Research on Beamforming Algorithm of Millimeter Wave System Based on Mobility of Network Vehicles

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Abstract. During the operation of mobile networked intelligent vehicles, beamforming training is often needed, which will lead to a significant increase in training time and adverse impact on system performance. This paper analyses this problem in detail, and establishes a new beamforming algorithm, that is, to predict the position and state information of the vehicle in the process of movement, and then beamforming based on the results obtained; the predicted vehicle position results have errors, so we need to reduce the position error as much as possible, calculate the optimal beamforming width, and significantly improve the system performance. The simulation results show that the performance of the beamforming algorithm proposed in this paper is significantly improved compared with IEEE 802.11ad, which can meet the requirements of practical application.

1. Introduction
Automatic driving of networked intelligent vehicles holds vital significance towards the intelligent transport system. Realization of the function requires the data transmission rate to reach kilo-mega per second, and the corresponding delay is very low. In order to meet the requirement, 5G millimeter wave (MMW) communication network of the next generation is needed, which can significantly improve the base station capacity of the aforesaid network and the service quality [1]. However, theoretical analysis suggests that the MMW, being relatively short, can easily encounter the problem of attenuation in the process of propagation in the space. Besides, its penetrability is weak. These defects of the MMW can impair the MMW’s communication performance, which also necessitate the beamforming design to properly gather its signal energy for the purpose of improving the signal energy received and the control accuracy of networked intelligent vehicles. This paper analyzes the aforesaid problem, and proposes the beamforming algorithm of MMW system based on the mobility of network vehicles so as to meet application requirements of this field.

According to relevant standards of IEEE 802.11 ad [2], two-way frame transmission is required upon beamforming [3]. Compared with the common antenna, the phased array antenna achieves a significant increase in the beam switching speed, which is generally no faster than 50ns. Thereby, it can be judged that a main influencing factor of the beamforming time cost is the number of switched frames. Literature [4] provides an optimized codebook design plan, which can be used to improve the beamforming training velocity, and reduce the corresponding expenditure as well. This can better meet the system’s real-time requirements. Nevertheless, the beamforming training is realized through the quasi-omnidirectional model, which thus cannot avoid some limitations. Affected by the Doppler shift, the performance attenuation caused by the vehicle shift cannot be effectively supplemented. The faster the vehicle moves, the faster the beamforming training velocity is required, which will also increase the cost, and impair the performance of networked vehicles. Some scholars, while examining this issue, have proposed the
heterogeneous network design idea, that is, to exchange the MMW beamforming training data beyond the MMW communication frame. Under the condition of the city’s short-distance communications, the corresponding data transmission rate for specialized short-distance communication can achieve a high level [5]. Literature [6] establishes a heterogeneous network based on the thinking, which makes use of the MMW antenna access technology. Upon the vehicle position sending and movement, the specialized short-distance communication beacon should be adopted. Thereby, the vehicle’s movement status is predicted and the beamforming training is realized. The method can satisfy requirements of practical applications. However, the position error is not taken into consideration. Besides, the vehicle velocity is hypothesized to remain the same, which is inconsistent with the practical situation. The vehicle’s position data are mostly collected via GPS, which cannot avoid some errors. This will also result in some biases of the beamforming algorithm. Comparative analysis suggests that the position error is observed in the three-dimensional space which is different from the GPS error. Additionally, errors of different directions might be different, which can also influence the research outcomes.

2. Algorithm model

2.1. Position error and vehicle mobility model
Experience shows that the initial position information of the vehicle acquired through GPS cannot avoid some errors [7]. Literature review suggests that the error averages at 3m, which is given by the test results of major regions under different environments, so the error average is widely applicable. When the building height exceeds certain range, the phenomenon of “urban crayon” will be formed, which will aggravate the GPS errors, and the impact is different on different urban scenarios. Research has implied that the error position information can be significantly brought down if the data integration algorithm can be properly combined with the movement data and position information for further processing. Literature [8] sets up an optimized positioning system, and its test results suggest that the position accuracy of the system under the urban scenario can be exact to the centimeter. This can significantly improve the positioning accuracy of vehicles, and hold vital application value to the automatic driving and positioning of networked vehicles.

