Cooperative Wideband Spectrum Detection Based on Maximum Likelihood Ratio for CR Enhanced VANET

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***Abstract*—**Cognitive radio (CR) enhanced vehicular ad hoc network (CR-VANET) is a special VANET that each vehicle could explore local spectrum gap and reduce data congestion by mitigating interference by dynamically accessing spectrum holes. One of the most important challenges for CR-VANET is to identify the presence of primary users (PU) over wideband spectrum at a particular time and specific geographic location. In this paper, maximum likelihood ratio (MLR) detection is proposed as an effective scheme for wideband spectrum detection in orthogonal frequency division multiplexing (OFDM) based overlay CR-VANET. OR fusion rule with square-law selection (SLS) is implemented at roadside to make global detection decision by means of the combination of each vehicle's local sensing results. Hence, cooperative wideband spectrum detection is implemented in dynamic topology CR-VANET to enhance the reliability of spectrum detection. Specifically, robust cooperative sensing technique is investigated with the consideration of sensing channel SNR, reporting channel fading, as well as inter-user error rate, with the purpose of exploiting diversity in multi-vehicle cooperative sensing scenario. Limitations of cooperative wideband spectrum sensing are presented with MLR detection in space-time block code (STBC) and time division multiple access (TDMA) protocols for practical consideration. Simulation results are presented to confirm our theoretical derivations. It is revealed that, compared with conventional energy detection (ED), cooperative wideband spectrum detection with MLR has adaptive detection thresholds. Moreover, robust cooperative sensing by roadside SLS OR rule and its limitations are also performed with receiver operation characteristics (ROC). It is proven that, MLR detection is available in robust cooperative sensing with dynamic threshold variations for CR-VANET practical applications.

***Index Terms*—**CR enhanced VANET (CR-VANET), maximum likelihood ratio (MLR), square-law selection (SLS), cooperative wideband spectrum detection, Inter-user error rate, receiver operation characteristics (ROC)

I. Introduction

Cognitive radio (CR) enhanced vehicular communications significantly reduce data congestion by mitigating interference and dynamically accessing to spectrum holes, which enables vehicles to opportunistically use the idle licensed spectrum in primary system, in order to improve the throughput and combat the interference among neighborhood vehicles. The dedicated short range communications (DSRC) band has been allocated in the USA at 5.9GHz for vehicle-to-roadside (V2R) and vehicle-to-vehicle (V2V) communications, while IEEE 802.11p working group has developed the enhancements of 802.11 standards to support intelligent transportation systems (ITS), vehicular communications and information applications [1]. Different from conventional point-to-point and point-to-multipoint communication paradigm [2], [3], vehicular communication is characterized by highly dynamic topology, predictable movement, and quickly varying network scale. For vehicular communication applications, response time and reliability are the major characteristics requirements [2], [3]. In addition, DSRC spectrum is envisioned to become increasing congested, especially when the density of vehicles becomes higher. Furthermore, in the extreme case, such as traffic jams or emergency incidences, the DSRC radio would be oversaturated, which results in the deterioration of communication quality-of-service (QoS) in vehicular ad hoc network (VANET).

Cognitive radio (CR) has been proposed to efficiently exploit the overall spectrum by allowing secondary users (SUs) to opportunistically access the dedicated spectrum that has been assigned to primary users (PUs). SUs are allowed to transmit and receive data over portions of spectrum when PUs are inactive [4], [5]. For V2V/V2R communications, dynamic spectrum sharing between SU vehicles and the licensed PUs can potentially improve communication efficiency as well as spectrum utilization. Cognitive radio enhanced vehicle communications allows vehicles to opportunistically use the idle licensed spectrum in the primary systems (*i.e.*, TV bands) to improve the throughput and mitigate the interference among the neighborhood vehicles. CR enhanced VANET (CR-VANET) is a special VANET that each vehicle could explore local spectrum gap and a central controller (roadside) coordinates the spectrum for cognitive vehicles to realize dynamic spectrum access (DSA), which is suitable to operate in CR-VANET scenario. To achieve the "invisibility" requirement, SU vehicles needs to sense primary spectrum holes via cooperation approach. This

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involves some sort of spectral analysis and sensing coordination [6], [7]. In general, when the nature of PU signal (TV band) is unavailable to SU vehicle, spectral analysis mainly relies on energy detection (ED), with higher requirements for sensitivity and frequency resolution [5], [8].

