Multi-Sensor Assisted Cooperative Beam Tracking for mmWave Vehicle-to-Vehicle Communication

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***Abstract*—This paper presents an inertial measurement assisted technique for beam alignment and tracking in massive multiple-input multiple-output (MIMO) vehicle-to-vehicle (V2V) communications based on millimeter waves (mmWave). Since directional communications in vehicular scenarios are severely hindered by beam pointing issues, a beam alignment procedure has to be periodically carried out to guarantee the communication reliability. When dealing with massive MIMO links, the beam sweeping approach is known to be time consuming and often unfeasible due to latency constraints. To speed up the process, we propose a method that exploits a-priori information on array dynamics provided by an inertial measurement unit on transceivers to assist the beam alignment procedure. Numerical results based on real measurements of on-transceiver accelerometers demonstrate a significant gain in terms of V2V communication throughput with respect to conventional beam alignment protocols.**

***Index Terms*—Beam alignment, inertial sensor, V2V, mMIMO**

I. Introduction

Vehicle-to-anything (V2X) communications enable fast exchange of massive sensor data and mobility patterns between autonomous vehicles, opening the door to the so-called cooperative sensing and maneuvering functionalities [1]–[3]. V2X requires ultra reliable, low latency communication (URLLC) [4], with the objective of ensuring high data-rate (1 Gbps), ultra-low packet loss (10^{-7}) and ultra-low latency (1 ms) for tactile-like safety-critical applications [5]. These requirements indicate millimeter-wave (mmWave) radio as one of the strongest candidate to support V2X. Communication at the mmWaves guarantees large bandwidth availability, but it is hindered by severe path loss [6], that needs to be compensate by the beamforming gain of large antenna arrays that form sharp radiation beams. Such massive multiple-input multiple-output (mMIMO) systems are expected to become a pervasive technology in smart mobility applications, thanks to the limited array dimension and moderate energy consumption. Due to the narrow beams, mmWave radio is sensitive to the misalignment between transmitter and receiver, especially in a highly unstable scenario as vehicular communication. Precise beam alignment (BA) and tracking procedures are fundamental in guaranteeing the continuity of the communication performance as the devices move, but an exhaustive (or hierarchical) search of the optimal transmit/receive beam pair is too time demanding in vehicular scenarios, considering the latency constraints.

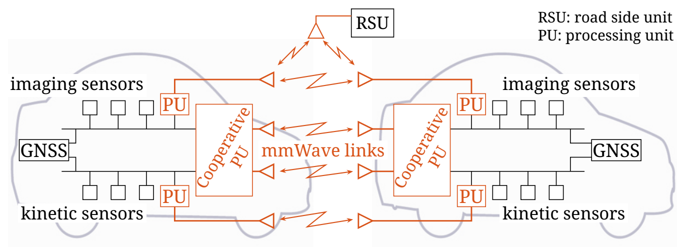

Fig. 1. Proposed ITS architecture with mmWave and sub-6 GHz connections cooperates in providing V2X connectivity.

We propose the joint contribution of local and distributed processing to fully support autonomous driving applications as in Fig. 1. In particular, V2X mmWave links provide the high data-rate necessary to exchange raw data from on-board sensors thus enabling cooperative processing. Other existing technologies could be used for redundancy, to provide additional low data-rate links and thus improving the system robustness against failure of the mmWave links. In this scenario, we advocate here a multi-sensor aided beam tracking for the mmWave, that leverages on the knowledge of the relative position and orientation of the vehicles to provide uninterrupted beam alignment, thus optimizing the performance of mmWave vehicle-to-vehicle (V2V) communications. Relative position and orientation of vehicles is obtained from ranging devices and from inertial measurements (IM). This multi-sensor assisted beam tracking results in a significant overhead reduction and in a continuous beam steering while data transmission occurs. The proposed approach applies also to vehicle-to-infrastructure (V2I) communications, with straightforward adaptations.

II. Multi-Sensor Assisted Beam Tracking

We consider two vehicles v_1 and v_2 equipped with mMIMO communication devices on front and rear bumper, respectively, as illustrated in Fig. 2. Let $t = 0, 1, 2, ...$ denote the discrete time with sampling interval Δt, a perfect alignment is observed right after the BA procedure at time $t = t_{\text{BA}}$, with the two vehicles v_1 and v_2 pointing their transmit/receive beams towards the line of sight (LOS) direction. As the vehicles move, V2V connectivity is affected by beam fluctuations due to the relative vibrations and tilting that can easily lead to communication drops when sharp beams are employed, as for $t \in [t_1, t_2]$ and $t \in [t_3, t_4]$ in Fig. 2. To avoid this problem, BA has to be periodically employed, by a beam sweeping

