

Inertial Sensor Aided mmWave Beam Tracking to Support Cooperative Autonomous Driving

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Abstract—This paper presents an inertial sensor aided 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 sensor on transceivers to assist the beam alignment procedure. The proposed inertial sensor aided technique allows a continuous tracking of the beam while transmitting, avoiding frequent realignment phases. 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.

Keywords—Beam alignment, beam tracking, inertial sensor, V2V, mMIMO

I. INTRODUCTION

Connected autonomous vehicles are expected to improve safety, efficiency and comfort of mobility, disrupting the paradigm of traditional human-controlled driving [1]. Vehicle-to-everything (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 [2]–[4], which have been proved to augment the perception capability and the traffic efficiency. Considered the challenging requirements in terms of latency and data-rate [5], [6], today the millimeter-wave (mmWave) technology is deemed as the only viable radio frequency approach to support the V2X connectivity, thanks to the large availability of bandwidth in this spectrum region. Ultra-reliable fifth generation (5G) cellular standards are currently under development to meet the automotive use case requirements. They aim at ensuring high data-rate (1 Gbps), ultra-low packet loss (10^{-7}) and ultra-low latency (1 ms) for tactile-like safety-critical applications [7]. However, the severe path loss faced at mmWave frequencies, along with the effects of the atmospheric absorption and human/environmental obstructions, might significantly hinder the communication performance if not properly addressed. Mobility, Doppler effect, blockage and lack of context information are also critical issues to be considered in vehicular environments [8].

A solution is to adopt large antenna arrays at both side of the communication system, so as to form sharp radiation beams and compensate the high path-loss. Such massive multiple-input multiple-output (mMIMO) systems are expected to become a pervasive technology in smart mobility applications, thanks to the feasible array dimension (proportional to the mmWave wavelength) and moderate energy consumption. This approach, however, requires precise beam alignment (BA) and tracking procedures to guarantee the continuity of the communication performance as the devices move. An exhaustive search of the optimal transmit/receive beam pair might be too time demanding in vehicular scenarios, considering the latency constraints. To speed up the BA procedure, different solutions have been proposed in the literature [9]–[12]. For vehicular applications, the authors of [13] propose to explore the channel and queue state information to optimize both transmission and reception beamwidths. Other promising approaches exploit side information to support the communication, such as information provided by a radar signal operating in a different mmWave band in [14] or vehicle motion prediction based on global positioning system (GPS) data in [15].

Integration of data by transceiver’s sensors is a leading concept that is expected to be a turning point for the development of vehicle-to-vehicle (V2V) communications. This paper proposes to use accelerometers on the array of antennas to optimize the performance of mmWave V2V communications. In particular, the BA phase carried out by two vehicles before the data transmission is substituted by a faster signaling of predictive information on mutual V2V array dynamics. This approach results in an overhead reduction and it allows a continuous beam steering while data transmission occurs. The proposed approach applies also to vehicle-to-infrastructure (V2I) communications, with straightforward adaptations.

II. BEAM ALIGNMENT PROBLEM

We consider two vehicles v_1 and v_2 equipped with mMIMO communication devices on front and rear bumper, respectively, as illustrated in Fig. 1. The transceiver on each vehicle is assumed to sense the information on the array of antennas dynamic. Let $t = 0, 1, 2, \dots$ 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

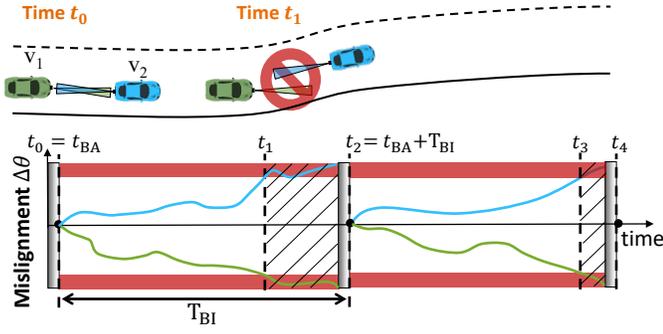


Fig. 1. BA problem: at time $t = t_0$ vehicles are correctly pointing their beams. At time $t = t_1$, the communication drops since beams are misaligned due to vehicle dynamics. To avoid this problem, vehicles must periodically perform a BA procedure with period T_{BI} .

