Antenna Array Based Localization Scheme for Vehicular Networks

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***Abstract*—Vehicular ad hoc networks (VANETs) are emerging as the possible solution for multiple concerns in road traffic such as mobility and safety. One of the main concerns present in VANETs is the localization and tracking of vehicles. This work presents a passive vehicle localization and tracking method based on direction of arrival (DOA) estimation. The proposed method does not rely on external sources of information such as Global Navigation Satellite Systems (GNSS) and can be used to mitigate the possibility of spoofing or to provide a second independent source of position estimation for integrity purposes. The proposed algorithm uses array signal processing techniques to estimate not only the position but also the direction of other vehicles in network. Furthermore, it is a fully passive method and can alleviate the network load since it does not require any location based data exchange and can be performed by any listening vehicle using the signal of any data transmission. A set of numerical simulations is used to validate the proposed method and the results are shown to be more precise than the average accuracy of Global Position System (GPS) receivers.**

***Index Terms*—Localization, VANETs, MIMO, Spoofing**

I. Introduction

Vehicular ad hoc networks (VANETs) is a promising technology finding applications such as road safety, traffic control, automated vehicle control, and platooning [1]. Many of such applications require the localization of all vehicles that compose a VANET to be known or estimated with a large degree of accuracy. Furthermore, not only must the accuracy be sufficient the estimate must also be reliable.

The localization of vehicles in VANETs is a parameters that can be estimated using a variety of methods. One of the main source of location information in a VANET is the usage of Global Navigation Satellite Systems (GNSS) information in order for each vehicle to obtain an estimate of it's location. GNSS such as the Global Positioning System (GPS) can provide location information with a mean error of fifteen meters in urban environments [2]. However, this accuracy is not sufficient for emerging applications in Intelligent transportation systems (ITS) such as platooning [3] or for safety applications. Furthermore, GNSS requires that a set of at least four line of sight signals are received from different satellites, this is not always possible in dense urban environments, leading to a possible large number of outages.

Other means of vehicle position estimation such as received signal strength indicator (RSSI) [4] can also be used and are capable of complementing GNSS information and making safety applications possible. Other vehicle location estimation approaches such as dead reckoning [5] can be used to provide position estimation during outages of GNSS. However, these approaches assume that the information that is provided by neighboring vehicles can be trusted.

Even in scenarios where the position provided by some vehicles can be assumed to be reliable and precise enough for the application at hand problems such as spoofing can still emerge. In a spoofing attack it is possible to falsify GNSS information such that a vehicle will obtain a position estimation that has been altered by the attacker. Furthermore, since GNSS information is usually spread using a data dissemination method [6], the position information can be falsified by the transmitting vehicle or by intermediary vehicles of the network. Position verification approaches [7] for VANETs can mitigate but not fully solve the problem of spoofing attacks.

A promising technology that can be applied to VANETs is the Multiple-input multiple-output (MIMO) communication scheme. MIMO has been used in modern wireless communications standards to allow for better spectral efficiency, faster data rates and more robust communication. Despite being a mature technology already employed in a multitude of standards, the study of MIMO for applications in VANETs has only recently gained traction [8]. Since the usage of MIMO requires the presence of multiple antennas at both receiver and transmitter, this antennas can be setup as, for instance, linear antenna arrays to allow the application of array signal processing techniques to provide an extra source of localization information on the network.

This work proposes the usage of array signal processing tools for direction of arrival (DOA) estimation to passively estimate the position of vehicles transmitting a signal. The proposed method allows the position of a vehicle to be estimated by all vehicles within its communication range passively. This estimation does not require the transmission of localization specific messages, thus, it can be used to alleviate the network load. The proposed estimation method is also robust to data falsification since it relies on parameters that are estimated on the physical layer and cannot be altered or falsified.

The reminder of this work is divided into five sections. Section II details the data model assumed for this work while

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Section III presents the scenario that is assumed for the proposed method. Section IV-B details the proposed localization and direction estimation method, its performance is accessed in Section V. Finally, conclusions are draw in Section VI.