Different from conventional ED local detection, this paper implement maximum likelihood ratio detection (MLR) approach at SU vehicle. MLR belongs to the generalized likelihood ratio test (GLRT) paradigm [9]. It has some unique features, such as adaptive detection threshold that can be changed with the received signal-to-noise ratio (SNR). In addition, due to each SU vehicle and roadside are distributed in the large geographic area, sensing (from PU TV band to SU vehicles) and reporting (from SU vehicles to roadside) channels' fading should be considered simultaneously (usually those channels' fading are time-frequency selective (double selective)) [7]. Moreover, with fast and agile sensing ability, SU vehicles must detect the spectrum holes opportunistically to improve the spectrum occupancy utilization [7]. However, once PU returns to access the licensed band, SU vehicles must immediately stop operating at the licensed band and shift to other available spectrum holes adaptively, which is denoted as CR overlay spectrum sharing paradigm [9, 10]. This fast switching can guarantee the minimum interference to PU normal communication. Hence, robust cooperative wideband sensing with MLR detection is investigated to cope with the problem of SU vehicle discontinuous data transmission. Meanwhile, this method also maintains QoS of PU communication, which serves as the motivation of this paper.

The main contribution of this paper is described as follows. Firstly, we investigate MLR scheme that is implemented by each vehicle for local spectrum detection. OR fusion rule with square-law selection (SLS) diversity scheme is applied at CR-VANET roadside. Then, robust cooperative sensing strategy is investigated with the consideration of sensing/reporting channels' fading and inter-user error rates. Global detection probability and the corresponding ROC performances are derived in cooperative wideband spectrum detection scenario. Finally, we present numerical results and analyze ROC performance with different sensing/reporting SNR and inter-user error rates to confirm our theoretical derivations.

The reminder of this paper is organized as follows. In Section II, we present system model of CR-VANET. Vehicle MLR spectrum detection and roadside OR fusion process with SLS are given in Section III. In this section, robust cooperative sensing with MLR detection is also derived, which is compared with traditional ED detection algorithm for different sensing/reporting SNR and inter-vehicle channel error rates. Section IV gives numerical results and analysis of MLR global detection performance, BER performance with reporting channel SNR, as well as ROC performance of robust cooperative detection. Finally, we provide some concluding remarks in Section V.

II. SYETEM MODEL OF CR ENHANCED VANET

This section describes system model of CR-VANET cooperative wideband spectrum detection, which takes the sensing/reporting channel fading and inter-user error rates into considerations.

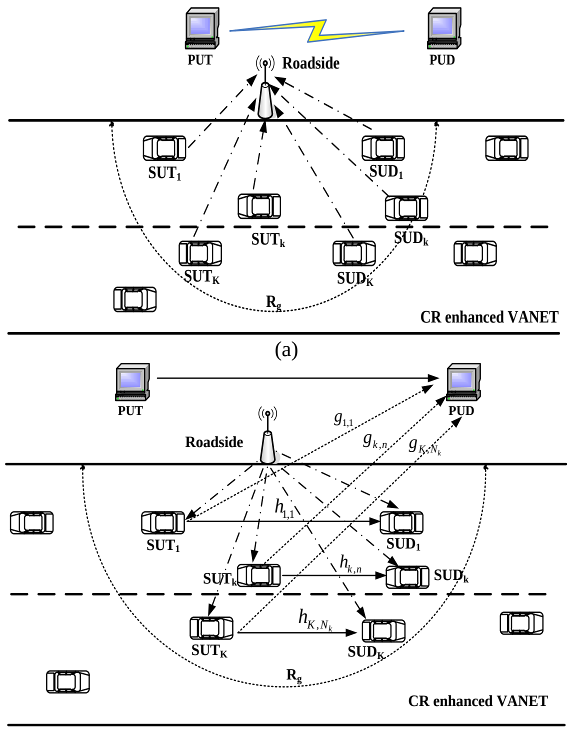

Fig. 1. System model of CR enhanced VANET. (a) Cooperative wideband spectrum sensing based on local MLR detection. (b) Roadside disseminates decision results and SU data transmission.

As depicted in Fig. 1 (a)-(b), we consider CR enhanced VANET with overlay communication paradigm, that is, multiple secondary vehicles access the licensed spectrum during PU transceivers are inactive. In the primary licensed TV band, PU transmitter (PUT) sends data to a PU destination (PUD) over the licensed ultra high frequency (UHF) band, often ranges at 400-800MHz. The licensed PUs in UHF bands usually are DTV users [6], [7]. Meanwhile, CR-VANET consists of cognitive vehicles that are equipped with CR devices. A cognitive vehicle can transmit its data to its corresponding cognitive receiver vehicle opportunistically over the same UHF TV band. Multiple CR vehicles cooperate to sense the available spectrum in order to improve the global detection performance [6], [7], [10].

