Multi-Vehicle Velocity Estimation Using IEEE 802.11ad Waveform

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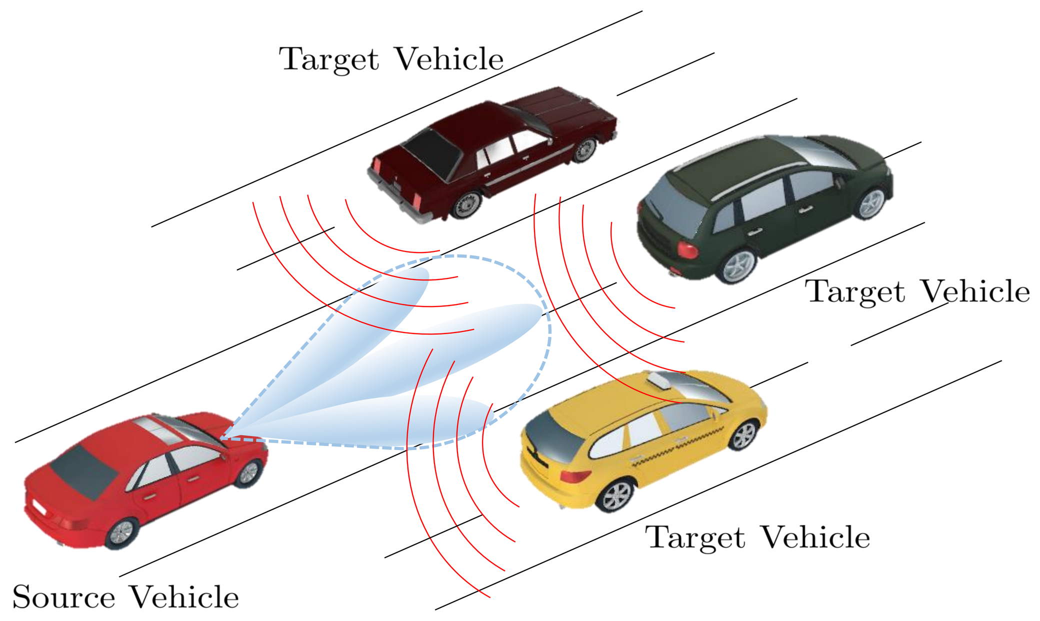
ABSTRACT

- Use of millimeter wave (mmWave) spectra for wireless communications
  - enable extra radar functionalities
- Dual functional systems for radar and communications
  - reduced power consumption & physical space
  - jointly optimized especially for vehicular environments
- IEEE 802.11ad waveform
  - good correlation property of preamble suitable for target sensing
- Proposed multi-vehicle velocity estimation technique
  - form a wide beam to detect multiple target vehicles
  - estimate round-trip delays and Doppler shifts
  - compensate the phase wrapping in Doppler shifts

SYSTEM MODEL

- **A vehicle-to-vehicle (V2V) multi-target scenario**



- Two-way radar channel model

$$\mathbf{H}(t)=\sum_{p=0}^{P-1}\sqrt{G_p(t)}\beta_p e^{j2\pi t\nu_p(t)}e^{-j2\pi f_c\tau_p(t)}\mathbf{a}^*_{\mathrm{RX}}(\phi_p(t),\theta_p(t))\mathbf{a}^{\mathrm{H}}_{\mathrm{TX}}(\phi_p(t),\theta_p(t))$$

P : The number of target vehicles; $\nu_p(t)$: Doppler shift; $\phi_p(t)$: Azimuth angle
$G_p(t)$: Large-scale channel gain; $\tau_p(t)$: Round-trip delay; $\theta_p(t)$: Elevation angle
β_p : Small-scale complex channel gain $\sim\mathcal{CN}(0,1)$

