

Effects of Interference on Beamforming-Enabled Vehicular Networks in Multipath Propagation Environments

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Abstract—This paper characterizes the impact of interference on vehicular communications employing beamforming links between transmitters and receivers operating within a multipath propagation environment. Different road scenarios, such as an intersection and a roundabout are considered to determine the performance characteristics of the vehicle communication link. By employing the results for different antenna array elements and by varying distance, we analyse the bit error rate (BER) of vehicles operating in multipath propagation environments with an interferer within the vicinity of a communication link.

Keywords—Directional beamforming, Multipath fading, Connected vehicles

I. INTRODUCTION

Exchanging information using vehicle-to-vehicle (V2V) communications can potentially improve traffic safety and help reduce accidents [1]. Situational awareness information used in real-time applications, such as accident warning systems, emergency braking and road merging, require immediate communications between vehicles with minimal latency in order for it to be useful [2, 3]. To achieve minimum delay communications, one approach is using short range V2V communications [4], which can be used by one vehicle to transmit its current location and additional information to other surrounding vehicles to perform real-time operations and mitigate onroad collisions. To improve the efficiency of data transmission and to mitigate delays, directional beamforming can be employed in order to transmit the information by focusing that signal and energy towards a desired receiver [5].

Beamforming enables a spatial dimension to the transmission of information by maximizing signal energy towards a desired receiver or signal-of-interest (SOI), and with spatial nulls pointing towards the directions of the interfering signal sources or signals-not-of-interest (SNOI) via antenna radiation patterns [6]. When antenna arrays are used for beamforming, capacity improvements are achieved, as is as a reduction in fading due to multipath. They can either cancel or combine the interfering signals possessing different directions-of-arrival (DOA) from the transmitted signal and the multipath components of the transmitted signal [7]. Figure 1 illustrates an intersection scenario, where two vehicles are beamforming in the direction of each other to minimize the interference of other wireless communication in the area.

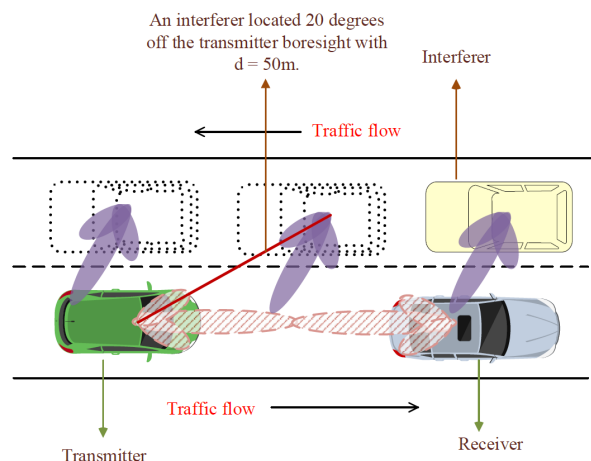


Figure 1: An illustration of how beamforming can be used in between a transmitter and a receiver in order to mitigate interference from other vehicles.

The primary objective of this paper is to analyse how the presence of an interferer can degrade performance in a multipath propagation environment when using directional beamforming approach. The novel contributions of this paper include::

- 1) A dual beamforming approach assuming a moving receiver: the transmitter is frequently updated with the estimated locations of the receiver for each time instant resulting in the boresight pointing at the desired direction. This assumption mitigates the delay caused by beamscanning to detect the location of the intended receiver.
- 2) Effect of an interference in a multipath environment: the effect of this source is evaluated by varying the number of antenna array elements and the distance between the transmitter and the receiver. By using the estimated location of the receiver obtained from the proposed state estimation algorithm (§ III), the bit error rate (BER) is determined.
- 3) Performance characteristics of the V2V communication link are evaluated in different road scenarios such as an

intersection and a roundabout.

The rest of this paper is organized as follows. Section II presents the mathematical details of our beamforming analysis. Section III presents details of the road geometry and state estimation of the location of the receiver in order to mitigate the delays and the location errors introduced in the V2V communication link. Section IV presents the performance characteristics by employing the proposed state estimation algorithm when the location of the receiver is known, as well as the impact an interference source causes to an established communication link in a multipath propagation environment. Finally, concluding remarks are provided in Section V.