To be specific, the wideband cooperative sensing process can be divided into two phases. Firstly, all cognitive vehicles arrive within the range of roadside R_g, and they detect the idle licensed TV band channel via MLR spectral detection scheme (denoted as the sensing phase). After this phase, these vehicles send their local results to the roadside, which is indicated as the reporting phase. Then, the central controller (roadside) implements a special data fusion rule to make global decision. If the licensed channels are available for cognitive vehicles to access, the roadside will disseminate the decision results in CR-VANET. Multiple cognitive vehicles will utilize these idle channels for data transmission to realize overlay spectrum sharing. Otherwise, they will continue to detect the licensed band and to seek available spectrum holes for opportunistic transmission [11], [12].

We denote the channel between SU transmitter (SUT) and PUD as interfering channel, while the one between SUT and its corresponding SU destination (SUD) as cognitive channel. We assume a total of K pairs of cognitive vehicles in CR-VANET that share N subcarriers in a fixed time with total bandwidth B. Due to channel gains are time-variant in CR-VANET, we consider the average interference and cognitive channel gains for the k-th cognitive vehicle with the n-th subcarrier, which are denoted as $E\left[\left|g_{k,n}\right|^2\right]$ and $E\left[\left|h_{k,n}\right|^2\right]$ respectively. The phases of cooperative wideband spectrum sensing and transmission are illustrated in Fig. 2.

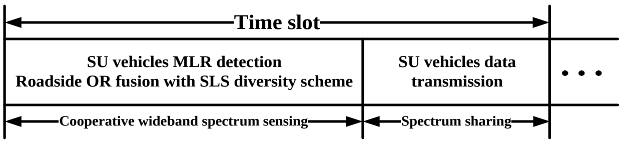

Fig. 2. The phases of cooperative wideband spectrum sensing and transmission.

III. Cooperative Wideband Spectrum Detection Based on MLR

A. MLR Local Spectrum Detection

Consider CR enhanced VANET with N subcarriers, the received signal at the n-th subcarrier for SUT can be written as

$$r_n = whs_n + \eta_n \tag{1}$$

where $w=1$ (or 0) denotes whether PU TV band radio transmits signal s_n or not, η_n represents the additive channel noise which is complex Gaussian random variable with zero mean and σ_η^2 variance. Channel fading coefficient h is written as $h=\alpha\exp(j\theta)$, where the amplitude α is a random variable conforms to Rayleigh distribution, and the phase θ is uniformly distributed among the azimuth in $[0,2\pi]$ [13].

We transform $\{r_n, n\in[0,N-1]\}$ to $\{R_k, k\in[0,N-1]\}$ in frequency domain by DFT, which can be written as

$$R_k = w\alpha\exp(j\theta)S_k + \xi_k, \quad k\in[0,N-1] \tag{2}$$

where $\{S_k\}$, $\{\xi_k\}$ are the N-point DFT of $\{s_n\}$ and $\{\eta_n\}$ respectively. When the time instant $t\to\infty$, according to central limit theorem (CLT) [14], the received signals at the n-th subcarrier $\boldsymbol{R}_n$, can be regarded as complex Gaussian process $\boldsymbol{R}_n \sim N(0,\sigma_{R_n}^2)$ [14], where $\sigma_{R_n}^2=\sigma_\eta^2(1+w^2\bar{\gamma}_n)$ denotes the variance of R_n, and $\bar{\gamma}_n=\frac{\sigma_h^2 s_n^2}{\sigma_\eta^2}$ is defined as the average SNR at the n-th subcarrier. Hence, we can normalize the amplitude of R_n as $x_n=\frac{|R_n|}{\sigma_\eta}$. Obviously, x_n is the Rayleigh distributed random variable with zero mean and variance $\sigma_{x_n}^2=\frac{1+w^2\bar{\gamma}_n}{2}$. According to Ref. [14], its probability density function (PDF) and cumulative distribution function (CDF) can be written as follows respectively

$$f_R(x_n)=\frac{x_n}{\sigma_{x_n}^2}\exp(-\frac{x_n^2}{2\sigma_{x_n}^2}) \tag{3}$$

$$F_R(\lambda_n)=\Pr\{x_n\le\lambda_n\}=\int_0^{\lambda_n} f_R(u)du = 1-\exp(-\frac{\lambda_n^2}{2\sigma_{x_n}^2}) \tag{4}$$

