mmWave Train-to-Train Communications for Next Generation Railways

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New Railway Applications

Current situation in road traffic:

- Very efficient use of roads
- 75% of freight, 82% of passengers
- Many accidents, traffic jams, less energy efficient

Current situation in railways:

- Very safe and energy efficient
- 18% of freight, 8% of passengers
- Inefficient use of railways due to old safety system
Evolution in road traffic:
- Electric vehicles
- Connected and autonomous driving
- Platooning

Evolution in railways:
European Rail Traffic Management System (ERTMS)
- GSM-R
- European Train Control System (ETCS)
  - Level 2:
    fixed block, no lineside signals, speed and track information continuously communicated with GSM-R into cockpit
  - Status:
    Swiss Railways for all train lines above 160 km/h, DB only Erfurt-Leipzig, Spain Madrid-Barcelona
New Railway Applications

Evolution in railways:
European Train Control System (ETCS)

• Level 2 fixed block
  – One train in a block
  – Distance to next train ≥ absolute braking distance, i.e. train can break at full speed and stop before entering next block

• Level 3 moving block
  – One train in a block
  – Block moves with train
  – Distance to next train = absolute braking distance

➔ New railway applications to further increase efficiency and flexibility

~2 min separation, 10 km for high speed train

~0.5 min separation, 3 km for high speed train

[5] [6]
New Railway Applications

Wireless Train Control and Monitoring System (TCMS)

[Image: Diagram of a train with various components labeled, such as HMI, VCU, Ethernet, PIS, HVAC, CCTV, MVB, WTB, Brakes & Sensors/diagnostics, Air production, Power electronics, Train (safety) lines, Mechanical coupler, Electrical coupler.]

[7]
New Railway Applications

Wireless Train Control and Monitoring System (TCMS)
New Railway Applications

Autonomous trains: Collision avoidance [8]
New Railway Applications

Autonomous trains: Collision avoidance [8]

Remote control:
Automatic coupling [9]
New Railway Applications

Autonomous trains: Collision avoidance [8]

Remote control:
Automatic coupling [9]

Virtual coupling:
Platooning [10]

Ultra-reliable low-latency communications and ranging essential for enabling new safety relevant railway applications
Automatic Coupling [9]

- Reliable wireless communication in industry
- Provide URLL communications and ranging (URLLC&R) over short distances
- Monitor train integrity, i.e. distance between coupled train sets and wagons
Automatic Coupling [9]

- Reliable wireless communication in industry
- Provide URLL communications and ranging (URLLC&R) over short distances
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![Diagram showing automatic coupling system](image-url)
Automatic Coupling: Channel & System Model

Two-path channel model:
\[ h_c(t) = a_0 \delta(t - \tau_0)e^{-\varphi(\tau_0)} + a_1 \delta(t - \tau_1)e^{-\varphi(\tau_1)} \]

System model:
\[ y[n] = a_0 s \left[ n - \frac{\tau_0}{T_s} \right] e^{-\varphi(\tau_0)} + a_1 s \left[ n - \frac{\tau_1}{T_s} \right] e^{-\varphi(\tau_1)} \]
Automatic Coupling: Cramér Rao Lower Bounds

Cramér Rao Lower Bound (CRLB) versus distance between two transmitters

$6\sigma$ [m] $\Rightarrow$ reliability of 99.9997% for ranging (beyond 5G URLLC&R)
**Automatic Coupling: CRLB Results**

Comparison of three wireless systems:

<table>
<thead>
<tr>
<th></th>
<th>mmWave</th>
<th>ITS-G5</th>
<th>IR-UWB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Center Frequency</strong></td>
<td>60 GHz</td>
<td>5.9 GHz</td>
<td>6 GHz</td>
</tr>
<tr>
<td><strong>EIRP</strong></td>
<td>31 dBm</td>
<td>31 dBm</td>
<td>-14.5 dBm</td>
</tr>
<tr>
<td><strong>Pulse shape</strong></td>
<td>Raised Cosine</td>
<td>OFDM</td>
<td>Second-order Gaussian monocycle</td>
</tr>
<tr>
<td><strong>BW</strong></td>
<td>500 MHz</td>
<td>10 MHz</td>
<td>500 MHz</td>
</tr>
<tr>
<td><strong>Sampling period</strong></td>
<td>0.2 nsec</td>
<td>10 nsec</td>
<td>0.2 nsec</td>
</tr>
<tr>
<td><strong>Number of Observed samples</strong></td>
<td>500 k</td>
<td>10 k</td>
<td>500 k</td>
</tr>
<tr>
<td><strong>Height from ground</strong></td>
<td>0.5 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Distance between nodes</strong></td>
<td>From 0.5 to 50 m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Automatic Coupling: CRLB Results