The synchronous flow traffic model has found extensive applications in the research field of vehicles’ mobility performance, and its advantage mainly lies in its accurate analysis of the vehicle mobility at certain traffic density and under the urban scenario [8]. In this model, the vehicle velocity follows the Gaussian distribution, whose average is \( v_{mg} \) and variance 2. Under the condition of no conditions for major traffic accidents, the vehicle driving model in the driving boundary is generally synchronous.

2.2. Beamforming alignment model based on position prediction
Based on the above discussions, one can notice that GPS errors can affect the accuracy of the estimated vehicle position, which can be written as 
\[
E_{pos} = C_{pos} + e_{GPS},
\]
where \( C_{pos} \) denotes the practical position, and 
\[
e_{GPS} \sim \log N(\mu, \sigma^2).
\]
In the process of positioning, when the light beam is aimed at the position based on the target vehicle (such as the received communication beacon), the angle, \( k^\circ \), corresponding to the reference plane can be given by the knowledge of the triangle. After that, the light beam is shifted to the vehicle. The details are illustrated in the following schematic diagram:
If the position data processed are expired, then the movement-sensed data can be adopted upon prediction of the vehicle movement. Networked intelligent vehicles can set up various sensors, such as the based on the magnetometer and gyroscope, application requirements. The data collected via these sensors can be used to identify the vehicle’s angular velocity information after being processed by the data integration algorithm. Following that, the parameter is decomposed into components, each at a different direction, including the vertical component $\omega_y$, horizontal component, $\omega_p$, and longitudinal axis, $\omega_r$. The angular displacement after the rotation in unit time can be described through the three components.

It is assumed that the vehicle maintains its angular velocity unhanged in the process of movement. Affected by the gravity, the actually-moving vehicle will stick to the surface of the Earth. The vehicle driving on the road can only change its direction on the road plane within a short period of time. On the contrary, no obvious changes happen at the vertical direction. In this way, in order to facilitate the handling process, the road and vehicle are regarded as a two-dimensional plan, and the vehicle is just moving on the plane. In the process of the vehicle’s movement, when the velocity is constant, its movement track is an arc. The specific situations are shown in Fig. 2 below. The interval between A and B is the distance over the unit time, which can be written as below:

$$\theta_{pr} = mAB = 2 \cdot \omega_y \cdot t_{pr}$$  \hspace{1cm} (1)

$$lAB_{pr} = \dot{v} \cdot t_{pr}$$  \hspace{1cm} (2)

Where, $t_{pr}$ denotes the time lag for the latest signal beacon to arrive at the current corresponding position. According to the aforesaid two equations, and combining the attributes of circle, this paper defines the radius and the length of the chord A to B:

$$R_{pr} = \frac{180^\circ \cdot lAB_{pr}}{2\pi \omega_p}$$  \hspace{1cm} (3)

$$AB_{pr} = 2 \cdot R_{pr} \cdot \sin(\omega_p \cdot t_{pr})$$  \hspace{1cm} (4)

Where, $AB_{pr}$ denotes the interval between the two points. with $R_{pr}$ denotes the radius. The prediction position, $P_{pos}$, can be identified via the following equation:

$$P_{pos}(x, y) = \begin{cases} P_{pos}(x) = E_{pos}(x) + \overline{AB_{pr}} \cdot \sin(\theta_{pr}) \\ P_{pos}(y) = E_{pos}(y) + \overline{AB_{pr}} \cdot \cos(\theta_{pr}) \end{cases}$$  \hspace{1cm} (5)
After modification of the above relational expression, the vehicle’s movement on the two-dimensional plane can be converted to one on the three-dimensional sphere.