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. 1. To avoid this problem, BA has to be periodically employed, by a beam sweeping procedure (e.g., exhaustive or hierarchical [9]) performed at the beginning of each beacon interval (BI) [13], i.e. with repetition time T_{BI} . 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.

Exemplifying the vehicle as a rigid body rotating around its three axis (longitudinal, perpendicular and lateral), in this work we consider only the vehicle rotation around the lateral one, i.e. the chassis pitch, which simplifies the analysis of BA problem relative to the vertical vibrations only. However, the proposed methodology is general enough to be extended to the complete 3D problem, where all the three rotations contribute to determine the vehicle attitude. Here, we analyze the impact of vertical vehicle oscillations (i.e., strokes) on the V2V communication between vehicles v_1 and v_2 and we propose a method to improve the beam pointing based on stroke measurements provided by an inertial sensor on antennas, as discussed in the following. As illustrated in Fig. 2, let \bar{h}_v be the height of the antenna array in rest conditions for vehicle v and $h_v[t]$ the height observed by an inertial sensor at time t , the pitch angle of vehicle v at time t is approximated

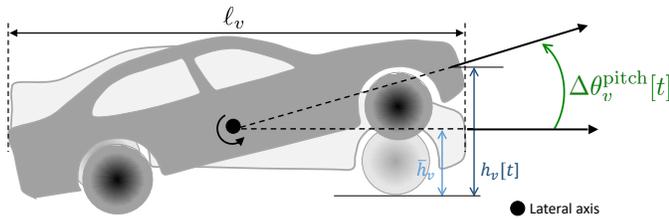


Fig. 2. Vehicle pitch from measurement of front height variations by a sensor inside the communication device.

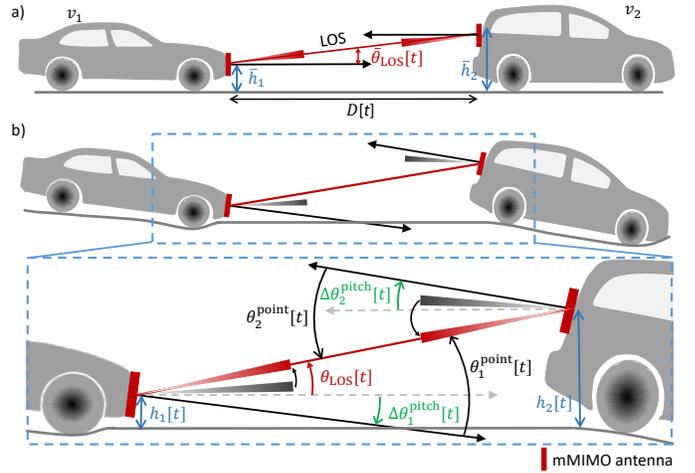


Fig. 3. a) V2V communication geometry in a rest condition. b) Impact of the chassis pitch with emphasis on beam steering.

by:

$$\Delta\theta_v^{\text{pitch}}[t] = \tan^{-1}\left(\frac{h_v[t] - \bar{h}_v}{0.5 \ell_v}\right), \quad (1)$$

where ℓ_v indicates the vehicle length. The pitch variations over time impact on the V2V communication link, as shown in Fig. 3.