II. BEAMFORMING PREPARATIONS AND CHANNEL MODEL

In this work, we employ a Uniform Linear Array (ULA) per vehicle, which is a type of phased array that is comprised of L antenna array elements spaced uniformly at a distance d . Each array element possess a different phase shift γ but maintains the amplitude [8]. The Array Factor (AF) for isotropic sources is given by the expression:

$$AF(\theta, \gamma) = 1 + e^{(j(d \cos(\theta) + \gamma))} + e^{(j2(kd \cos(\theta) + \gamma))} + \dots + e^{(j(L-1)(kd \cos(\theta) + \gamma))}, \quad (1)$$

where k is the wavenumber magnitude equal to $\frac{2\pi}{\lambda}$, θ is the azimuthal angle, and λ is the wavelength. Alternatively, this expression can also be written as:

$$AF(\theta, \gamma) = \sum_{l=1}^L e^{(j(l-1)(kd \cos(\theta) + \gamma))}. \quad (2)$$

The maximum array gain can be achieved by increasing the number of antenna array elements, resulting in a very narrow beam. If the location of the receiver is known, then the beam can be steered by changing the amplitude and the phase shift of the AF [9]. In this case, the AF can be reduced to:

$$AF(\theta, \gamma) = \frac{1}{L} \left(\frac{\sin(\frac{L}{2}\chi)}{\sin(\frac{1}{2}\chi)} \right), \quad (3)$$

where $\chi = kd \cos(\theta) + \gamma$.

Multipath propagation is due to the reflections of the transmitted signals present in the vicinity of the receiver [10]. In several scenarios, one copy of the transmitted signal will travel directly from the transmitter to the receiver while the other copies of the signals will be intercepted at the receiver and represented as a large summation of reflected rays from different directions. In most cases, the direct path signal possesses the strongest signal strength when compared with all the other received signal copies. These reflections depend on the power of the direct signal, as well as the delay, and phase with which they arrive at the receiver [11]. Based on the geometry of the channel, the characteristics of the multipath channels changes over time. A small difference in the arrival time between two copies of a signal can result in a large

difference in the quality of the received signal [12]. Suppose we define the direct copy versus of the transmitted signal as:

$$v(t) = \cos(\omega_0 t), \quad (4)$$

where ω_0 is the angular operating frequency. In this work, we employed a 5-ray propagation model, where the reflected rays are represented as:

$$v_{r,n} = \rho_n \cos[\omega_0(t - \tau_n)], \quad (5)$$

with ρ_n being the difference in the amplitude between the directly transmitted ray and the n^{th} reflected ray. The variable τ_n is the difference of time between the two rays, that is, the direct ray and the n^{th} reflected ray. Since we are considering five reflected signals, including the line of sight propagation, then $n = 5$. Equation(5) can also be represented as:

$$v_{r,n} = \rho_n \cos[\omega_0 t - \phi_n], \quad (6)$$

where $\phi_n = -\omega_0 \tau_n$. Therefore, the signal received by the receiving antenna is of the form:

$$\begin{aligned} v_{rx}(t) &= \cos(\omega_0(t)) + \rho_1 \cos[\omega_0(t - \tau_1)] + \\ &\quad \rho_2 \cos[\omega_0(t - \tau_2)] + \rho_3 \cos[\omega_0(t - \tau_3)] + \\ &\quad \rho_4 \cos[\omega_0(t - \tau_4)] \\ &= \cos(\omega_0(t)) + \rho_1 \cos[\omega_0 t - \phi_1] + \\ &\quad \rho_2 \cos[\omega_0 t - \phi_2] + \rho_3 \cos[\omega_0 t - \phi_3] + \\ &\quad \rho_4 \cos[\omega_0 t - \phi_4] \end{aligned} \quad (7)$$