For simplicity, H_1 (or H_0) is used to represent the event whether PU TV band radio is actually utilizing the n-th subcarrier or not, which corresponds to $w=1$ (or 0). Assume that the average channel gain is known to each vehicle by channel estimation. We can address the MLR model as follows [14]

$$\Lambda=\frac{f(x_n\mid H_1)}{f(x_n\mid H_0)}=\frac{1}{1+\bar{\gamma}_n}\exp(\frac{\bar{\gamma}_n x_n^2}{1+\bar{\gamma}_n})>\beta_n \tag{5}$$

where β_n is the MLR threshold at the n-th subcarrier. If H_1 is true, decision region can be expressed as $DR=\{x_n:\Lambda>\beta_n\}$. Then we select the upper bound of MLR threshold, that is

$$\beta_n=\Lambda\mid_{x_n=\lambda_n}=\frac{1}{1+\bar{\gamma}_n}\exp(\frac{\bar{\gamma}_n\lambda_n^2}{1+\bar{\gamma}_n}) \tag{6}$$

Hence, we can easily get the decision threshold $\lambda_n=\sqrt{\frac{1+\bar{\gamma}_n}{\bar{\gamma}_n}\ln[\beta_n(1+\bar{\gamma}_n)]}$. For $\beta_n\ge1$, λ_n is proportional to β_n, thus we get the lower bound of decision threshold $\lambda_n\ge\sqrt{\frac{1+\bar{\gamma}_n}{\bar{\gamma}_n}\ln(1+\bar{\gamma}_n)}$, and the corresponding decision region is $DR=\{x_n>\lambda_n\}$. Therefore, the detection probability, false alarm probability and missing detection probability at the n-th subcarrier can be written as below respectively

$$\Pr_{D,n}=\int_{DR} f(x_n\mid H_1)dx_n=\exp(-\frac{\lambda_n^2}{1+\bar{\gamma}_n}) \tag{7}$$

$$\Pr_{Fa,n}=\int_{DR} f(x_n\mid H_0)dx_n=\exp(-\lambda_n^2) \tag{8}$$

$$\Pr_{m,n} = 1 - \Pr_{D,n} = 1 - \exp\left(-\frac{\lambda_n^2}{1+\bar{\gamma}_n}\right) \tag{9}$$

It is apparent that a larger number of MLR threshold β_n results in a more accurate decision, as expressed in Eq. (5). However, as seen from Eq. (7) to Eq. (9), a large number of β_n leads to large number of λ_n and small value of $\Pr_{D,n}$. Hence, it is essential to make a tradeoff between detection probability and sensing accuracy. The upper bound of detection threshold λ_n with the relationship of missing probability threshold $\Pr_0$ can be written as

$$\lambda_n \le \sqrt{-(1+\bar{\gamma}_n)\ln(1-\Pr_0)} \tag{10}$$

Substitute λ_n in Eq. (10) into Eq. (6), it is easily to obtain MLR threshold upper bound, which can be expressed as

$$1 \le \beta_n \le \frac{1}{1+\bar{\gamma}_n}(1-\Pr_0)^{-\bar{\gamma}_n} \tag{11}$$

For λ_n is proportional to β_n as Eq. (6) indicates, it is obvious that

$$\sqrt{(1+\frac{1}{\bar{\gamma}_n})\ln(1+\bar{\gamma}_n)} \le \lambda_n \le \sqrt{(1+\frac{1}{\bar{\gamma}_n})\ln[\beta_u(1+\bar{\gamma}_n)]} \tag{12}$$

where the upper bound of MLR threshold is shown in Eq. (11), that is, $\beta_u = \frac{1}{1+\bar{\gamma}_n}(1-\Pr_0)^{-\bar{\gamma}_n}$. It is apparent that MLR threshold β_n is related with the missing probability threshold $\Pr_0$ and SU vehicle average received SNR at the n-th subcarrier $\bar{\gamma}_n$.

In general, $\{S_n\}$ in Eq. (2) is unknown because PU TV radio signal is usually uncertain, which induces that $\{\bar{\gamma}_n\}$ is hardly to obtain. Hence, we utilize maximum likelihood (ML) algorithm to estimate $\bar{\gamma}_n$ [13, 14], that is

$$\hat{\bar{\gamma}}_n = \arg\max_{\bar{\gamma}_n} f(x_n \mid \bar{\gamma}_n, H_1) = x_n^2 - 1 \tag{13}$$

Substitute Eq. (13) into Eq. (5), it yields to the final decision criterion for MLR, which is shown as

$$\Lambda = \frac{f(x_n \mid H_1)}{f(x_n \mid H_0)} = \frac{1}{x_n^2}\exp(x_n^2 - 1) > \beta_0 \tag{14}$$

where $\beta_0 \in [1, \beta_u]$. From Eq. (6) to Eq. (9), it is known that once MLR threshold β_0 is selected, the decision threshold λ_n at the n-th subcarrier can also be determined. If the average received SNR $\bar{\gamma}_n$ is given, then the detection probability $\Pr_{D,n}$, false alarm probability $\Pr_{Fa,n}$ as well as missing detection probability $\Pr_{miss,n}$ can be obtained simultaneously.

