# Enabling Millimeter Wave Multi-Gbps Wireless Broadband for High Speed Trains

CENTER FOR TRANSPORTATION RESEARCH

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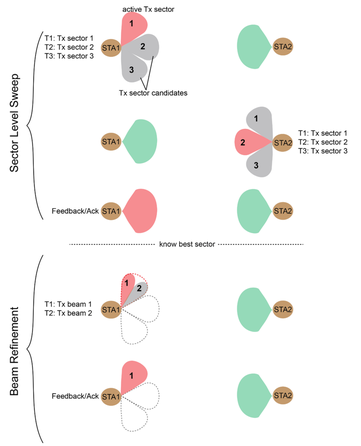
- Importance of high speed trains w/ total line > 54,400 km by 2025 [1]
- Providing broadband service on-board is crucial
- MmWave has potential in providing Gbps data rate
- Require accurate beam alignment to compensate high path loss
- Most existing methods are designed for low mobility scenarios

Our Contributions:

- Show limitation of conventional beam alignment methods
- Analyze performance of beam alignment leveraging train position info

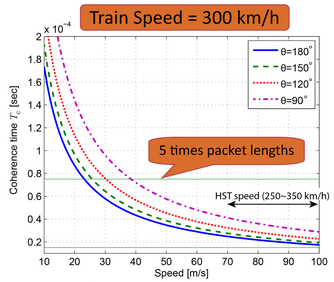
## Limitation of Conventional Beam Alignment

- Existing beam alignment methods are based on beam sweeping
- Hierarchical beam codebook is key to efficient beam sweeping
- Wide RX beamwidths are more affected by Doppler spread [2]



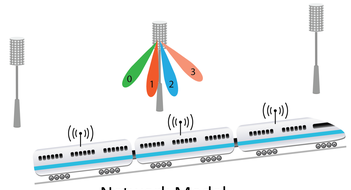

Beam alignment example from IEEE 802.11ad

| Beamwidth | Allowed Max Speed |
|---|---|
| 90° | 38.4 m/s |
| 120° | 30.2 m/s |
| 150° | 25.7 m/s |
| 180° | 23.2 m/s |

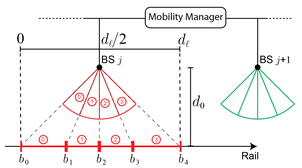



Correlation time at 0.5 correlation

## System Model



Network Model




Network Model (bird view)

- No overlap between beams
- Periodic feedback (current position and estimate velocity) from the train control system

Beamwidth and gain

$$G \simeq \frac{\pi^2}{\Theta_{3\mathrm{dB}}\Psi_{3\mathrm{dB}}} \simeq \frac{\pi^2}{\theta_{\mathrm{b}}^2}$$

Azimuth, Elevation, Square array

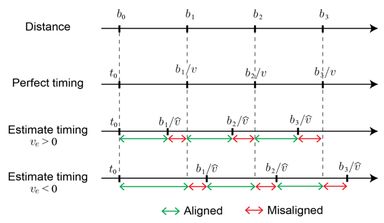
Receive power

$$P_{\mathrm{rx}}(t,\theta_{\mathrm{b}}) = A\left(\frac{\pi}{\theta_{\mathrm{b}}}\right)^2 \frac{1}{[(vt)^2+d_0^2]^{n/2}}$$

Assuming always transmit at EIRP limit: $10\log_{10}(A) = \mathrm{EIRP}_{\mathrm{dBm}} - W + 10n\log_{10}\frac{\lambda}{4\pi}$

## Beamwidth Optimization

- Goal is to find relationship between beamwidth and velocity estimation
- Beam switching according to estimate position
- Assuming position information update at cell boundaries




Optimization problem

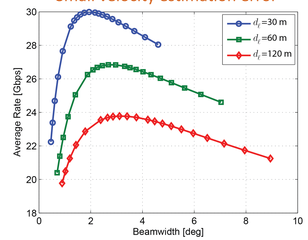
$$\theta_{\mathrm{b}}^{\star} = \arg\max_{\theta_{\mathrm{b}}} \sum_{i=1}^{N} \mathbb{E}_{v_{\mathrm{e}}}\left[\frac{v+v_{\mathrm{e}}}{d_\ell} D_i(t,\theta_{\mathrm{b}})\right]$$

$$\mathbb{E}_{v_{\mathrm{e}}}\left[\frac{v+v_{\mathrm{e}}}{d_\ell} D_i(t,\theta_{\mathrm{b}})\right] = \int_0^{\frac{b_{i+1}-b_i}{b_{i-1}}v} \frac{v+v_{\mathrm{e}}}{d_\ell} D_i(t,\theta_{\mathrm{b}}|v_{\mathrm{e}}\geq 0) f_{v_{\mathrm{e}}}(v_{\mathrm{e}})\mathrm{d}v_{\mathrm{e}} + \int_{\frac{b_i-b_{i+1}}{b_{i-1}}v}^{0} \frac{v+v_{\mathrm{e}}}{d_\ell} D_i(t,\theta_{\mathrm{b}}|v_{\mathrm{e}}<0) f_{v_{\mathrm{e}}}(v_{\mathrm{e}})\mathrm{d}v_{\mathrm{e}}$$

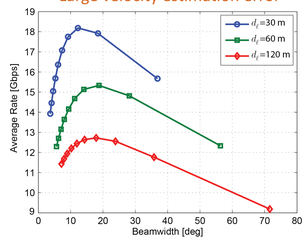
***This work has been submitted for publication in the 2015 IEEE 81st Vehicular Technology Conference.**

## Numerical Example

Small velocity estimation error




Large velocity estimation error




| Parameter | Value |
|---|---|
| $n$ | 2 |
| $B$ | 2.16 GHz |
| frequency | 60 GHz |
| Speed | 300 km/h |
| EIRP (USA) | 40 dBm |
| Noise (dBm) | -174+10log($B$)+6 |

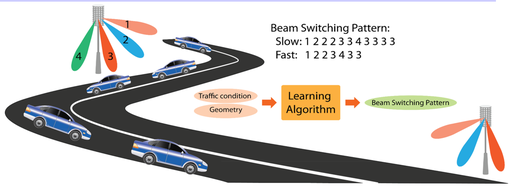
- Narrower beams are more sensitive to estimation error and wider beams are needed for larger errors
- Longer inter-BS spacing resulting in larger optimal beamwidth due to accumulation of estimation error
- Inter-BS distance of 100 meters order

## Conclusion and Future Work

- Conventional beam alignments cannot support high speed train application
- Beam alignment leveraging position info could provide multi-Gbps data rate

Future Work

- Extend to less predictable cases, e.g. cars on highway




[1] International Union of Railways, http://www.uic.org

[2] G. D. Durgin and T. S. Rappaport, "Theory of multipath shape factors for small-scale fading wireless channels," *IEEE Transactions on Antennas and Propagation*, vol. 48, no. 5, pp. 682–693, May 2000

[3] J. Kim and A. F. Molisch, "Enabling Gigabit services for IEEE 802.11ad-capable high-speed train networks," in *IEEE Radio and Wireless Symposium (RWS)*, Jan. 2013, pp. 145–147.

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