In ideal conditions with null pitch, i.e. for $\Delta\theta_1^{\text{pitch}}[t] = \Delta\theta_2^{\text{pitch}}[t] = 0$ (Fig. 3a), the LOS angle between vehicles v_1 and v_2 is:

$$\bar{\theta}^{\text{LOS}}[t] = \tan^{-1}\left(\frac{\bar{h}_2 - \bar{h}_1}{D[t]}\right), \quad (2)$$

where $D[t]$ indicates the inter-vehicle distance at time t . Assuming that the transmit/receive beams at the two vehicles are steered according to the nominal LOS direction (2), if a chassis pitch occurs (e.g., due to road conditions, electro-mechanical vehicle configurations, engine vibrations), it causes vertical oscillations of the antenna arrays which modifies the beam pointing geometry. This effect is highlighted in Fig. 3b, where the LOS has changed to

$$\begin{aligned} \theta^{\text{LOS}}[t] &= \tan^{-1}\left(\frac{h_2[t] - h_1[t]}{D[t]}\right) \\ &\approx \bar{\theta}^{\text{LOS}}[t] - \Delta\theta_1^{\text{pitch}}[t] - \Delta\theta_2^{\text{pitch}}[t] \end{aligned} \quad (3)$$

due to the rotations $\Delta\theta_v^{\text{pitch}}[t]$ at the two vehicles $v = 1, 2$. The above change of the LOS elevation angle, together with the rotation of the two antenna arrays, leads to a change in the beams' directions which are no more pointing towards the TX-RX link (black beams in Fig. 3b). Note that the approximation in (3) holds since the vibrations (in the order of few centimeters) are much smaller than the inter vehicle distance (in the order of several meters) and thus it is $|h_v[t] - \bar{h}_v|/D[t] \ll 1$.

To reduce the misalignment, in the following section we propose an on-antennas inertial sensor assisted beam tracking solution. Each array uses its own sensor data and a prediction of the other array dynamics based on V2V data exchange to

track the pitch terms in (3) inside the BI and dynamically steers its beam according to the predicted LOS. This technique allows to improve the beam pointing inside the BI and to avoid too frequent time-consuming BA procedure by relying only on sensor data and predictive filters, thus increasing the communication throughput. A visual representation of this concept is highlighted in Fig. 3b where the wrongly pointing black beams have to be steered to point along the LOS link at best (red beams).

III. INERTIAL SENSOR ASSISTED BEAM TRACKING

In the inertial sensor aided beam tracking system, a prediction is made by each transceiver on the behavior of its sensor based on past dynamics measurements. The prediction is then sent to the transceivers of the surrounding vehicles, with negligible overhead. Finally, each transceiver adjusts the beam pointing direction according to its own sensor data and the information received from the transceivers of the other vehicles. The steps of the proposed technique are detailed in the following.

A. Strokes prediction

The basis of beam tracking is a prediction of the stroke dynamics $h_v[t]$ performed at each transceiver $v = 1, 2$ at the beginning of the BI. Given the vehicle stroke $h_v[t]$, the future process samples $h_v[t + i]$, $i > 0$, are predicted locally as a combination of its own past samples. To guarantee this step, a memory with the recent history of antennas dynamics has to be saved as essential for stroke prediction.

B. V2V communication

Once a set of I predicted stroke samples $\hat{h}_v[t + i]$, $i = 1, \dots, I$, has been calculated at transceiver v , it is communicated to the other transceiver over the V2V link and used for beam tracking within the next BI. Assuming a time division duplex (TDD) protocol for mmWave communications, where signaling for beam pointing is handled at the beginning of each frame, we propose a frame structure which reduces the occurrence of BA procedures and maximizes the payload.

We consider as a reference the IEEE 802.11ad/WiGig standard [16], [17], a widely adopted mmWave technology operating in the 60 GHz band mainly designed for stationary/quasi-stationary applications and here adapted to the context of V2V communications. As presented in Fig. 4, the transmission frame is divided into two main access periods: a beacon header interval (BHI), dedicated to the exchange of management information and network announcements, and a data transmission interval (DTI), where data are transmitted. The BHI consists of three sub-intervals, the beacon transmission interval (BTI), the association beamforming training (A-BFT) and the announcement transmission interval (ATI). Even if the analysis of the frame structure is out of the scope of this work, the review on BI structure is necessary to detail the BA procedure. In the IEEE 802.11ad standard, BA consists of two different phases: a sector level sweep (SLS) and a beam refinement protocol (BRP) phases. An initial coarse-grained