- Wide beam

$$\mathbf{f}_{\mathrm{TX},x}=\sum_{i=1}^{N_c}\gamma_i\mathbf{a}_{\mathrm{TX},x}(\varphi_i,\vartheta_c),\ \mathbf{f}_{\mathrm{TX},y}=\mathbf{a}_{\mathrm{TX},y}(\vartheta_c)\ \Rightarrow\ \mathbf{f}_{\mathrm{TX}}=\frac{\mathbf{f}_{\mathrm{TX},x}\otimes\mathbf{f}_{\mathrm{TX},y}}{\|\mathbf{f}_{\mathrm{TX},x}\otimes\mathbf{f}_{\mathrm{TX},y}\|}$$

N_c : The number of combined beams; φ_i : Azimuth angle of the i-th beam
γ_i : Weight coefficient for the i-th beam; ϑ_c : Fixed elevation angle

- Radar echo signal model

$$y[m,k]=\sum_{p=0}^{P-1}\sqrt{P_{\mathrm{TX}}}h_p e^{j2\pi\nu_p^m(k+mK)T_s}s[k-\ell_p^m]+z[m,k]$$

h_p : Backscattering coefficient $\left(h_p\approx\sqrt{G_p}\beta_p\mathbf{f}^{\mathrm{H}}_{\mathrm{RX}}\mathbf{a}^*_{\mathrm{RX}}(\phi_p,\theta_p)\mathbf{a}^{\mathrm{H}}_{\mathrm{TX}}(\phi_p,\theta_p)\mathbf{f}_{\mathrm{TX}}\right)$

$m=0,1,\cdots,M-1$; M : the number of frames in one coherent processing interval (CPI)
$k=\ell_0^m,\ell_0^m+1,\cdots,K_{\mathrm{pre}}-1+\ell_0^m$; K_{pre} : the number preamble samples

DELAY ESTIMATION

- **Golay complementary sequences**
  - Used for the preamble of IEEE 802.11ad waveform
  - Correlation property

$$\mathbf{a}_N=[a_0,a_1,...,a_{N-1}]^{\mathrm{T}},\mathbf{b}_N=[b_0,b_1,...,b_{N-1}]^{\mathrm{T}}$$

$$R_{\mathbf{a}_N}[k]+R_{\mathbf{b}_N}[k]=2N\delta[k],\ \text{where}\ R_{\mathbf{c}}[k]=\sum_{q=0}^{N-k-1}c[q]c[q+k],$$

- **Delay estimation method**
  1. Define a correlation function

$$\mathbf{s}_c=[-\mathbf{a}^{\mathrm{T}}_{128}-\mathbf{b}^{\mathrm{T}}_{128}-\mathbf{a}^{\mathrm{T}}_{128}\,\mathbf{b}^{\mathrm{T}}_{128}]^{\mathrm{T}}$$

$$R_{\mathbf{s}_c\tilde{\mathbf{y}}_m}[\ell]=\sum_{k_c=0}^{511}s_c[k_c]\tilde{y}^*_m[\ell+k_c]=\sum_{k_c=0}^{511}s_c[k_c]y^*[m,\ell+k_c+2048]$$

  2. Find a delay $\hat{\ell}^m_{\mathrm{D}}=\mathrm{argmax}_\ell\ |R_{\mathbf{s}_c\tilde{\mathbf{y}}_m}[\ell]|$
  3. Search ℓ, which results in $|R_{\mathbf{s}_c\tilde{\mathbf{y}}_m}[\ell]|$ greater than a certain threshold σ_{th}, both backward and forward from $\hat{\ell}^m_{\mathrm{D}}$

$$\tilde{\mathbf{z}}^{\mathrm{H}}_m\mathbf{s}_c\le\|\mathbf{s}_c\|\cdot\|\tilde{\mathbf{z}}_m\|=512\cdot\sigma_{\mathrm{cn}}=\sigma_{\mathrm{th}}$$
$$\sigma^2_{\mathrm{cn}}=N_oW+P_c$$