1% of the distance accuracy threshold

\[ 6\times \sigma_{\text{CRLB}} \text{ [m]} \]

\[ 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10^{0} \]

Distance [m] vs. 6*\sigma_{\text{CRLB}} [m]

- mm-Wave
- ITS-G5
- IR-UWB

+ BW + SNR
+ BW - SNR
+ SNR - BW
Automatic Coupling: CRLB Results
Rain Effect

1% of the distance accuracy threshold

- Heavy rainfall
- Very heavy rainfall
- Extreme rainfall
Automatic Coupling: Hardware Description – RUSK-DLR Channel Sounder

- Center frequency: up to 5.2 GHz
- Bandwidth: 120 MHz
- Signal period: 12.8 µs
- Measurement time grid: 1.024 ms
- Max. Doppler frequency: ±488 Hz
- Rubidium clocks: 10 MHz
Automatic Coupling: Hardware Description – mmWave Frontend

- IP67 water and dust proof with Passive cooling
- Radome sheets
- Connectors to DLR channel sounder
Automatic Coupling: Hardware Description – mmWave Frontend
Automatic Coupling: Hardware Description – mmWave Frontend

- mmWave synthesizer: Output frequency range 50 to 67 GHz
- Mixer: Waveguide up- and down-converters
- Attenuator: 0-30 dB waveguide variable attenuator
- LNA: 20 dB low noise amplifier with 3.5 dB noise figure
- Antenna: Directive rectangular horn antenna with 12° 3 dB beam width and 23 dB gain
Automatic Coupling: Open field Measurements
Automatic Coupling: Open field Measurements, First Results

-40
-45
-50
-55
-60
-65
-20 40 60 80 100
Distance [m]

Measured received power [h=1.28m]
Measured received power [h=2.63m]
Free-space pathloss
Automatic Coupling: Parking Lot, Dynamic Measurements

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Automatic Coupling: Parking Lot, Dynamic Measurements
Automatic Coupling: Parking Lot, Dynamic Measurements, Preliminary Results

![Graph showing received power and free-space pathloss over time.

- Received power
- Free-space pathloss

Distance [m]

- Estimated distance
- Average of estimated distance
- Reference distance

Time [s]

- 0 to 250 seconds

[Data points and graph details for analysis.]
Automatic Coupling: Parking Lot, Dynamic Measurements, Preliminary Results

Received power drop due to misalignment

99% of errors < 0.3 m
Automatic Coupling: Parking Lot, Dynamic Measurements, Preliminary Results
Automatic Coupling: Parking Lot, Dynamic Measurements, Preliminary Results
Automatic Coupling: Measurement Campaign

- Department of Rail Vehicles and Transport Systems (IFS) RWTH Aachen
- 300 m long track, 2 experimental trains
Automatic Coupling: Measurement Campaign
Automatic Coupling: Measurement Campaign

- 1 day of measurements (24 July)
- Up to three runs per environment (38 runs in total):
  - Open field
  - Platform
  - 1 metallic sheet
  - 2 metallic sheets
  - Bushes and trees
  - Train driving in a parallel track
- Up to 130 m separation between the trains
- Relative speed up to 5 km/h
Automatic Coupling: Measurement Campaign
Measured Received Power – Open Field

P_{RX} [dB]

Distance [m]

Run 1
Run 2
Run 3
Free-space pathloss
Automatic Coupling: Measurement Campaign
Measured Ranging Accuracy – Distance Estimation Error
Automatic Coupling: Measurement Campaign

Measured Ranging Accuracy – Errors CDF

- 99.73% for 0.55 m
- 68.27% for 0.21 m
Automatic Coupling: Measurement Campaign
Special Thanks to Team!
Summary and Conclusions

• mmWave channel sounder for dynamic measurements
  – Mean receive power ~ free space path loss & 15 dB above noise floor @ 110 m
  – Highly directive antennas: Multipath propagation

• Example automatic coupling
  – mmWave URLLC&R for automatic approach and train integrity monitoring
  – Best ranging accuracy for mmWave system at short distances, only slightly worse for severe rain

• New railway applications to further increase efficiency and flexibility
  – Wireless TCMS, autonomous trains & collision avoidance, automatic coupling, virtual coupling
  – 5G URLL communication and ranging (C&R) essential for enabling new safety relevant railway applications
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• New railway applications to further increase efficiency
  – Wireless TCMS, autonomous trains & collision avoidance, automatic coupling, virtual coupling
  – 5G URLL communication and ranging (C&R) for relevant railway applications

Questions?
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