The direct transmitted signal copy has a phasor of unit length with the zero degree phase angle, whereas the reflected signal copies possess phasors of lengths ρ_n and the angle ϕ_n varied across 0° to 360° . Per [13], with N reflections the received signal is given by the form:

$$y(t) = \sum_{x=0}^N s_x(t) + n(t) + i(t), \quad (8)$$

where $i(t)$ is the interference, $n(t)$ is the Additive White Gaussian Noise (AWGN), and $s_x(t)$ is transmitted signal. The receiver's antenna array elements intercepts the transmitted and reflected signals, and is expressed as:

$$y(t) = \sum_{x=0}^N a_i(t) s_x(t) + n(t) + i(t), \quad (9)$$

where $y(t) = [y_1(t), y_2(t), \dots, y_L(t)]^T$ contains the signal of each antenna array elements, and a_i is the steering vector of phase delays affecting the signal in each antenna element.

To locate the receiver, the beampatterns are swept at a constant rate. Directional beamforming is employed to support the spatial filtering of data between the two connected vehicles. In this paper, there are M signals, $\{S_m(k)\}$, being received by $N > M$ array elements with N adjustable weights, $W_n(k)$. For zero mean AWGN, the array output is given by [14] [15]:

$$y_k = \tilde{W}^T(k) \tilde{x}(k), \quad (10)$$

where $\tilde{x}(k) = \tilde{a}^T(\theta_i) \tilde{s}_k + \tilde{n}_k$, with $\tilde{w}(k) = W_1(k), \dots, W_N(k)$. $\tilde{a}$ is the steering vector for the angle of arrival θ_i and $\tilde{n}_k$ is the noise at each of the array element.

III. STATE ESTIMATION MODEL

We estimate the state variable of the ego vehicle (transmitter) and a receiver vehicle, denoted $x_e = (s_e, v_e)$ and $x_o = (s_o, v_o)$, respectively. Here, the subscripts e and o denote the ego vehicle (transmitted) and the other vehicle (receiver) respectively; s_e, s_o denote displacement along the road from a reference, and v_e, v_o denote speeds along the road. The mathematical expressions and the proposed state estimation model are from our previous work [16]. The effects of multipath fading and an interferer source on the communication link are analyzed using beamforming based on estimated receiver position made available by the proposed estimator. The state evolution and the measurement model of the ego vehicle is,

$$\dot{x}_e = Ax_e + B(u_e + \eta_e), \quad y_e = h_e x_e + n_e,$$

where $A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$,

u_e, u_o are the accelerations of the two vehicles, η_e denotes the acceleration measurement noise, $h_e(x_e) = [p_e(s_e), v_e]^T$ and n_e denote the localization and speed measurement noise.

The state evolution and the measurement model of the other vehicle with respect to the ego vehicle is:

$$\dot{x}_o = Ax_o + B(u_o + \eta_o), \quad y_o = h_o(x_o) + n_o, \quad (11)$$

where η_o is the acceleration measurement noise, $h_o(x_o) = [p_o(s_o), v_o]^T$ and n_o denote the localization and speed measurement noise. Here, $p_e(s_e)$ and $p_o(s_o)$ are the coordinates in a prespecified Cartesian coordinate system. The ego vehicle is assumed to update its location for every δt_e s and is transmitted over the time instants $t_{o,0}, t_{o,1} \dots$. Therefore, a discrete-time model is:

$$x_e(t_k) = \Phi_{\delta t} x_e(t_{k-1}) + \Psi_{\delta t} (u_e(t_{k-1}) + \eta_e(t_{k-1})),$$

$$x_o(t_k) = \Phi_{\delta t} x_o(t_{k-1}) + \Psi_{\delta t} (u_o(t_{k-1}) + \eta_o(t_{k-1})),$$

$$y_e(t_k) = h_e(x_e(t_k)) + n_e(t_k),$$

$$y_o(t_k) = h_o(x_o(t_k)) + no(t_k),$$

where $\delta t = t_k - t_{k-1}$ and:

$$\Phi_{\delta t} = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix}, \quad \Psi_{\delta t} = \begin{bmatrix} \frac{\delta t}{2} \\ 1 \end{bmatrix} \delta t. \quad (12)$$