DOPPLER SHIFT ESTIMATION

- **Backscattering coefficient estimation**
  - Approximation at the 0-th frame by the small symbol period T_s (wide bandwidth)

$$y[0,k]\approx\sum_{p=0}^{\hat{P}-1}\sqrt{P_{\mathrm{TX}}}s[k-\hat{\ell}^0_p]h_p+z[0,k]$$

$$e^{j2\pi\nu_p^0kT_s}\approx 1$$

  - Least square estimation (LSE) concatenating all the echo samples

$$\mathbf{y}_0=\sqrt{P_{\mathrm{TX}}}\mathbf{S}_0\mathbf{h}+\mathbf{z}_0\ \xrightarrow{\text{LSE}}\ \hat{\mathbf{h}}=\frac{(\mathbf{S}^{\mathrm{H}}_0\mathbf{S}^{\mathrm{H}}_0)^{-1}\mathbf{S}^{\mathrm{H}}_0\mathbf{y}_0}{\sqrt{P_{\mathrm{TX}}}}$$

- **Effective radar channel estimation** — K : the number of samples in one frame
  - Approximation for posterior frames using the fact $k\ll mK$

$$y[m_{\mathrm{d}},k]\approx\sum_{p=0}^{\hat{P}-1}\sqrt{P_{\mathrm{TX}}}s[k-\hat{\ell}^{m_{\mathrm{d}}}_p]\underbrace{h_pe^{j2\pi\nu_p^{m_{\mathrm{d}}}((2\hat{\ell}^{m_{\mathrm{d}}}_0+K_{\mathrm{pre}}-1)/2+m_{\mathrm{d}}K)T_s}}_{\text{Effective radar channel}}+z[m_{\mathrm{d}},k]$$

  - Least square estimation (LSE) concatenating all the echo samples

$$\mathbf{y}_{m_{\mathrm{d}}}=\sqrt{P_{\mathrm{TX}}}\mathbf{S}_{m_{\mathrm{d}}}\mathbf{h}_{m_{\mathrm{d}}}+\mathbf{z}_{m_{\mathrm{d}}}\ \xrightarrow{\text{LSE}}\ \hat{\mathbf{h}}_{m_{\mathrm{d}}}=\frac{(\mathbf{S}^{\mathrm{H}}_{m_{\mathrm{d}}}\mathbf{S}^{\mathrm{H}}_{m_{\mathrm{d}}})^{-1}\mathbf{S}^{\mathrm{H}}_{m_{\mathrm{d}}}\mathbf{y}_{m_{\mathrm{d}}}}{\sqrt{P_{\mathrm{TX}}}}$$

- **Doppler shift estimation**

$$\hat{\nu}^{m_{\mathrm{d}}}_p=\frac{\angle(\hat{h}_{m_{\mathrm{d}}}[p]/\hat{h}[p])}{2\pi((2\hat{\ell}^{m_{\mathrm{d}}}_0+K_{\mathrm{pre}}-1)/2+m_{\mathrm{d}}K)T_s}\quad(p=0,\cdots,\hat{P}-1)$$

- **Phase wrapping compensation**
  - Magnitude difference of Doppler shift estimates

$$\hat{c}_p=|\hat{\nu}^{m_{\mathrm{d}}}_p|-|\hat{\nu}^{m_{\mathrm{i}}}_p|\quad\text{for}\quad p=0,1,\cdots,\hat{P}-1$$

  - For true phases

$$\zeta^{m_{\mathrm{d}}}_p=\angle(\hat{h}_{m_{\mathrm{d}}}[p]/\hat{h}[p]),\quad D_{m_{\mathrm{d}}}=\frac{1}{2\pi((2\hat{\ell}^{m_{\mathrm{d}}}_0+K_{\mathrm{pre}}-1)/2+m_{\mathrm{d}}K)T_s}$$