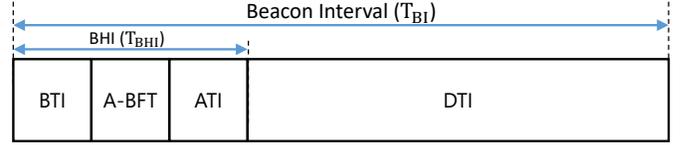


Fig. 4. IEEE 802.11ad frame. Besides the slot dedicated to data transfer (DTI), the frame presents an additional payload for signaling information (BHI).

antenna sector configuration is determined in the SLS and it is further refined during the BRP. Relying on a contention-based approach, the SLS occurs during BTI and A-BFT slots, while the BRP can be done in the ATI or DTI. A typical BI length for stationary, or quasi-stationary, applications is 100 ms. However, for latency-critical tactile-like applications where short BI lengths are needed, the overhead for time-consuming BA procedures severely impacts on the communication throughput, as the DTI is significantly compressed. Considering that in V2X applications, a BI ≤ 30 ms is typically considered to face the high mobility [15], [18], a reduction of the BHI signaling is advisable. Indeed, 5G mobile systems (where V2X communication is a primary use case) rely on a 10 ms long radio frame.

The key idea of the proposed beam tracking approach is to reduce the signaling for beam alignment so as to shorten the BHI period and extend the DTI, with benefits in transmission efficiency. By exploiting inertial sensor assisted predictive models, the best beam pair search between transmitter and receiver is substituted by beam pointing based on predicted stroke information $\hat{h}_v[t + i]$, with negligible additional signaling payload (i.e., the transmission of the predicted samples only). Denoting with T_S the overall BI overhead due to signaling information and with T_{BA} the overhead portion for the BA procedure (i.e., SLS and BRP), we can define the transmission efficiency as the ratio of the time interval dedicated to data transfer over the BI duration T_{BI} , as follows:

$$\eta = \begin{cases} 1 - \frac{T_S + T_{BA}}{T_{BI}} \approx 1 - \frac{T_{BHI}}{T_{BI}} & \text{conventional BA protocol,} \\ 1 - \frac{T_S}{T_{BI}} & \text{sensor aided beam tracking.} \end{cases} \quad (4)$$

Considering that BA is the dominant signaling payload, the T_{BA} removal by the proposed technique leads to significant benefits in terms of transmission efficiency, as discussed in Sec. V by numerical analysis.

C. Beam tracking

As BA is essential for mmWave directional communications, the choice of the optimal pointing direction is crucial to guarantee reliable communications. This issue is far more critical when dealing with mMIMO systems, where the beamwidth is narrow. Focusing for convenience on a single BI period, at time instant $t = 0, 1, \dots, T_{BI}$, vehicle v_1 should direct the beam towards the ideal pointing angle $\theta_1^{\text{point}}[t]$ given by (see Fig. 3b):

$$\theta_1^{\text{point}}[t] = -\Delta\theta_1^{\text{pitch}}[t] + \theta^{\text{LOS}}[t], \quad (5)$$

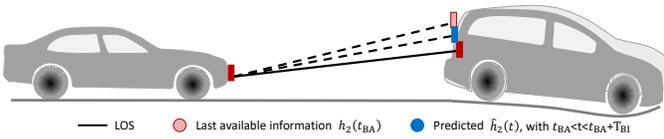


Fig. 5. Beam tracking effect: a prediction on the stroke dynamics based on an inertial sensor in the communication device allows to properly point the beam, reducing misalignments.

where $\Delta\theta_1^{\text{pitch}}[t]$ accounts for the rotation of the antenna array at vehicle v_1 . However, due to lack on real-time knowledge of the dynamics of the communication device at vehicle v_2 , the pointing angle of v_1 is

$$\hat{\theta}_1^{\text{point}}[t] = -\Delta\theta_1^{\text{pitch}}[t] + \hat{\theta}^{\text{LOS}}[t], \quad (6)$$

where $\hat{\theta}^{\text{LOS}}[t]$ is the estimate of the elevation angle of the LOS path connecting the two V2V devices (see Fig. 3):

$$\hat{\theta}^{\text{LOS}}[t] = \begin{cases} \tan^{-1}\left(\frac{h_2[t_{\text{BA}}] - h_1[t]}{D[t]}\right) + n_{\text{BA}} & \text{conventional BA} \\ & \text{protocol,} \\ \tan^{-1}\left(\frac{\hat{h}_2[t] - h_1[t]}{D[t]}\right) & \text{sensor aided beam} \\ & \text{tracking.} \end{cases} \quad (7)$$