II. Data Model

This data model considers a set of d wavefronts impinging onto an uniform linear antenna (ULA) array composed of M antennas. The received signal can be expressed in matrix form as

$$\mathbf{X} = \boldsymbol{A}\boldsymbol{S} + \boldsymbol{N} \in \mathbb{C}^{M \times N}, \tag{1}$$

where $\boldsymbol{S} \in \mathbb{C}^{d \times N}$ is the matrix containing the N symbols transmitted by each of the d sources, $\boldsymbol{N} \in \mathbb{C}^{M \times N}$ is the noise matrix with its entries drawn from $\mathcal{CN}(0, \sigma_n^2)$, and

$$\boldsymbol{A} = [\boldsymbol{a}(\theta_1), \boldsymbol{a}(\theta_2), ..., \boldsymbol{a}(\theta_d)] \in \mathbb{C}^{M \times d}, \tag{2}$$

where θ_i is the azimuth and elevation angles of the $i-$th signal, and $\boldsymbol{a}(\theta_i) \in \mathbb{C}^{M \times 1}$ is the antenna array response.

The received signal covariance matrix $\boldsymbol{R_{XX}} \in \mathbb{C}^{M \times M}$ is given by

$$\boldsymbol{R_{XX}} = \mathrm{E}\{\boldsymbol{X}\boldsymbol{X}^{\mathrm{H}}\} = \boldsymbol{A}\boldsymbol{R_{SS}}\boldsymbol{A}^{\mathrm{H}} + \boldsymbol{R_{NN}}, \tag{3}$$

where $(\boldsymbol{.})^{\mathrm{H}}$ stands for the conjugate transposition, and antenna array composed of M antennas. $\boldsymbol{R_{SS}}$ is the received baseband signal covariance matrix is where and $\boldsymbol{R_{NN}} \in \mathbb{C}^{M \times M}$ is a matrix with σ_n^2 over its diagonal and zeros elsewhere. An estimate of the received signal covariance matrix can be obtained by

$$\hat{\boldsymbol{R}}_{\boldsymbol{XX}} = \frac{\boldsymbol{X}\boldsymbol{X}^{\mathrm{H}}}{N} \in \mathbb{C}^{M \times M}. \tag{4}$$

III. Scenario Description

This work assumes that the vehicles connected to the VANET are equipped with two linear antenna arrays at two distinct locations on their frames. Figure 1 presents an example of two vehicles with antenna arrays equipped at the wing mirror position.

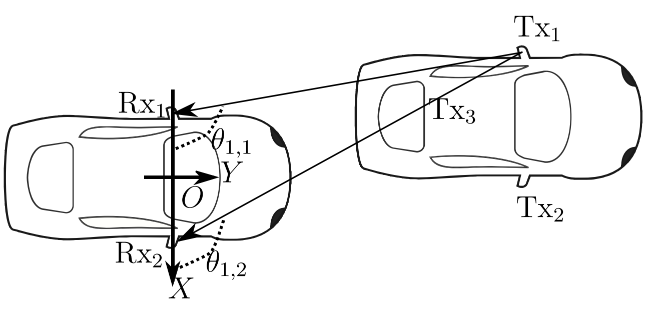

Fig. 1. Scenario description for two vehicles

To avoid ambiguities in DOA estimation the antenna elements of the array must be placed no further than half a wave length apart. Assuming the communication occurs at the 5.8 GHz frequency band and that DOA estimation is to be done at carrier frequency the antenna elements can be placed as far as 2.5 cm apart. Antenna elements can be installed close together to allow more antennas to be installed on the same area or to reduce the total size of the antenna array, however this comes at the cost of increasing mutual coupling between antenna elements. This work assumes that the antenna arrays are installed at the wing mirror position of the vehicles composing the network.

IV. Proposed Localization Method

This section presents the steps performed by the proposed localization method to obtain a non ambiguous localization and direction. Subsection IV-A presents an overview on the employed DOA estimation method. Subsection IV-B details the calculation of a localization estimate while subsection IV-C presents the calculation of the direction estimation. Finally, in subsection IV-D the removal of front and back ambiguity is detailed and possible applications of the proposed method are discussed.

A. Direction of Arrival Estimation

This work proposes using DOA estimation to acquire a position estimation of neighboring transmitting vehicles. The estimation of signal parameters via rotational invariance techniques (ESPRIT) [9] is a closed form high resolution hat can be very easily extended to multidimensional scenarios. This work employs ESPRIT due to its high resolution and the reduced computational complexity when compared to other DOA estimation methods.