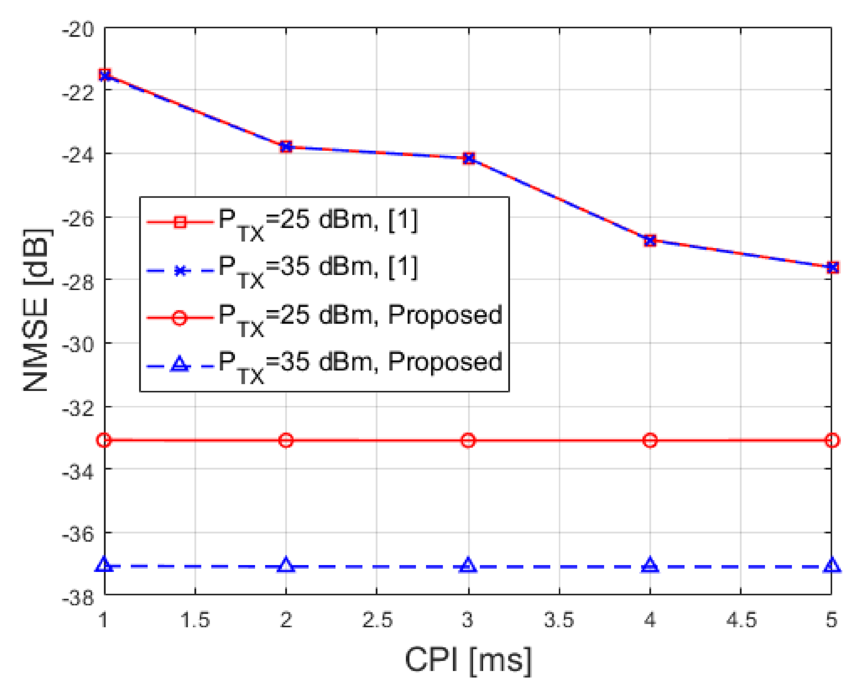
$$\begin{aligned}c_p&=|\nu^{m_{\mathrm{d}}}_p|-|\nu^{m_{\mathrm{i}}}_p|\\&=|\zeta^{m_{\mathrm{d}}}_pD_{m_{\mathrm{d}}}|-|\zeta^{m_{\mathrm{i}}}_pD_{m_{\mathrm{i}}}|\\&=|(2\pi N_p+\zeta^{m_{\mathrm{d}}}_{p,\mathrm{wrap}})D_{m_{\mathrm{d}}}|-|(2\pi N_p+\zeta^{m_{\mathrm{i}}}_{p,\mathrm{wrap}})D_{m_{\mathrm{i}}}|\end{aligned}$$

$$\bar{N}_p\approx\begin{cases}\left\lfloor\frac{\hat{c}_p}{2\pi(D_{m_{\mathrm{i}}}-D_{m_{\mathrm{d}}})}\right\rceil, & \text{for}\quad\zeta_{p,\mathrm{wrap}}>0\\ \left\lfloor-\frac{\hat{c}_p}{2\pi(D_{m_{\mathrm{i}}}-D_{m_{\mathrm{d}}})}\right\rceil, & \text{for}\quad\zeta_{p,\mathrm{wrap}}<0\end{cases}\ \Rightarrow\ \bar{\nu}^{m_{\mathrm{d}}}_p=\hat{\nu}^{m_{\mathrm{d}}}_p+2\pi\bar{N}_pD_{m_{\mathrm{d}}}$$

- **Vehicular velocity**
  - Using the definition of Doppler shift & small angle approximation

$$\nu^{m_{\mathrm{d}}}_p=\frac{2v^{m_{\mathrm{d}}}_p}{\lambda}=\frac{2(V_s-V_p)\cos(\phi^{m_{\mathrm{d}}}_p)}{\lambda}\approx\frac{2(V_s-V_p)}{\lambda}\ \Rightarrow\ \hat{V}_p\approx V_s-\frac{\bar{\nu}^{m_{\mathrm{d}}}_p\lambda}{2}$$

SIMULATION RESULTS



- Simulation set-up
  - 3dB azimuth beamwidth: 0.4084 rad
  - TX anteanns: 8x2 UPA
  - RX antennas: 8x2 UPA
- Comparison scheme [1]
  - use delay-Doppler map estimation
- The proposed technique outperforms the scheme in [1] for all CPI values even with lower TX power than [1].

High velocity estimation accuracy within a short CPI

REFERENCE

[1] P. Kumari, J. Choi, N. Gonz´alez-Prelcic, and R. W. Heath, "IEEE 802.11 ad-Based Radar: An Approach to Joint Vehicular Communication-Radar System," IEEE Trans. Veh. Technol., vol. 67, no. 4, pp. 3012–3027, 2017.