2.3. Correlation among position error, beam width and vehicle velocity

Under the condition, it is necessary to build a vehicle movement model: The vehicle is moving on the track as shown in Fig. 3, and RSU is located at the track rim. It can be seen that the vehicle is moving in a random way. In the case of position error, failure of beamforming alignment might happen, and when the position error components are different, the corresponding impact is different too. Therefore, to facilitate research, the two-dimensional movement of the vehicle is projected to the x-axis and y-axis. When the vehicle position is predicted, there is no error under ideal conditions. Meanwhile, when the new-type beamforming algorithm is adopted, it can well satisfy the application requirements under the condition of no interruption. But in the field of actual applications, the vehicle position information collected by the GPS equipment might be found with the error. Under the condition, if the beamforming alignment relies on the GPS information alone, the interruption interval will be unavoidably caused, thus influencing the system performance. Theoretical analysis shows that the vehicle velocity and the beamforming width are two main influencing factors of the total driving time under the scenario of beamforming alignment. In this way, the correlation among the three can be described by the function, namely $T(v, \theta)$.

Under different error conditions, the system is subject to different degrees of impact. Under the condition of the position error, the interruption interval of the corresponding beamforming can be identified. Besides, the two are closely correlated. When the position error is zero, the interruption interval is the minimum. However, the vehicle position error is unlikely to be zero, particularly in a real-life system. Literature [9] observes that, in a two-dimensional system, GPS error can be decomposed into the error component in the x-axis and y-axis. The system performance is subject to the influence of the position error of the roadside receiving unit. As one observes in Fig. 3, the influence of interruption on the x-axis is more obvious than that on the y-axis.

When the position error is different, factors influencing the error should be further analyzes. According to the analysis results, the correction algorithm targeted at specific errors can be adopted for intervention, thus effectively avoiding the problem of serious interruption of communication and improve the system performance. Concerning the failure of alignment caused by the non-zero error, theoretical analysis shows that a non-zero beamwidth can be identified to achieve the optimal status [10].
2.4. Correlation between antenna gain and beamwidth

Upon performance optimization, it is necessary to derive the antenna model about the correlation between gain and beamwidth so as to achieve the optimal system performance after rational settings of beamwidth. To facilitate analysis, it is assumed that the ideal light beam has the even gain and the sidelobe power is constantly zero. When the specific antenna is analyzed, the approximate value can be adopted as a replacement to improve the accuracy of results obtained. The following equation can be used to describe the antenna direction associated with the beam solid angle, $\Omega_d$ [11]:

$$D = \frac{4\pi}{\Omega_d}$$

Under the above ideal beam representation, $\Omega_d$ is approximated to $\Omega_d \approx \theta_1 \theta_2$. $\theta_1$ and $\theta_2$ are the half-power beamwidth on different planes.

$$G = \eta D$$

Where, $\eta$ is the antenna efficiency, whose main influencing factor is the antenna pore diameter. To an ideal antenna, the index is 100%. To the ideal beam, $\theta_1 = \theta_2$. According to the above discussions, the following equation can be used to describe the correlation between the antenna gain and the beamwidth, $\theta$:

$$G = \frac{4 \cdot 180^\circ}{\theta^2 \pi}$$

3. Theoretical analysis

3.1. Analysis of SNR and chain budget

According to the above discussions, the antenna’s receiving signal-to-noise ratio (SNR) can be given by the ratio of $P_{rx}$ to $P_{noise}$, and the receiving power mainly consists of the following parts [12]:

$$P_{rx} = P_t + G_r + G_s - PL$$

Where, $P_t$ is the transmitting power. $G_r$ and $G_s$ are the corresponding antenna gain. Under the model, the beamwidth of the two antennas is consistent with each other, and both are found with the ideal beam. Therefore, the antenna gains of the receiving and sending end is consistent as well, or $G_{rx} = G_{tx}$. PL denotes the path loss, which can be written as below:

$$PL = 10 \cdot n \cdot \log_{10} d + SF + C_{att} + R_{att} + A_{att}$$

Where, n denotes the path loss index; SF denotes the random shadow effect [13], which obeys the Gaussian distribution with the variance being $SF \sim N\left(0, \sigma_{SF}^2\right)$, $\sigma = 5.8$. $A_{att}$ and $R_{att}$ denote the
average attenuation of the atmosphere and the precipitation. $C_{att}$ denotes the signal channel attenuation of the chain at certain distance, which under general conditions is a fixed constant \[14\]. The model of this paper is regarded as the transmission chain of the line-of-sight transmission.