B. Roadside OR Fusion Process with SLS

Each SU vehicle sends local detection result to roadside that performs global decision judgment by OR fusion rule with square-law selection (SLS). In SLS diversity scheme, suppose that each vehicle's sensing/reporting channels are independent and identical distributed (i.i.d), channel with the maximum output decision statistic from the square-law devices (square-and-integrate operation per channel) should be selected at roadside [8]. Specifically, assume $\{y_k\}_{k=1}^{K}$ denotes the received signal energy from square-law device at each vehicle, then the statistic expression $y_{\text{SLS}} = \max\{y_1, y_2, \cdots y_K\}$ is to be selected at roadside. SLS diversity scheme is also denoted as OR rule, which means roadside infers the presence of PU signal when there exists the maximum decision statistic from cognitive vehicles. According to Ref. [10, 15], OR rule is very conservative for CR vehicles to access the licensed PU band, which guarantees the minimization of interference to PU. For many cases of practical interest, OR rule obtains better performance than other fusion rules.

In this paper, cognitive OFDM-based overlay scenario is implemented in CR enhanced VANET, which is proposed as a promising approach for enhancing spectral efficiency [9, 14, 16]. For cognitive OFDM-based CR-VANET, a few subcarriers are selected to report the instantaneous SU vehicle local decision results. To avoid the interference generated by other SU vehicles, each subcarrier is exclusively assigned to one SU vehicle for opportunistic utilization [16, 17]. Due to subcarriers are orthogonal in OFDM, different SU vehicles are only allowed to transmit their local MLR detection results via orthogonal subcarriers. Hence, total subcarriers N is equivalent to the numbers of SU vehicles K in reporting phase [10, 15].

Suppose the local decision of the k-th SU vehicle is given by

$$d_k = \begin{cases} 1 & H_1 : y_k > \lambda_k \\ 0 & H_0 : y_k < \lambda_k \end{cases}, \ k = 1, 2, \cdots, K \tag{15}$$

where y_k is the received signal energy at the k-th SU vehicle, and λ_k indicates the decision threshold with specific detection scheme (*i.e.*, ED or MLR). Each SU vehicle sends local decision result d_k to roadside for fusion, and roadside performs the global decision with specific fusion rule. Assume OR fusion rule with SLS at roadside, and each SU vehicle performs local MLR detection, then the global false alarm probability Q_{Fa} can be evaluated using the CDF of y_{SLS} given by binary hypothesis testing H_0 [8,9], yielding

$$Q_{Fa,\text{SLS}} = 1 - F_{y,\text{SLS}}(\lambda \mid H_0) = 1 - \prod_{k=1}^{K}\left[1 - \Pr_{Fa,k}\right] \tag{16}$$

Similarly, the global missing probability with SLS can be obtained as

$$Q_{miss,\mathrm{SLS}} = \prod_{k=1}^{K} \Pr_{m,k} \tag{17}$$

where $\Pr_{Fa,k}$ and $\Pr_{m,k}$ are given in Eq. (8) and Eq. (9) respectively.

C. Robust Cooperative Sensing Based on MLR

The local detection results will also experience fading and shadowing during the reporting process, which deteriorates the transmission reliability and affects the global detection result inevitably [10, 18]. A cross-layer approach is proposed to reduce the unreliable reporting by anomaly spectrum usage detection in multihop CR networks [17]. According to the Ref. [10, 18], MLR sensing results are reported from SU vehicles to roadside through the dedicated reporting channels in cooperative wideband sensing phase. Hence, the global false alarm probability Q_{Fa} and missing detection probability Q_{miss} expressed in Eq. (16) and Eq. (17) are rewritten as follows.

$$Q_{Fa} = 1 - \prod_{k=1}^{K} [(1-\Pr_{Fa,k})(1-\Pr_{e,k}) + \Pr_{Fa,k}\Pr_{e,k}] \tag{18}$$

$$Q_{miss} = \prod_{k=1}^{K} [\Pr_{m,k}(1-\Pr_{e,k}) + (1-\Pr_{m,k})\Pr_{e,k}] \tag{19}$$

where $\Pr_{e,k}$ denotes the reporting error probability during the reporting transmission of local MLR decision [10,18].

Suppose each SU vehicle has identical local sensing result and the local MLR decision experiences i.i.d fading report channels, namely, $\Pr_{e,k} = \Pr_e$, for $k = 1, 2, \cdots, K$. As a result, the global false alarm probability has lower bound, which can be written as $Q_{Fa} \ge \bar{Q}_{Fa} = 1-(1-\Pr_e)^K \approx K\Pr_e$.