The ESPRIT parameter estimation technique is based on subspace decomposition that can be applied in rotational invariant arrays, such as the uniform linear array (ULA) shown in Figure 2. Matrix subspace decomposition is usually done by applying the Singular Value Decomposition (SVD). The SVD of the matrix $\boldsymbol{X} \in \mathbb{C}^{M \times N}$ is given by

$$\boldsymbol{X} = \boldsymbol{U}\boldsymbol{\Lambda}\boldsymbol{V}^{\mathrm{H}}, \tag{5}$$

where $\boldsymbol{U} \in \mathbb{C}^{M \times M}$ and $\boldsymbol{V}^{N \times N}$ are unitary matrices called the left-singular vectors and right-singular vectors of $\boldsymbol{X}$ and $\boldsymbol{\Lambda} \in \mathbb{C}^{M \times N}$ is pseudo diagonal matrix containing the singular values of $\boldsymbol{X}$. The signal subspace $\boldsymbol{E}_S \in \mathbb{C}^{M \times d}$ of $\boldsymbol{X}$ can be constructed by selecting only the singular vectors related to the d largest singular values, the remaining singular vectors form the noise subspace $\boldsymbol{E}_N \in \mathbb{C}^{M \times M - d}$ of $\boldsymbol{X}$. Notice that the maximum number of signal parameters that can simultaneously estimated is $M - 1$.

With this subspace estimate at hand ESPRIT can be used to acquire the DOA estimate for ϕ as shown in Figure 2. This estimated can be obtained by solving

$$\boldsymbol{J}_1\boldsymbol{E}_S\boldsymbol{\Phi} = \boldsymbol{J}_2\boldsymbol{E}_S, \tag{6}$$

where $\boldsymbol{J}_1$ and $\boldsymbol{J}_2$ are selection matrices selecting the first and last $M - 1$ rows of $\boldsymbol{E}_S$ and $\boldsymbol{\Phi}$ is matrix whose eigenvalues are related to ϕ by

$$\phi = \arcsin\left(-\frac{\arg(v)}{2\Pi\Delta}\right), \tag{7}$$

where v is an eigenvalue of $\boldsymbol{\Phi}$ and Δ is the separation between the antenna elements of the array as shown in Figure 2.

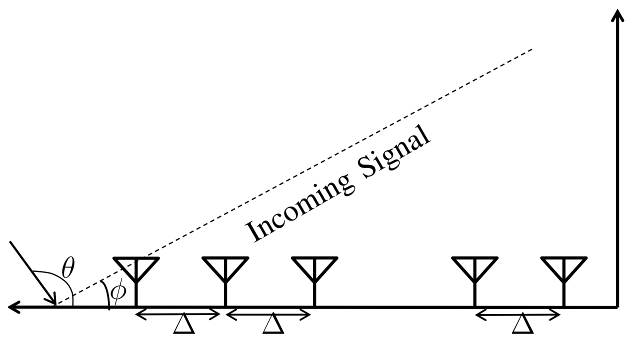

Fig. 2. Graphical representation of receiving array and wave front DOA

Other DOA estimation methods such as [10], [11] can be employed to achieve better performance or to deal with the presence of correlated signals, such as multipath signals.

B. Localization Estimation

Once the DOAs have been estimated the next step is to obtain a line representing the direction of the received signals. The angles estimated at the receiver are the angles between the wavefronts and the arrays. The center of the line crossing the car and both wing mirrors is considered to be the origin of the reference coordinate system and shall be denoted as O. Antennas are considered as points in the space and are contained within the line representing the signal they irradiate. To obtain an estimate of the localization of a vehicle is it necessary to obtain the angle θ. The relationship between ϕ and θ is given by

$$\theta = -\frac{1}{\phi}. \tag{8}$$

With this parameter at hand and following the coordinate system shown in Figure 1 the lines representing the signal received at Rx_1 and Rx_2 can be written as

$$y = \tan(\theta_{1,1})x - \tan(\theta_{1,1})x_{Rx_1}, \tag{9}$$

$$y = \tan(\theta_{1,2})x - \tan(\theta_{1,2})x_{Rx_2}, \tag{10}$$

where x_{Rx_1} and x_{Rx_2} are the position of the center of the antenna arrays at Rx_1 and Rx_2 over the X axis.

The position of the transmitting array Tx_1 can be obtained by calculating the point where (9) and (10) meet, this can be done by solving

$$x = \frac{\tan(\theta_{1,1})x_{Rx_1} - \tan(\theta_{1,2})x_{Rx_2}}{\tan(\theta_{1,1}) - \tan(\theta_{1,2})}, \tag{11}$$

$$y = \frac{\tan(\theta_{1,1})\tan(\theta_{1,2})\left(x_{Rx_2} - x_{Rx_1}\right)}{\tan(\theta_{1,2}) - \tan(\theta_{1,1})}. \tag{12}$$

Obtaining the position of one of the transmitting arrays can be sufficient for some applications. The localization of a wing mirror can be sufficient, for instance, to increase the accuracy of a dead reckoning method in the temporary absence of a GNSS lock.