The noise power, $P_{noise}$, can be written as below:

$$P_{noise} = N_{floor} + 10 \log_{10} B + NF \quad (11)$$

Where, $NF$ is the noise coefficient and $B$ is the bandwidth. As mentioned above, the beamwidth can influence the antenna gain. After the time is postponed, the interval between the receiver and the vehicle is also constantly changing. Under the given time, $t$, the estimated position of the vehicle can be identified, and the distance parameter can be identified conveniently. Therefore, the SNR can be worked out by the time and beamwidth, and the function expression can be written as below:

$$\text{SNR}(t, \theta) = \frac{P_{in}(t, \theta)}{P_{noise}} \quad (12)$$

Where, $N_{floor}$, $NF$ and $C_{att}$ are both constants.

### 3.2. Sensitivity analysis of the error element

As one observes in the following equation, when the beamwidth and time are both certain, the instant signal channel capacity of the MMW can be identified by the following equation:

$$C(t, \theta) = B \cdot \log_{2}(1 + \text{SNR}(t, \theta)) \quad (13)$$

According to the prediction model proposed above, when the vehicle covers the region’s rim, the beam will change its direction. The interval between two alignments can be pinpointed according to the lag of time between the $t_i$ (of the i beam) and $t_{i+1}$ (of the i+1 beam). Please refer to Fig. 3 for more details. As to every $t_i$, its position, $P_i$, can be identified.

Regarding the scenarios described in 2.3, the vehicle drives along the set track under the condition, but within a large scope of time, its track is basically the same, namely vibrating from the starting point along the x-axis. It is assumed that there is only position error in the system. Under the condition, the vehicle’s actual movement and the predicted movement are consistent. The corresponding error appears on the x-axis and y-axis. To facilitate handling, it is assumed that the vehicle’s track within $[t_i, t_{i+1}]$ is a straight line. Then, under the given $\theta$ and interval $[t_i, t_{i+1}]$, the following equation can be obtained:

$$D_i(t, \theta) = \int_{t_i}^{t_{i+1}} B \cdot \log_{2}(1 + \text{SNR}(t)) \, dt \quad (14)$$

However, under the practical movement status, the error cannot be avoided between the predicted position and the actually-measured one. Meanwhile, there is the error between the beamforming moment and the real moment, which can cause the interruption. Theoretical analysis suggests that the following equation can be used to identify the two wrong components:

$$P_e(x_e, y_e) = \begin{cases} x_e = x_{est} - x_e \\ y_e = y_{est} - y_e \end{cases} \quad (15)$$

Where, $(x_e, y_e)$ is the coordinate of the vehicle’s practical position, while $(x_{est}, y_{est})$ is the estimated value of the corresponding position. Errors of the x-axis and y-axis can appear under the following circumstances: 1) When $x_e \geq 0$ or $x_e < 0$; 2) When $y_e \geq 0$ or $y_e < 0$. Theoretical analysis suggests that, when $x_e > 0 \Rightarrow x_{est} > x_e$, it can be judged that the beam switches the direction ahead of time, which can cause the interruption. Therefore, the following equation can be used to identify the alignment moment of the i beam:

$$t_i = \sqrt{\left(\frac{P_{in} - P_{in_0}}{P_{in}}\right)^2 + \left(\frac{P_{in} - P_{in_0}}{P_{in}}\right)^2} \quad (16)$$
throughput upon the beam alignment of the vehicle by Eq. (14). Analysis shows that only when the data throughput is calculated under the condition of alignment will it be meaningful. If there is no alignment, the data throughput is zero.

It is assumed that the estimated position error is not serious, which has not resulted in the complete failure of alignment. Under the condition, the degree of influence of different error components on the system performance can be estimated. According to Literature [13], the partial derivative can be computed to obtain the sensitivity coefficient, $U$, of the specific independent variable. When the beamwidth is certain, it is assumed that one of the position error components is fixed. By the definition of the partial derivative, the correlation between various error components and the information throughput of the $i$ beam can be written as below:

$$U_i(e^i) = \frac{\partial D_i(\epsilon^i, \theta^i)}{\partial e^i} = \frac{\partial}{\partial e^i} \int_{t_i}^{t_{i+1}} B \cdot \log_2 (1 + SNR(t)) dt$$