Here, $\hat{D}[t] = D[t] + n_d[t]$ denotes the measured inter-vehicle distance modeled with $n_d[t] \sim \mathcal{N}(0, \sigma_r^2)$, where σ_r represents the measurement accuracy provided, for example, by a radar system. The additional term n_{BA} takes into account for misalignments occurring while searching the best beam pair in conventional BA protocol. It is modeled as a random variable uniformly distributed as $n_{\text{BA}} \sim \mathcal{U}(-\theta_{3\text{dB}}, +\theta_{3\text{dB}})$, where $\theta_{3\text{dB}}$ denotes the antenna resolution. For a uniform linear array (ULA) the resolution is evaluated as the 3-dB beamwidth in angle-space, which is typically related to the number of antenna elements N by the approximation $\theta_{3\text{dB}} \approx 0.866/N$ rad [19]. From (7), it is evident that a perfect awareness of the self dynamics is not sufficient to get a perfect pointing since $\hat{\theta}^{\text{LOS}}[t]$ depends also on v_2 device dynamics.

In traditional BA systems transceivers are unaware of the other transceiver dynamics inside the BI and vehicles can only use the information available at the time BA is performed (i.e., at time $t = t_{\text{BA}}$). Using side information on predicted dynamics exchanged at the beginning of the BI as in the proposed approach the term $\hat{\theta}^{\text{LOS}}[t]$ can be updated all over the BI, i.e. $\forall t \in (t_{\text{BA}}, t_{\text{BA}} + T_{\text{BI}})$. In this way, the transceiver v_1 can optimize its pointing angle $\hat{\theta}_1^{\text{point}}[t]$ over time, approaching the ideal condition of perfect LOS communication, as shown in Fig. 5. The benefit of the proposed system is twofold, i.e. an increased transmission efficiency η due to the signaling reduction (appreciated especially for short BI) and a beam tracking gain provided by dynamics prediction (for longer BI).

IV. V2V MMWAVE CHANNEL MODELING

In the following, we evaluate the impact of the mismatch between the true and estimated beam-pointing, $\theta_v^{\text{point}}[t]$ and $\hat{\theta}_v^{\text{point}}[t]$, at vehicles $v = 1, 2$ on the V2V transmission

capacity. We assume a mmWave mMIMO LOS and narrow band communication link between the two vehicles, with a ULA of N antennas at both vehicles.

The received power at time t is modeled as:

$$P_{\text{rx}}^{\text{dB}}[t] = P_{\text{tx}}^{\text{dB}} + G_1[t] + G_2[t] - PL^{\text{dB}}[t] \quad (8)$$

where $P_{\text{tx}}^{\text{dB}}$ is the transmitted power, $G_1[t]$ and $G_2[t]$ are the ULA antenna gains at the two vehicles and $PL^{\text{dB}}[t]$ the channel path loss. The latter is defined as:

$$PL^{\text{dB}}[t] = 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10\kappa\log_{10}D[t] + \chi_{sh}, \quad (9)$$

where λ is the carrier wavelength, κ the path loss exponent and χ_{sh} is the log-normal distributed shadowing, $\chi_{sh} \sim \mathcal{N}(0, \sigma_{\text{dB}}^2)$ [20].