For practical consideration, all the local MLR detection results from SU vehicles to roadside are assumed in accordance with TDMA protocol, hence, roadside gathers the orthogonal K decisions without mutual interference. The reception performance of multiple SU vehicles in TDMA is the same as that of one SU. One SU binary hypothesis testing problem is just the same as binary phase shift keying (BPSK) modulation during reporting transmission. Consider the corresponding symbol error rate (SER) of BPSK modulation over Rayleigh fading channel [10, 13] shown as

$$\Pr_{e,\mathrm{TDMA}} = \frac{1}{2}\left(1 - \sqrt{\frac{\bar{\eta}}{1+\bar{\eta}}}\right) \tag{20}$$

where $\bar{\eta}$ denotes the average received SNR.

On the other hand, SU vehicles can cooperate with each other to form a virtual antenna array, thus cooperative diversity can be achieved in this way [10]-[11], [18]-[19]. Space-time (ST) coded cooperative sensing is implemented to realize transmit diversity [19], [20]. However, the virtual antenna array formed by vehicle cooperation is different from a real transmit antenna array formed by multiple antennas at a transmitter. This is because inter-user channel fading should be considered in a virtual antenna array [18]. In distributed STBC, cooperative SU vehicles exchange local MLR detection information, which is performed via sending request-to-send (RTS) and clear-to-send (CTS) frames between SU vehicles and the roadside. In two vehicles cooperation scenario, if both SU vehicles correctly decode the signals transmitted from the other side, then STBC can be implemented. Otherwise, SU vehicles will report their own decisions to the roadside by TDMA protocol. Hence, MLR detection decisions are reported to the roadside by either direct transmission using TDMA protocol or transmit diversity via STBC, based on the quality of inter-vehicle channels.

Ref. [10], [18] give the SER expression of BPSK modulation using STBC over Rayleigh flat fading reporting channel, which is denoted as

$$\Pr_{e,\mathrm{STBC}} = \frac{1}{2}\left[1 - \mu\sum_{k=0}^{K-1}\binom{2k}{k}\left(\frac{1-\mu^2}{4}\right)^k\right] \tag{21}$$

where K is the number of cooperated SU vehicles, and $\mu = \sqrt{\frac{\bar{\eta}/K}{1+\bar{\eta}/K}}$. Let ε represent the possible error rate occurred in inter-vehicle channel, then $\alpha = (1-\varepsilon)^2$ denotes the probability of the cooperated vehicles both correctly decode the received signals that come from each other. Hence, the reporting error rate is expressed as

$$\Pr_e = \alpha\Pr_{e,\mathrm{STBC}} + (1-\alpha)\Pr_{e,\mathrm{TDMA}} \tag{22}$$

The proposed vehicle cooperation is combined TDMA protocol with STBC transmit diversity. For good inter-vehicle channel, ε approaches to zero, and $\Pr_e \approx \Pr_{e,\mathrm{STBC}}$, which indicates the two cooperative vehicles could always correctly decode the received signals. The transmit diversity gain could be obtained in reporting channel. Apply Eq. (22) into Eq. (18) and Eq. (19), we can obtain the global false alarm probability and missing detection probability of robust cooperative wideband spectrum sensing with MLR local detection.

In multiple SU vehicles scenario, collaborative clusters are formed under the control of roadside, which means some closely located SU vehicles cooperate with each other to form a cluster [6], [18]-[19]. STBC could be implemented in those clusters. For different clusters, TDMA could also be implemented in the process of reporting. That is to say, each vehicle cluster will be assigned a time slot to report the decisions, and roadside will receive the signal from one cluster only in a given time slot without causing interference to other clusters [10], [18]-[19].

IV. Numerical Results and Analysis

In this section, we evaluate cooperative wideband spectrum sensing performance based on the proposed MLR local detection in CR-VANET. BER performance with reporting channel SNR and the corresponding ROC performance with different sensing/reporting SNR and inter-vehicle error rates are presented respectively. Numerical results are implemented with K SU candidate vehicles. Refer to Ref. [6,8,10,14,18], parameter setting are given as below:

- The number of SU vehicles: $K = 1/2/4$.
- The time-bandwidth product for ED is $m = 5$, and ED thresholds are set to be equivalent to MLR thresholds.
- Amplitude of received signal for the n-th subcarrier: $x_n = 1/2/3$. According to Eq. (14), MLR decision thresholds: $\beta_k = 1/\frac{1}{4}e^3/\frac{1}{9}e^8$.
- Cooperative wideband spectrum sensing combined with TDMA protocol and STBC transmit diversity, and inter-vehicle error rate: $\varepsilon = 0.03/0.3$.
- Sensing channel SNR $\bar{\gamma} = 10/20\text{dB}$, reporting channel SNR $\bar{\eta} = 15/30\text{dB}$, reporting channel error probability $\Pr_e = 10^{-3}/10^{-4}$.
- Roadside OR rule with SLS diversity scheme is implemented.