As discussed in detail in our previous work [16], a discrete-time Kalman filter is implemented to estimate the boresight angle:

$$\alpha_{est} = \arctan \frac{p_{y,o}(\hat{s}_o) - p_{y,e}(\hat{s}_e)}{p_{x,o}(\hat{s}_o) - p_{x,e}(\hat{s}_e)}.$$

A. Geometry of the Considered Road Scenarios

Two road scenarios are considered for this paper: an intersection of two straight roads, and the intersection of a straight road with a roundabout. For the straight road intersection scenario, the road geometry is given by,

$$\begin{aligned} p_e(0) &= \begin{bmatrix} 525 \\ 0 \end{bmatrix} m, & p_e(s_e) &= p_e(0) + s_e \begin{bmatrix} \cos 70^\circ \\ \sin 70^\circ \end{bmatrix}, \\ p_o(0) &= \begin{bmatrix} 0 \\ 450 \end{bmatrix} m, & p_o(s_o) &= p_o(0) + s_o \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \end{aligned}$$

For the roundabout scenario, the road geometry is given by:

$$p_e(0) = \begin{bmatrix} 100 \\ 0 \end{bmatrix} m, \quad p_e(s_e) = p_e(0) + s_e \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$p_o(s_o) = \begin{bmatrix} 100 \\ 285 \end{bmatrix} + \rho \begin{bmatrix} \cos(\frac{s_o}{\rho} + \theta_0) \\ \sin(\frac{s_o}{\rho} + \theta_0) \end{bmatrix} m,$$

where $\rho = 100$ m and $\theta = \frac{\pi}{2}$.

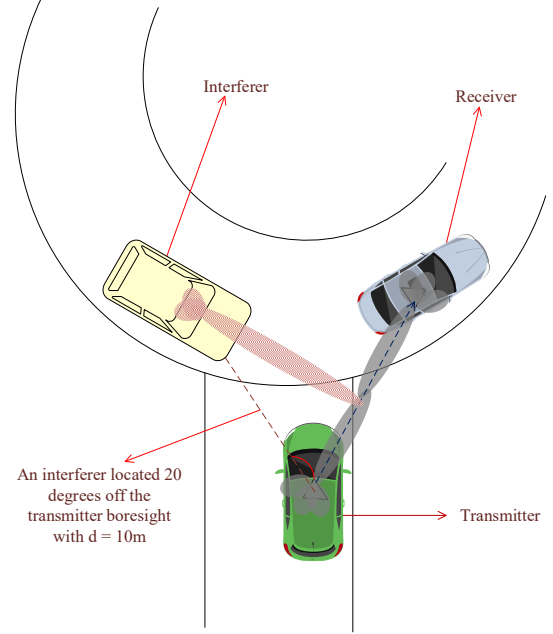


Figure 2: An illustration of the roundabout scenario considered in this paper with an interference source located 20° off the transmitter boresight with $d=10\text{m}$ at a particular time instant.

Figure 2 represents the roundabout road scenario considered in this paper. The green car and the blue car are the transmitter and the receiver, whereas the yellow vehicle is an interference source. This figure illustrates the position of an interference source at a particular time instant and at a particular distance from the transmitter and receiver.

IV. PROPOSED INTERFERENCE ANALYSIS AND DISCUSSION

In this section, we show the performance characteristics for the straight road intersection and the roundabout scenario, considering the effect of an interference source in a multipath-propagation environment. Using MATLAB, the simulation was carried out by varying the number of antenna array elements namely, $L = 4, 8, 16$. This is achieved by using the Equation(3). Moreover, leveraging Discrete-time Kalman filtering we are able to obtain the estimated location of our receiver. Therefore, the performance characteristic of our communication link is analysed with the location information obtained from our proposed state estimation model and from the GPS error location information obtained from the overhead channels . In this paper, we consider the power transmitted to be 1Watt with a transmitter gain of -8dB. For the straight road