The main vehicle dynamics-dependent parameters in (8) are the antenna array gains $G_v[t]$, $v = 1, 2$, which depend on the beam-pointing mismatch that for ideal uniform linear array is:

$$\begin{aligned} G_v[t] &= G\left(\hat{\theta}_v^{\text{point}}[t] \middle| \theta_v^{\text{point}}[t]\right) \\ &= \frac{1}{N} \left| \mathbf{a}(\hat{\theta}_v^{\text{point}}[t])^H \mathbf{a}(\theta_v^{\text{point}}[t]) \right|^2 \\ &= \left| \frac{\sin\left[\pi\left(\frac{\sin(\hat{\theta}_v^{\text{point}}[t]) - \sin(\theta_v^{\text{point}}[t])}{2}\right)N/2\right]}{N \sin\left[\pi\left(\frac{\sin(\hat{\theta}_v^{\text{point}}[t]) - \sin(\theta_v^{\text{point}}[t])}{2}\right)\right]} \right|^2. \end{aligned} \quad (10)$$

$\mathbf{a}(\theta) = [a_1(\theta), \dots, a_N(\theta)]^T \in \mathbb{R}^{N \times 1}$ is the steering vector modeling the antenna array response to a direction θ that for a half-wavelength spacing between the antenna elements is:

$$a_n(\theta) = h_n e^{-j\pi(n-1)\sin\theta}, \quad 1 \leq n \leq N. \quad (11)$$

The term h_n is introduced to account for the mismatches of the transceivers radio frequency (RF) circuits at the antenna elements and array calibration errors due to hardware themselves and properties of surrounding environments (e.g., temperature and moisture). The RF mismatch is modeled as $h_n = \rho_n e^{j\psi_n}$, with log-normally distributed amplitude $10\log(\rho_n) \sim \mathcal{N}(0, \delta^2)$ and uniformly distributed phase $\psi_n \sim \mathcal{U}(-\phi, +\phi)$ [21], [22].

The noise power at the receiver is evaluated as

$$P_{\text{noise}}^{\text{dB}} = N_{fl} + 10\log_{10}B + NF, \quad (12)$$

where N_{fl} is the noise floor ($N_{fl} = -174$ dBm/Hz), B is the system bandwidth and NF is the noise figure. The signal-to-noise ratio (SNR) is finally evaluated as the ratio between the receive and noise power as:

$$\text{SNR}[t] = \frac{P_{\text{rx}}[t]}{P_{\text{noise}}[t]}, \quad (13)$$

Recalling the definition of η in Sec. III-B, the maximum achievable data rate in the V2V link between v_1 and v_2 in a single BI is obtained as:

$$R_{12}[t] = \eta B \log(1 + \text{SNR}[t]). \quad (14)$$

The above V2V data rate is used in the following section to assess the performance of the proposed inertial sensor aided beam tracking technique.

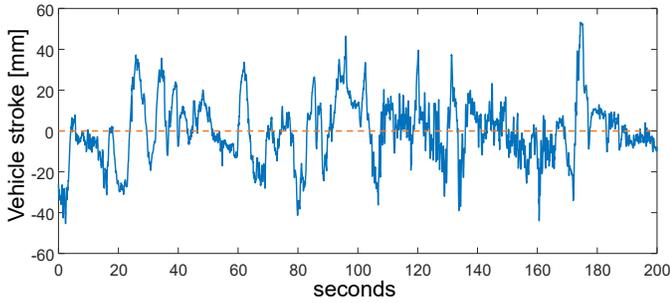


Fig. 6. Real measurements of vehicle strokes provided by the inertial sensor.

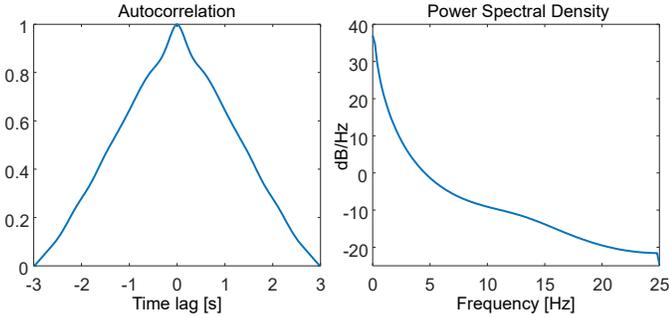


Fig. 7. Vehicle stroke properties: autocorrelation and power spectral density.