Notice that a linear array is not capable of resolving whether a signal received is arriving from the front or back of the array. Therefore, this estimate alone cannot be used to fully locate a vehicle on the network unless previous or external information regarding the localization is available.

C. Direction Estimation

By estimating the position of both transmitting arrays Tx_1 and Tx_2 it is possible to obtain not only a localization estimate but also a direction estimate. Let $(x_{\mathrm{Tx}_1}, y_{\mathrm{Tx}_1})$ and $(x_{\mathrm{Tx}_2}, y_{\mathrm{Tx}_2})$ be the coordinates of the transmitting arrays, the line that cuts both antenna arrays can be given by

$$y - y_{\mathrm{Tx}_1} = \frac{y_{\mathrm{Tx}_2} - y_{\mathrm{Tx}_1}}{x_{\mathrm{Tx}_2} - x_{\mathrm{Tx}_1}}\left(x - x_{\mathrm{Tx}_1}\right). \tag{13}$$

The line giving the direction of the transmitting vehicles must pass through the midpoint between $(x_{\mathrm{Tx}_1}, y_{\mathrm{Tx}_1})$ and $(x_{\mathrm{Tx}_2}, y_{\mathrm{Tx}_2})$ and be perpendicular to (13). The angle $\theta_{\mathrm{direction}}$ that this line forms with the X defines the direction that the transmitting vehicle is facing with respect to the coordinate system of the receiving vehicle, and is given by

$$\theta_{\mathrm{direction}} = \arctan\left(\frac{x_{\mathrm{Rx}_1} - x_{\mathrm{Rx}_2}}{y_{\mathrm{Rx}_1} - y_{\mathrm{Rx}_2}}\right). \tag{14}$$

With an estimate of the direction of vehicles on the network it is possible to tell whether a vehicle is turning and how fast it is turning. This information can be useful for road safety systems or collision prevention systems.

D. Ambiguity Removal

As mentioned in subsection IV-B, a ULA is not capable of resolving whether the transmitter is at the front or backside of the array. This effect is highlighted in Figure 3.

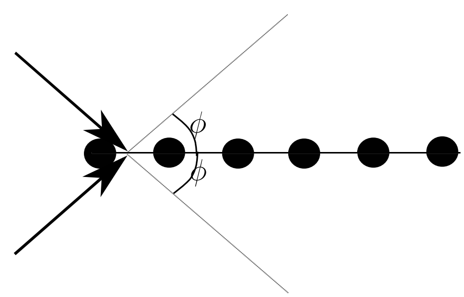

Fig. 3. Front and back ambiguity of a ULA

In order to circumvent this limitation this work proposed the usage of a third transmitting antenna. This antenna can be placed anywhere outside of the the line containing Tx_1 and Tx_2 on the transmitting vehicle. Figure 1 presents one such antenna labeled as Tx_3. After the positions of the three antennas have been estimated by the receiving vehicle, two different localization estimations will be available as shown in Figure 4.

Under the assuming that the transmitting vehicle is moving forward, it is possible to select the proper localization estimation as one of the estimations will present a reversed vehicle.

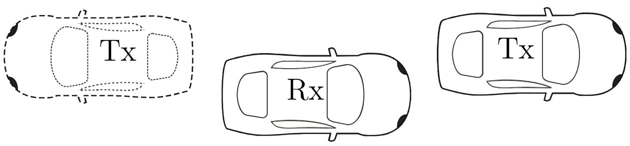

Fig. 4. Ambiguity solving using third transmitting antenna

This allows the proposed method to be used as a stand alone localization and direction estimation method.

One of the main advantages of the proposed method is that it is a physical layer based localization method. This characteristic allows it to be employed using data transmissions that are already happening on a VANET, as it does not require any specific data for the estimation to be performed. It is possible even to estimate the localization of vehicles that are transmitting encrypted data that can't be decoded at the receiver. Allowing a secure transmission between a pair of vehicles to serve as the input for localization for all nearby vehicles. Therefore, the proposed method can be employed even in VANETs that have their communication channel already close to its maximum capacity.

Furthermore, also due to the reliance on the physical layer, it is hard to spoof a position estimation at the receiver. For the receiver to wrongly estimate the position of a transmitting vehicle it would be necessary to alter the antenna positioning at the transmitting vehicle, and, even then, such alterations could be detected easily be calculating the distances between the detected antenna locations and checking whether they follow the expected patter. This characteristic is promising for safety applications, as it can serve as an integrity check for localization information received from other methods, such as a vehicle broadcasting a fake or wrong GPS position. During the broadcast the localization can be estimated and checked against the received position, telling the receiving vehicles whether the transmitted data can be trusted or not.

