E_b/N_0 is sufficiently large, the proposed two methods, Liu et al., MZB and SC-80 methods can attain $P(3) = 100\%$. Conversely, the SC-32 method has poor performance for all SNR values.

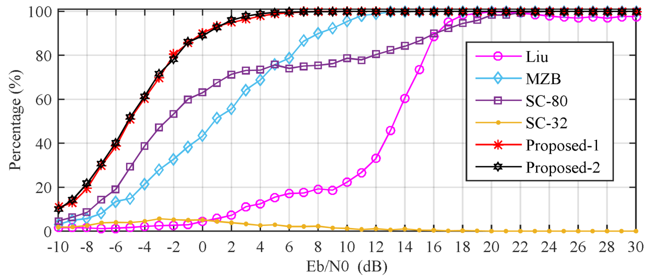

FIGURE 17. Probability that the timing error is less than 3% in the ITU-A channel.

When E_b/N_0 is small, the proposed two methods have the best performance, followed by the SC-80, MZB, Liu, and SC-32 methods.

VI. CONCLUSION

In this paper, a low complexity, high accuracy ranging estimation method based on correlate and sum of the IEEE802.11p short preamble has been developed for vehicular positioning. At the same time, two thresholds are proposed, denoted as Proposed-1 and Proposed-2. The mean absolute error of the proposed methods are shown to be better than several well-known methods such as SC-80, MZB, Liu methods. In addition, the percentage of correct estimation shows that the proposed methods are more robust than other methods especially in high noise environments. At the same time, a seamless and high accuracy positioning method based-on short-range positioning, GNSS, and non-radio positioning information fusion is proposed.

The proposed correlate and sum of the OFDM short preamble positioning approach can also be used in other future 5G OFDM wireless communications systems with repeated preamble symbols.

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