V. NUMERICAL RESULTS

In this section we assess the performance of the proposed inertial sensor aided beam tracking technique based on real measurements of vehicle strokes. A measurement campaign has been carried out for an acquisition interval of 200 s, where data have been gathered with a sampling frequency of 50 Hz. The data have been collected on a high-end passenger car (sedan), using the accelerometers transformed to vertical component only. These data are plotted in Fig. 6, while their statistical properties, namely the normalized autocorrelation and the power spectral density, are presented in Fig. 7. The vehicles' strokes $h_1[t]$ and $h_2[t]$ are modeled as autoregressive AR(10) processes with parameters calibrated on the real measurements. To match the strokes resolution to the BI duration, an interpolation factor of 10 is applied to $h_1[t]$ and $h_2[t]$ to have a resolution in time of $\Delta t = 2$ ms. The following results are obtained assuming a constant V2V distance of $D(t) = 5$ m, which is a typical value in platooning applications. Its estimate $\hat{D}(t)$ is updated by the vehicles every 200 ms. The simulation parameters are summarized in Tab. I.

We compare the performance of the proposed inertial sensor aided beam tracking approach with respect to conventional BA techniques, taking the IEEE 802.11ad standard as a reference protocol. We also consider as upper bound the performance of an ideal V2V communication system with perfect BA based on exact knowledge of the geometrical parameters at each time t . The maximum achievable V2V data rate (in Gbps) is used as a performance indicator and it is presented versus the array resolution $\theta_{3\text{dB}}$ in Fig. 8-(a) and versus the BI duration T_{BI} in Fig. 8-(b). The results are presented for three different values of radar accuracy σ_r , which impacts the performance only in the sensor aided technique. In the throughput evaluation, we consider a frame to be erroneously received if $\exists t \in \text{BI s.t.}$

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Length ℓ_1	4.5 m	Length ℓ_2	5 m
Height \bar{h}_1	0.5 m	Height \bar{h}_2	1 m
Overhead T_{BA}	1.9 ms	Overhead T_{S}	0.1 ms
Predictor length p	11	V2V distance D	5 m
Carrier Frequency	60 GHz	System Bandwidth B	2.16 GHz
Tx Power P_{t_x}	1 dBm	Path Loss Exponent κ	2
Shadowing σ_{dB}	5.8 dB	Noise Factor NF	6 dB
RF mismatch δ_{dB}	1 dB	RF phase mismatch ϕ	3°

$$\text{SNR}[t] < \text{SNR}_{\text{ideal}}[t] - 6\text{dB}.$$

Results in Fig. 8 indicate that sharp beams (or equivalently small $\theta_{3\text{dB}}$) increase the throughput as the power is concentrated in a narrower angular space, however they are more sensitive to the variation of vehicle dynamics and to the inter-distance accuracy in the V2V distance estimate. A sensor aided beam tracking method can closely approach the performance of an ideal communication system with perfect alignment if the V2V distance is perfectly estimated (i.e., for $\sigma_r = 0$ cm). On the other hand, degrading effects due to poor ranging systems (e.g., for $\sigma_r = 30$ cm) occur at small $\theta_{3\text{dB}}$. Considering that a typical accuracy in V2V application is $\sigma_r = 10$ cm, we can conclude that a sensor aided beam tracking system can provide a higher V2V throughput for $\theta_{3\text{dB}} > 0.2^\circ$ for any T_{BI} with respect to conventional BA protocols. Note that for long BI ($T_{\text{BI}} = 50$ ms), the use of sharp beams reduces the throughput even for conventional BA systems, as vehicles are likely to be in misalignment conditions.

VI. CONCLUSIONS

In this paper, we developed an innovative solution for beam tracking in V2V communications based on side information of antenna array dynamics. The proposed inertial sensor aided 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 any frame duration and for array resolution $\theta_{3\text{dB}} > 0.2^\circ$ when typical values of ranging accuracy (e.g., $\sigma_r = 10$ cm) are used. The proposed methodology can be extended to handle the communication between a vehicle and a fixed station, as for V2I.