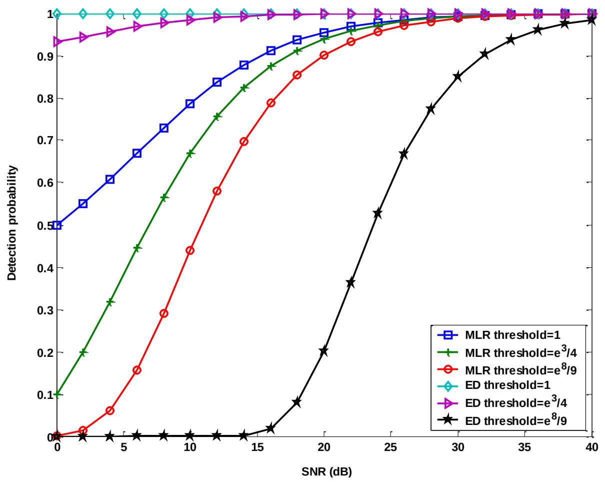

Fig. 3. Local detection performance comparison between MLR and ED.

Fig. 3 indicates SU local detection performance comparison between MLR and ED with the same decision threshold. As shown in Eq. (14), the threshold in MLR is the exponential function of the squared amplitude of received signals. In the case of smaller threshold, ED has better detection performance. However, when the decision threshold increases sharply, ED would degrade detection performance obviously. Due to the decision threshold of MLR is associated with the received SNR of SU vehicles (sensing channel SNR), hence, the rapid fluctuation of threshold influences the detection performance slightly for MLR local detection. Therefore, MLR is fit for adaptive spectrum sensing with dynamic detection threshold variations for SU vehicle local decision in CR-VANET.

Fig. 4 shows reporting channel BER performance with different inter-vehicle channel qualities in two/four cooperative vehicles scenario. The case of ε from 0 to 1 represents STBC and TDMA respectively. However, it is apparent that the smaller value of inter-vehicle channel error rate ε leads to better BER performance at the same number of cooperative vehicle scenario. From Eq. (22), for a very poor inter-vehicle channel when $\varepsilon = 0.3$, it is still obtain 3dB coding gain, which is better than TDMA ($\varepsilon = 1$) [10]. On the other hand, with the same inter-vehicle channel error rate ε, the increasing of collaborative vehicle numbers could improve BER performance, especially for smaller ε values. For the case of $\varepsilon = 0.3$, two and four cooperative vehicles just have the same BER performance in reporting channels. Hence, reporting channel BER performance could be improved with the decreasing of inter-vehicle channel error rate and the increasing of cooperative vehicle numbers.

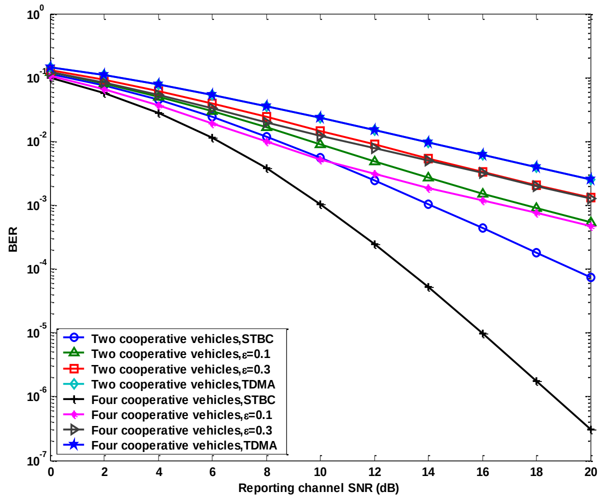

Fig. 4. Reporting channel BER performance with different inter-vehicle channel qualities.

Fig. 5 illustrates ROC of cooperative sensing with different inter-vehicle channel error rate and reporting channel SNR based on local MLR detection. Given sensing channel SNR $\bar{\gamma} = 10\text{dB}$ and reporting channel SNR $\bar{\eta} = 15/30\text{dB}$. It is obvious that, the increasing of reporting channel SNR and the reduction of inter-vehicle channel error rate lead to better ROC performance for two SU vehicles cooperation situation. In addition, reporting channel SNR 30dB with TDMA performs even better than reporting channel SNR 15dB with STBC, which means improving channel SNR is more efficient than the reduction of inter-channel error rate for the global enhancement of ROC performance. For reporting channel SNR 30dB, curve with $\varepsilon = 0.03$ approximately approaches to the curve with STBC, which reflects that inter-vehicle channel error rate contributes little to the improvement of cooperative wideband spectrum detection performance at higher reporting channel SNR region.

