Beamforming Optimization based on Kalman Filter for Vehicle in Constrained Route

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***Abstract*—By analyzing a simplified model for vechicles in a constrained route like High Speed Railway (HSR), it is found that when the distance between transmitter and route is short, the Direction of Arrival (DOA) changing speed is not a negligible effect. A Kalman Filter based solution is then proposed to fuse the vehicle speed sensor and DOA estimation. By using the filtered angle from Kalman filter, power loss due to angle mismatch could be reduced by more than 4dB for 4 elements antenna beamformer in the simulated scenario.**

I. INTRODUCTION

Wireless communication is advancing rapidly to meet the ever increasing demands for high mobility and high throughput communication. Beamforming is widely used in modern wireless standard like 5G and WiFi under the generalized name of precoding to improve signal quality. As adopted in 802.11ac, the closed loop beamforming becomes more popular since it makes transmit beamforming possible. It is done through a sounding process where beamformer sends sounding packet to individual beamformee. The beamformee needs to feedback Channel State Information (CSI) back to beamformer by analyzing the training field. As investigated in [1], [2], the delayed CSI feedback can degrade the beamforming performance significantly.

The degradation becomes even worse for High Speed Rail kind of scenario where the distance is close and DOA angle change is fast. Clearly there is a need to further investigate the challenges for the HSR scenario. The objective of this paper is to use the knowledge of the constrained route to optimize the beamforming performance under the fast angle change scenario. The rest of the paper is organized as follows. Firstly a simplified channel model for constrained route is described and DOA change characteristics and its impact on beamforming is analyzed. Then a solution based on Kalman filter is proposed to fuse the DOA estimation and vehicle speed sensor so that a predicted correction could be applied to the beamforming steering matrix. Finally the numerical simulation result is presented to conclude the proposed solution.

II. PROBLEM FORMULATION

Doppler spectrum and multiplath delay profile is usually used to characterize wireless channel. The higher the doppler spectrum bandwidth, the faster the change of channel gains hence the less coherence time. In the constrained route scenario like HSR, a strong Line of Sight (LOS) path exist as measured in [4]. A simplified model for HSR scenario is illustrated in Fig. 1 for analyzing the dynamics of doppler spectrum and DOA change over time.

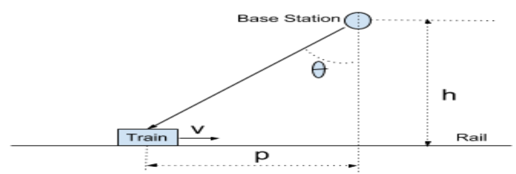

Fig. 1. Signal Model for Vechicle in Constrained Route

In Fig. 1, the train moving along the constrained route (rail) with velocity v. The base station is deployed along the road with distance of h. In actual case, there are multiple base station deployed along the road every several hundred meters. Here only one is illustrated for clarity. The instantaneous DOA $\theta(t)$ at time t is related to the v and the relative position in the road $p(t)$ by the following equation:

$$p(t) = h\tan(\theta(t)) \tag{1}$$

Taking derivative of (1), we can derive the instantaneous $\theta(t)$ changing speed in (2).

$$\dot{\theta(t)} = \frac{v}{hcos^2(\theta(t))} \tag{2}$$

The doppler shift caused by the train speed is

$$f_d = f_c\frac{v}{c}sin(\theta(t)) \tag{3}$$

where f_d, f_c, c is the doppler frequency shift, carrier frequency and light speed respectively.

It is clearly shown from (2) and (3) that when $\theta(t)$ is small, the doppler shift is small but the DOA changing is at its fastest speed. And the changing speed is inversely proportional to the distance h. So the DOA change speed is a unique problem for HSR like scenario where the base station and the route distance h is usually small. It could be around 1-10 meters which is much shorter than usual 5G base station to vehicle.

This poses a serious problem for beamforming performance due to the mismatch of beamforming steering vector and actual DOA.

III. PROPOSED SOLUTION

The proposed solution is to use Kalman filter to combine the knowledge of the constraint route rules as in (1) and (2) to reduce estimation error and minimzed the angle mismatch. As the vechicle speed v could be easily detected by a speed sensor, a Kalman filter could be used to fuse the DOA estimation θ and sensor detected speed v with the DOA estimation run at a lower rate. The state space transition of Kalman filter could then use the linear interpolated version of the DOA estimation.