The signal channel capacity function of Eq. (14) contains the original function. In this way, $C(t)$ can be given by the calculus rules:

$$D_i(\epsilon^i, \theta^i) = \int_{t_i}^{t_{i+1}} c(t) dt = C(t_{i+1}) - C(t_i)$$

(17)

Based on the chain rule for derivative solution, and combining Eq. (18), Eq. (17) is converted into Eq. (19) below:

$$U_i(e^i) = \frac{\partial D_i(\epsilon^i, \theta^i)}{\partial e^i} = C'(t_{i+1}) \frac{\partial (t_{i+1})}{\partial e^i} - C'(t_i) \frac{\partial (t_i)}{\partial e^i}$$

(18)

(19)

The numerical simulation approach is used to cope with the above equation. The sensitivity coefficient of the error component can be given by the partial derivative. It is of vital importance to clarify the correlation between various error components and system performance.

4. Optimization of beamwidth

Improvement of the position accuracy can lead to a synchronous improvement of the system performance. Nevertheless, under the current technical conditions, the vehicle position cannot yet be accurately identified. After the position error occurs, the problem of interruption cannot be avoided. Thereby, in order to improve the system performance, it is necessary to identify the optimal beamwidth. Hereby, it is assumed that $P_e$ is a random variable. The beamwidth related to the maximum data throughput based on the probability can be written as below:

$$\theta^e = \arg \max_{\theta^e} E_{P_e} [D_i(t, \theta^e)]$$

(20)

$P_e$ can be decomposed into two components, namely $x_e$ and $y_e$. Besides, the two are both random variables, and $E_P [\cdot]$ denotes the positive linear function. Then, the above equation can be written as below:

$$\theta^e = \arg \max_{\theta^e} E_{x_e} [D_i(t, \theta^e)] + \arg \max_{\theta^e} E_{y_e} [D_i(t, \theta^e)]$$

(21)

The probability density function of the two variables can be written as $f(x_e)$ and $f(y_e)$, respectively. The two expected value of the above equation can be identified via the following equations:

$$E_{x_e} [D_i(t, \theta^e)] = \int_{-\infty}^{\infty} D_i(t, \theta^e) f(x_e) dx_e$$

(22)

$$E_{y_e} [D_i(t, \theta^e)] = \int_{-\infty}^{\infty} D_i(t, \theta^e) f(y_e) dy_e$$

(23)

The above two equations have some limitations. Specifically, they are targeted at the ideal condition that is without the interruption interval. Therefore, in order to get an accurate value of the data throughput
on $P_e$ in the research process, it is necessary to realize dynamic update of the upper and lower limit of the above two integrals.

When $P_e$ exceeds the beamwidth, the serious condition of full non-alignment might occur. Within the time domain, the following equation can be identified: 1) When $x_e < 0$ and $y_e \geq 0$, $t_i > t_{i+1} \iff P_i/\vec{v} > P_{i+1}/\vec{v}$; 2) When $x_e \geq 0$ and $y_e < 0$, $t_i > t_{i+1} \iff P_i/\vec{v} < P_{i+1}/\vec{v}$.

Derivation is carried out based on the above relational expression, and the overall non-alignment conditions are clarified and can be written as below:

$$x_e = \begin{cases} x_e > P_{i+1} - P_i, x_e \geq 0 \\ x_e < P_{i+1} - P_i, x_e < 0 \end{cases}$$

$$y_e = \begin{cases} y_e < P_{i+1} - P_i, y_e < 0 \\ y_e > P_{i+1} - P_i, y_e \geq 0 \end{cases}$$

Thereby, Eq. (22) and Eq. (23) can be converted as Eq. (26) and Eq. (27), respectively:

$$E_x \left[D_x(t, \theta^e)\right] = \int_{x_e(0)}^{x_e(t)} D_x(t, \theta^e) f(x_e) dx_e + \int_{x_e(t)}^{x_e(t) - P_i} D_x(t, \theta^e) f(x_e) dx_e$$

$$E_y \left[D_y(t, \theta^e)\right] = \int_{y_e(0)}^{y_e(t)} D_y(t, \theta^e) f(y_e) dy_e + \int_{y_e(t)}^{y_e(t) - P_i} D_y(t, \theta^e) f(y_e) dy_e$$

Through the mathematical simulation analysis of the above relational expression, the optimal beamwidth for the specific position error can be identified:

5. Algorithm simulation and analysis

This section focuses on model building. It is assumed that the vehicle moves under a random model. On the road, there are four tracks and each track are 3.5 wide. The corresponding driving distance of each track is length of the road barrier, $r_b$. In the movement process, the speed maintains constant.