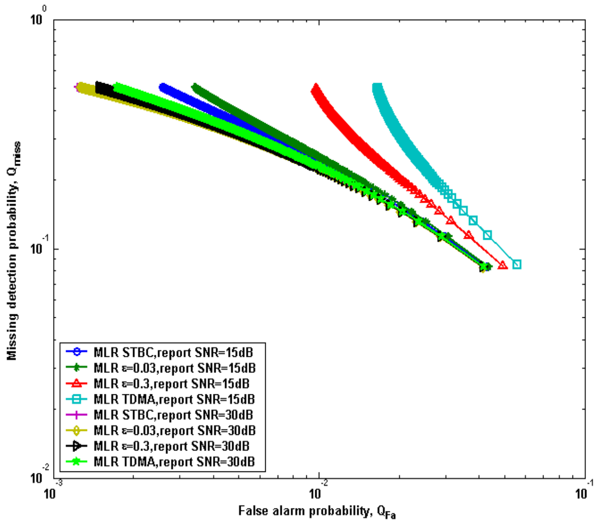

Fig. 5. ROC of cooperative sensing with different inter-vehicle channel error rate and reporting channel SNR.

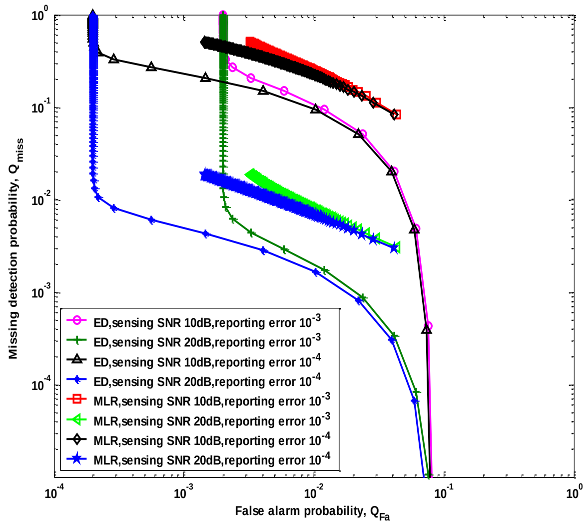

Fig. 6. Comparison of cooperative wideband detection ROC performance between MLR and ED with different sensing channel SNR and reporting channel error rates.

Comparison of cooperative wideband detection ROC performance between MLR and ED with different sensing channel SNR and reporting channel error rates is shown in Fig. 6. It is mainly given by numerical results implemented in Eq. (18) and Eq. (19) respectively. For two cooperative SU vehicles, both implement MLR or ED for local detection. The sensing channel is experienced Rayleigh flat fading with channel SNR $10\,\text{dB}$ and $20\,\text{dB}$ respectively, and the reporting channel error probability $\Pr_e$ is assumed to be 10^{-3} and 10^{-4} respectively. From this figure, we find that ED performs better than MLR in smaller decision threshold region, which is consistent with Fig. 3. However, Q_{Fa} with ED has its limitation, which tends to a lower bound that is related with the number of cooperated vehicles K and reporting error rate $\Pr_e$. *i.e.*, when $\Pr_e$ is 10^{-3}, the lower bound is 0.002, if $\Pr_e$ is 10^{-4}, the bound turns to be 0.0002. However, MLR has no Q_{Fa} bound. It indicates that, if sensing channel SNR is high enough while reporting error is very low, Q_{Fa} of cooperative sensing based on MLR could approach to lower value than that of cooperative detection based on ED. Therefore, MLR achieves better ROC performance than ED in this situation. In addition, cooperative wideband spectrum detection based on MLR has adaptive detection threshold that is related with average sensing channel SNR. This feature enables it to be suitable in dynamic topology CR-VANET.

V. Conclusions

In this paper, we mainly propose adaptive threshold local MLR detection as an effective scheme for cooperative wideband spectrum detection in CR enhanced VANET. OR fusion process with SLS is implemented at the roadside for local decision gathering. With the consideration of reporting channel fading and inter-vehicle channel error rates, robust cooperative wideband spectrum detection is taken into consideration in practical dynamic topology CR-VANET scenarios. Simulation results indicate that, compared with traditional ED, wideband spectrum detection with MLR has adaptive detection threshold in accordance with sensing channel SNR. Reporting channel BER performance as well as ROC performance of two SU vehicles' cooperation are all presented to confirm our derivation. Due to dynamic threshold variations, robust cooperative wideband spectrum sensing strategy based on local MLR detection is feasible to CR-VANET practical applications.

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