The discrete Kalman filter system used to track the DOA is described in (4) and (5)

$$\boldsymbol{x}_{k+1} = \boldsymbol{A}\boldsymbol{x}_k + \boldsymbol{Q} \tag{4}$$

$$\boldsymbol{z}_k = \boldsymbol{C}\boldsymbol{x}_k + \boldsymbol{R} \tag{5}$$

where $\boldsymbol{x}_{k+1}$ $\boldsymbol{x}_k$ are the $k+1^{th}$ and k^{th} state vector $\begin{bmatrix} p \\ v \end{bmatrix}$, $\boldsymbol{A}$ is state transition matrix, $\boldsymbol{Q}$ is process covariance matrix, $\boldsymbol{z}_k$ is observation output vector, $\boldsymbol{C}$ is observation matrix and $\boldsymbol{R}$ is observation covariance matrix.

For this simplified model, the state transition matrix could be set as $\boldsymbol{A} = \begin{bmatrix} 1 & T_s \\ 0 & 1 \end{bmatrix}$ where T_s is the state sampling interval since the train speed is assumed to be constant over the sampling period. As for the observationi matrix, although the observed parameter are speed v and angle θ, (1) can be used to convert to angle θ to distance parameter p, so the observation matrix could be set as $\boldsymbol{C} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$.

IV. Numerical Simulation and Result Analysis

In Fig. 2, a train moves in the different speeds is simulated to show the drastic angle change and fast transition of doppler shift when the train passing by the base station when the h is set to 1 meter with carrier frequency of 5GHz.

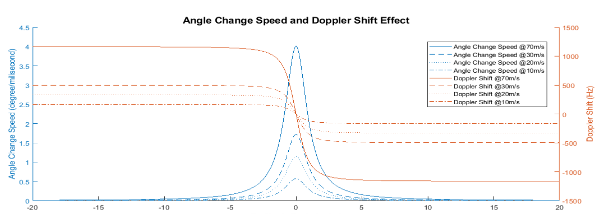

Fig. 2. DOA Changing Speed and Doppler Shift

An antenna array with 4 elements spaced with half wavelength is used for the Minimum Variance Distortionless Response (MVDR) beamforming simulation. Figure 3 shows the power loss could be 4dB even for a 4 element array. The loss would be more severe with increased number of antenna due to the sharper beam pattern.

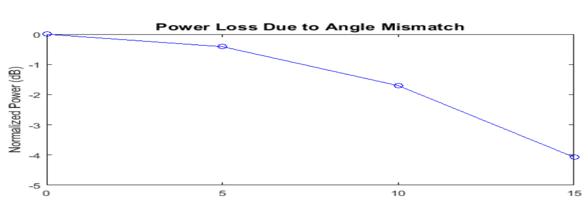

Fig. 3. Beamformer Power Loss Due to Angle Mismatch

In Fig. 4, a train with initial DOA of $-87°$ moving at speed of $20m/s$ along the route is simulated at sampling speed of $10ms$. The Kalman filter tracking performance is simulated for both every steps and interpolated measurement. It is shown that the filter is able to converge to the steady state quickly even when the initial setting is wrong. The interpolated measurement result also gives out satisfactory result which makes the angle estimation less frequent. The MVDR beamformer performance is then illustrated in Fig. 5. It shows that the Kalman filtered reduces the variation when there is a big jump in estimated angle.

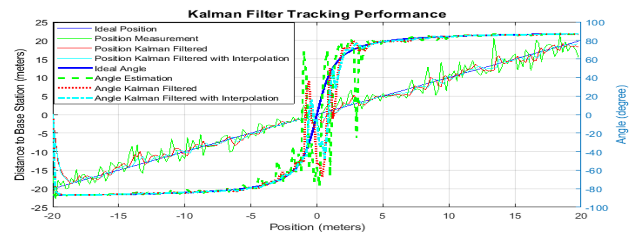

Fig. 4. Kalman Filter Tracking Performance

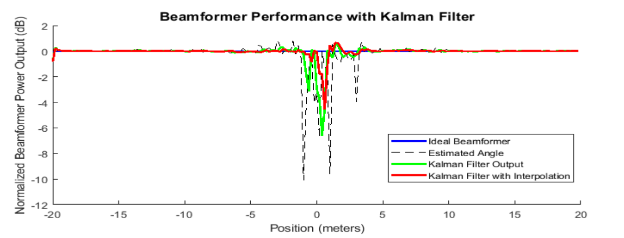

Fig. 5. Beamformer Performance Simulation

V. Conclusion

A simple model for vechicles in constrained route is analyzed for the impact of DOA and its changing speed in the beamformer performance. The beamformer performance could be degraded several dBs or more depends on the DOA, vechicle speed and base station distance to the route. A Kalman filter based method is proposed to fuse the speed sensor and DOA estimation. The simulation results shows effective results.

References

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