In Fig. 4, the average network throughput velocity under various GPS errors and velocities are identified. Besides, the results thus obtained and the velocity under IEEE 802.11 ad are compared. Based on the sensitivity power provided by IEEE 802.11 ad, this research chooses the differentiated modulation and coding plan to process the SNR. When the average position error is 3m, comparison shows that the performance of the beamforming algorithm is consistent with that by IEEE 802.11 ad. Under the condition that the average position error is alleviated, the performance of the algorithm proposed in this paper significantly improves. When the vehicle velocity increases, the average network throughput of the algorithm proposed in this paper and the traditional algorithm both decreases. The only difference is that the decrease of the algorithm proposed by this paper is less significant. Thus, it is apt to tell that the vehicle velocity has a relatively weak influence on the network throughput of the system. When the vehicle velocity is high, the network throughput can reach a high level. So, it outperforms the traditional beamforming plans to some extent.
Figure 4. Average network throughput rate under GPS error and speed

Based on the equation proposed in 3.2, the influence of the single error component is analyzed. Under the condition that the error component is not random, the other error component is regarded as fixed. In this way, the value of various error components will have no limitations. The details are shown in Fig. 3. Upon prediction, the average position error is adopted as the average absolute distance between the predicted position and the actually-measured value. Then, the average position error is set to be zero under the condition that the error component is fixed. Suppose that the road sections where the vehicle moves are consistent with each other. The vehicle speed is 14 m/s. Under the above conditions, the simulation analysis is conducted. According to Fig. 5, when the two errors are consistent with each other, the influence of the x-axis on the system performance is more significant than the y-axis. Hence, it is highly necessary to analyze the position error of the specific path that is already known, and identify the degree of influence of different errors. On the basis of design optimization, the influence of various error components on the system performance is alleviated to improve the traffic safety.

Figure 5. Difference sensitivity of error components

The average channel capacity under different position errors can be identified via computation and analysis. As shown in Fig. 6, the results under various position errors and the ideal results are comparatively analyzed. Analysis shows that the predicted vehicle position information contains no error under the ideal conditions, which is consistent with the actually-measured value. On the contrary, when the position error appears, the beamwidth is close to 0°. This means that when the position error is very small, failure of complete non-alignment can still occur to exert a negative influence on the system performance. When the beamwidth is large, and the SNR decreases, the system’s channel capacity will be influenced. Analysis shows that when the position error is zero, the beamwidth and the channel capacity are negatively correlated. Along with the constant improvement of the beamwidth, the channel capacity decreases constantly. As to the reason behind this phenomenon, when the beamwidth is close to 0°, and the position error is small, the problem of no beam alignment might be caused. Under the condition, the beam directionality will be significantly improved, so will the system performance. After the beamwidth increases, the antenna gains declines, and the system’s channel capacity and SNR both
experiences decrease to some extent. Based on the specific position error, the optimal beamwidth can be identified, which can help obtain the optimal average channel capacity. On the curve of Fig. 6, the beamwidth under the condition is labelled by circles. In the process of designing the networked intelligent vehicle system, the advantage of choosing the optimal beamwidth is obvious, which can significantly improve the system’s comprehensive performance. When there is a specific error, slight adjustments can be made properly to achieve a significant improvement of the system performance.

Figure 6. Average channel capacity under various position errors

6. Conclusions
In terms of automobile service quality, IEEE 802.11ad cannot meet the requirement of the end-to-end delay (< 10ms). In order to effectively address this problem, this paper establishes a new-type beamforming plan. This plan, when being use, requires no exchange of information within the band to conveniently realize beamforming, which can significantly reduce the training time. This can provide reliable support to improve the networked intelligent vehicle, and meet the requirement of the specific communication throughput. This can also provide references for beamforming.

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