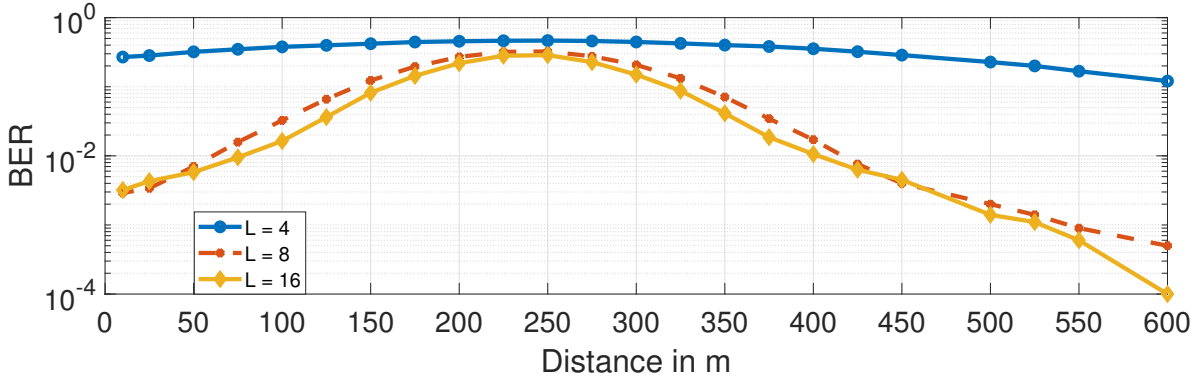


Figure 3: BER plot indicating the effect of an interferer source to the communication link between the transmitter and the receiver, assuming the vehicles are moving at a constant speed for different antenna array elements $L = 4, 8, 16$.

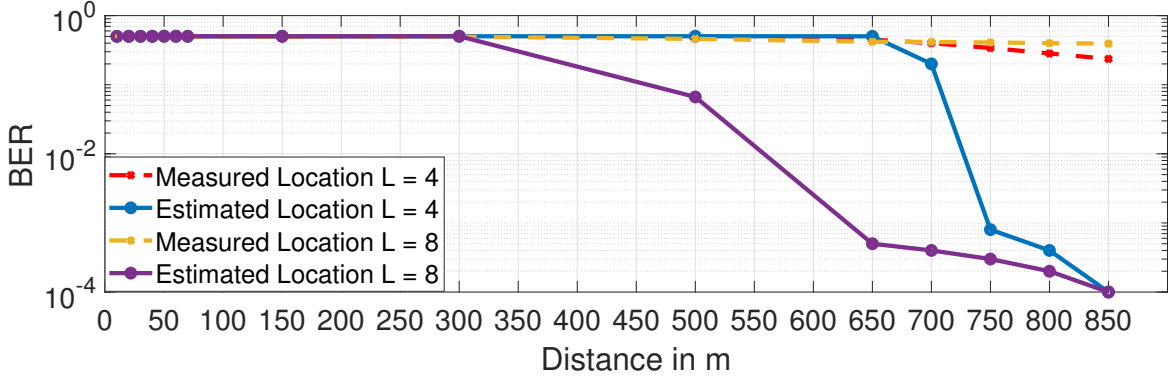


Figure 4: BER plot for the measured and the estimated location of the receiver for straight-road intersection scenario with $L = 4, 8$ with respect to varying distance and an interferer located 50m away from the transmitter.