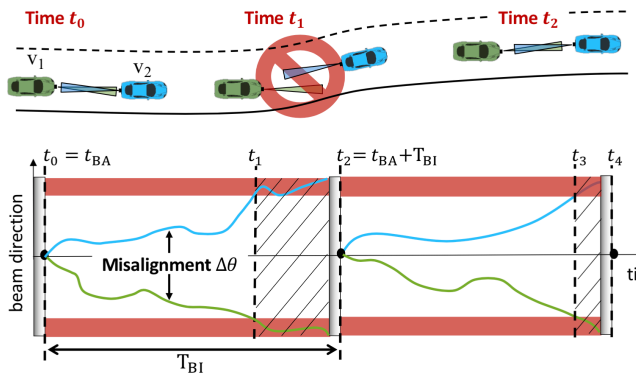

Fig. 2. BA problem: at time $t = t_0$ vehicles are correctly pointing their beams. At time $t = t_1$, the communication drops since beams are misaligned due to vehicle dynamics. To avoid this problem, vehicles must periodically perform a BA procedure with period T_{BI}.

procedure (e.g., exhaustive or hierarchical [7]) performed at the beginning of each beacon interval (BI) [8]. The BI length T_{BI} should be selected so as to optimize the throughput, as a short T_{BI} reduces the effective time for data transfer, while a long one might be inefficient to track the vehicle dynamics. The multi-sensor assisted beam tracking avoids the beam sweeping procedure by exploiting information about inter-vehicle distance and about the pose (orientation and position) of each vehicle extracted from IM. Each vehicle estimates its pose and exchanges this estimate with the surrounding vehicles, with negligible overhead. Finally, each transceiver adjusts the beam pointing direction according to its own pose and that of the other vehicles. In this work, we focus on the BA problem in case of vertical vibrations, but the analysis can be extended to any 3D orientation.

III. Numerical Results

The performance of the proposed multi-sensor assisted beam tracking technique is evaluated by considering real measurements of vehicle vertical displacement which, together with the inter-vehicle distance, is the primary cause of beam misalignment. The performance of the proposed beam tracking approach is simulated in a LOS and narrow-band channel with signal bandwidth of 2.16 GHz centered at 60 GHz, with inter-vehicle distance of 5 m. The IEEE 802.11ad standard adopting a conventional BA technique is used as a reference protocol, while, as upper bound, an ideal V2V communication system with perfect BA and exact knowledge of the geometrical parameters is chosen. The maximum achievable V2V data rate (in Gbps) is the selected performance indicator and it is presented versus the array resolution $\theta_{3\mathrm{dB}}$ in Fig. 3. The results are presented for three different values of accuracy σ_r in estimating the inter-vehicle distance, which impacts the performance only in the multi-sensor assisted technique.

Results indicate that, if the V2V distance is perfectly estimated (i.e., for $\sigma_r = 0$ cm), an IM-aided beam tracking method can closely approach the performance of an ideal communication system. However, considering realistic case of V2V distance measurement uncertainty (e.g., $\sigma_r = 10 - 30$ cm), sharp beams (small $\theta_{3\mathrm{dB}}$) are more sensitive to the variation of vehicle dynamics, resulting in a degradation of performance. To cope with this uncertainty, the use of broader beams is shown to be robust enough to significantly increase the throughput with respect to conventional BA protocols.

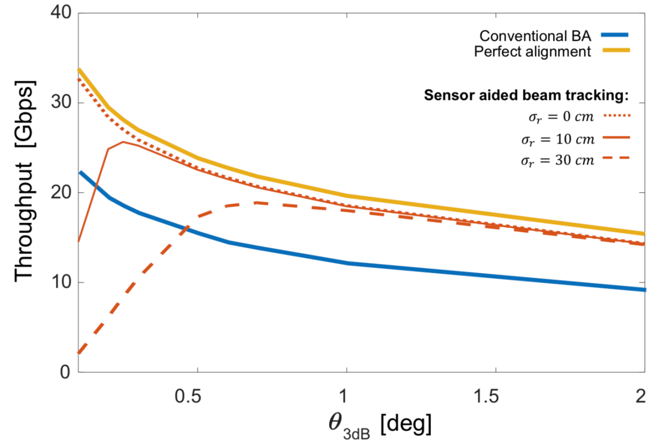

Fig. 3. V2V communication throughput comparison. The IM-aided beam tracking is compared to conventional BA protocol and to an ideal communication with perfect alignment.

IV. Conclusions

We developed an innovative solution for beam tracking in V2V communications based on side information of antenna array dynamics. The proposed multi-sensor assisted beam tracking system allows to continuously steer the beam while transmitting, it reduces the signaling payload of the communication and, lastly, it avoids a time-consuming search of the best beam pair between transmitter and receiver. Results demonstrated an increase in the V2V data rate with respect to conventional BA protocols for array resolution $\theta_{3\mathrm{dB}} > 0.2^\circ$ when typical values of ranging accuracy are used. The proposed methodology can be straightforwardly extended to handle V2I communication.

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