V. Simulations

The proposed algorithm have been tested using numerical simulations. The antenna arrays at the wing mirrors are considered to be an ULA composed of $M = 4$ antennas with inner element spacing of $\frac{\lambda}{2}$. For obtaining $\hat{\boldsymbol{R}}_{\boldsymbol{XX}}$ we use $N = 100$ snapshots and the Root Mean Squared Error (RMSE) is calculated with respect to 1000 Monte Carlo simulations. The antenna arrays are assumed to be placed 1.80 m apart, the average car width. The Signal to Noise Ratio (SNR) is defined as $\mathrm{SNR} = \frac{\sigma_1^2}{\sigma_\mathrm{n}^2} = \frac{\sigma_2^2}{\sigma_\mathrm{n}^2} = \frac{\sigma_3^2}{\sigma_\mathrm{n}^2}$.

For the first simulations, the transmitting vehicle is placed 20 m apart in front of the receiving vehicle and 2 m to the right, as if occupying a different lane in traffic. Figure 5 presents the mean error performance of the proposed localization method. The error is measured as the cartesian distance between the real and estimated location of the wing mirror of a vehicle. As expected, the performance of the proposed method increases as the SNR of the received signal increases, as the performance of ESPRIT also increases. At a SNR of 7 dB the proposed method is capable of a 1 m precision, superior to that of GPS. At SRNs higher than 15 dB the proposed method was capable of providing a very high localization accuracy that can be used for applications such as colision avoidances and road safety.

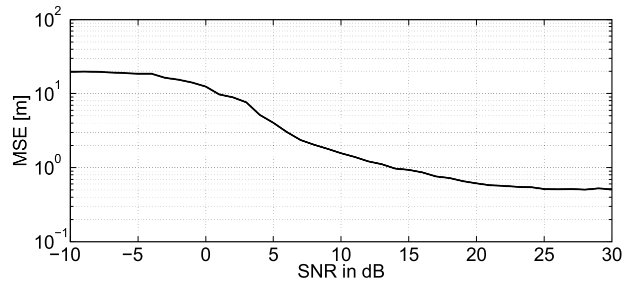

Fig. 5. Performance of proposed localization method

The second set of simulations analyses the accuracy of the proposed method when estimating the direction of transmitting vehicles on the network. Similar to the localization performance a moderate SNR is necessary in order to achieve reasonable accuracy. At the 7 dB SNR threshold the direction error is smaller than one degree.

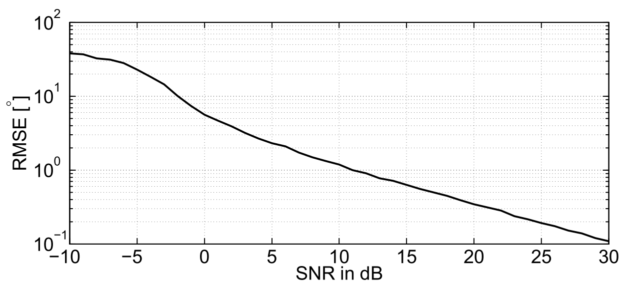

Fig. 6. Performance of proposed direction estimation method

The simulation results show that the proposed method can provide results superior to that of GPS for moderate SNR scenarios. Since communication ranges at VANETs are expected to be relatively small and the transmission power can be made relatively high, the SNR range necessary for the proposed method to achieve a good performance can be obtained.

VI. Conclusion

This work presented a passive localization and direction estimation method for VANETs. The proposed method relies on the presence of antenna arrays at the vehicles constituting VANETs. The direction of arrival of a set of signals transmitted by a vehicle on the network is estimated and the estimates are used to estimate the position of direction of vehicles across the network. The proposed method can be used as a stand alone localization estimation method as well as for localization spoofing mitigation as it relies on the estimation of parameters from the physical layer. Furthermore, it does not require any specific data to be transmitted and can be applied when any data exchange is happening on the network, therefore the proposed method does not imply an increased network load for the VANET.

Results show that the technique is capable of achieving accurate results at a moderate SNR. For SNRs of 7 db the localization error of the proposed error is of 1 m, superior to that of a GPS receivers. At higher SNRs the proposed method is capable of achieving very accurate results, suitable for safety and collision avoidance applications.

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