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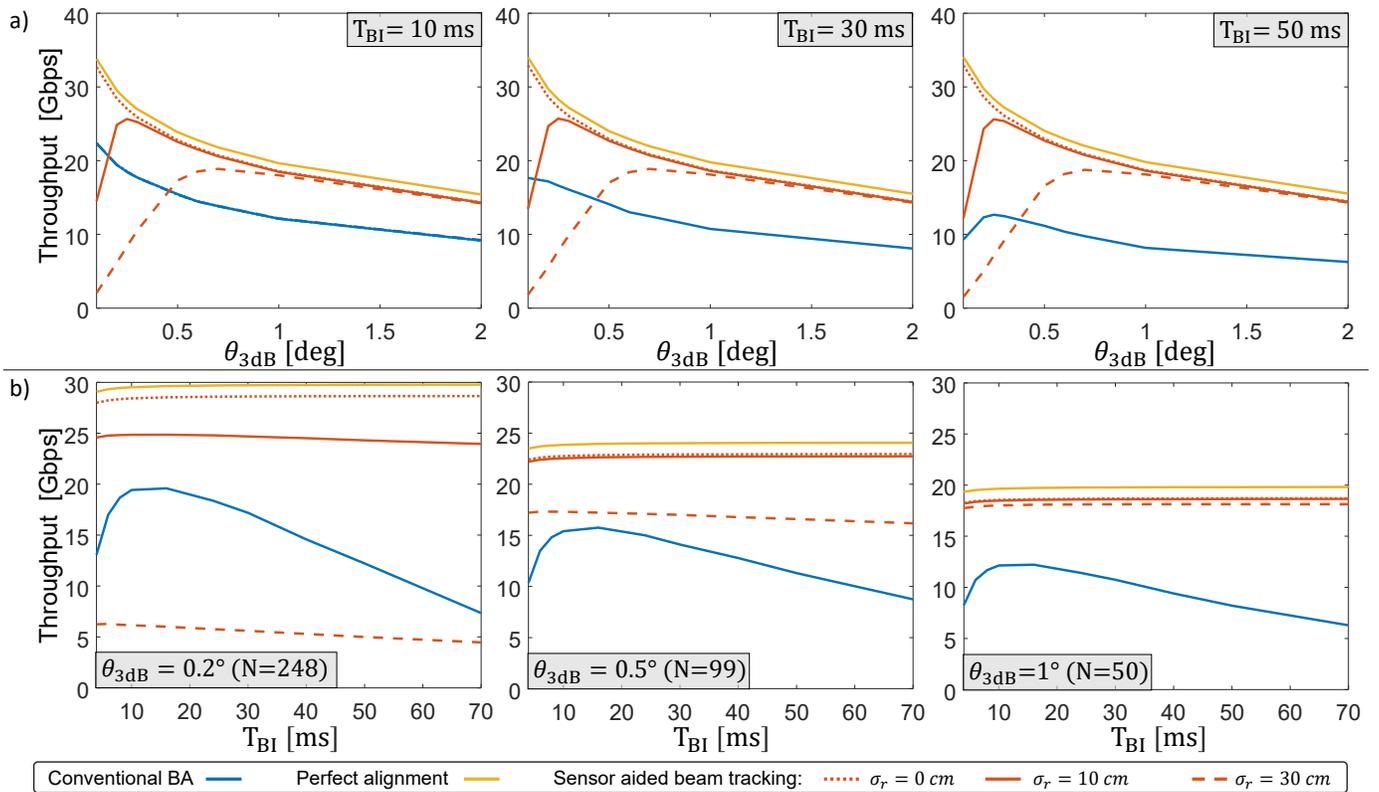


Fig. 8. V2V communication throughput comparison. The inertial sensor aided beam tracking is compared to conventional BA protocol and to an ideal communication with perfect alignment. a) The V2V throughput is plotted versus the BI duration T_{BI} for three different beamwidth. b) The V2V throughput is presented versus the beamwidth for three different T_{BI} .

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