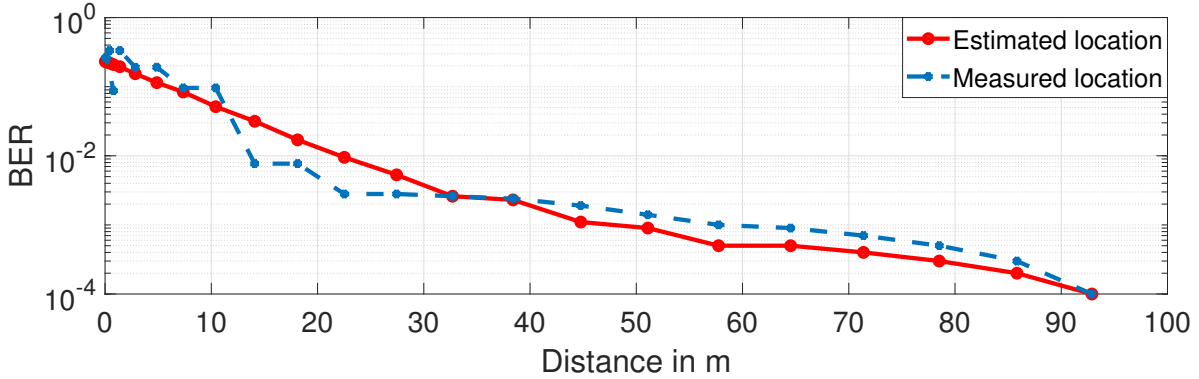


Figure 5: The BER plot for the measured and the estimated location of the receiver for the roundabout road scenario with $L = 4$ with respect to varying distance and an interferer located 10m away from the transmitter.

intersection scenario, the number of antenna array elements is varied and the result is compared between the estimated location of the vehicle and the measured location. The interferer is located at a distance of 50m and is steered at an angle of 20° off the transmitter boresight.

Figure 3 shows the effect on the established communication link due to an interference source moving in opposite direction of the traffic flow. Both the ego vehicle and the other (receiver) vehicle vehicles are assumed to be moving at a constant speed

with a distance of separation $d = 250$ m. By Fig. 3, we infer that the BER increases due to the signal interruption from the interference source. As the interference moves farther from the established link, the BER decreases. Also, for $L = 16$ antenna array elements, the communication is stronger when compared with $L = 4$ due to a wider beam angle.

Figure 4 shows the BER plot with respect to the distance d between the transmitter and the receiver. The transmitter vehicle is assumed to be stationary whereas the receiver

is in motion with an interference source present. With an interference source 50m away from the transmitter, we can see that for $L = 4$ almost 50% of the bits are corrupted. The BER is high even when the receiver is 600m away but as the distance increases, the BER gradually becomes low still indicating a weak communication link. For the same case, if the transmitter gets updated with the estimated location of the receiver, the BER increases. Similarly, for $L = 8$ the BER is high for the measured error location of the receiver indicating a poor communication link with a large number of bits being corrupted. However, when the receiver is 350m away from the transmitter or as the distance increases, the communication link becomes stronger due to the transmitter steering its main beam towards the predicted estimated location of the receiver.

In the case of the roundabout road scenario, the interferer is assumed to be located 10m away from the transmitter steered at an angle of 20° off the transmitter boresight. The interference source has a power of 0.001watt with a gain of -20dB. The receiver's location and the beam angle is varied as it changes for every time instant. When the receiver is close to the transmitter, even though there is a perfect link the signal is corrupted since the interference source contributes to the intercepted signal causing the BER to be very high. When the receiver is near the transmitter, the BER decreases, but as the distance increases the established link is not strong leading to the corrupted message. However, with the estimated location, the communication improves leading to lower number of bits getting corrupted. Since it is a roundabout, the geometry of the road is designed in such a way that the receiver moves farther away from the transmitter and again comes closer to it. The result we plotted is for the case when the receiver moves farther away from the transmitter. However, when the transmitter is near to the receiver vehicle, the communication significantly improves.

V. CONCLUSION

In this paper, we examined the effect of vehicular communication interference on the delivery of bit error rate in vehicular networks. We analyzed the performance characteristics for different road scenarios straight road intersection and for the roundabout. Our results illustrated that by making use of the proposed state estimation algorithm, by knowing the estimated location of the receiver, the delay is minimized as the beam is pointed towards the desired direction. When compared to the measured error location of the receiver, the established lock is stronger aiding in successful transmission of data in a multipath environment.

VI. ACKNOWLEDGEMENT

This research is supported in part by the US National Science Foundation (1646367).

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