

# Simulation und Modellierung von Fahrzeug-zu-Fahrzeug Kommunikation für autonom fahrende Fahrzeuge

Masterarbeit, RWTH Aachen

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Zweiter Prüfer: Prof. Dr.-Ing. Stefan Kowalewski

Betreuer: Dipl.-Ing. Evgeny Kusmenko

# Autonomes Fahren

## ► Zukünftige Schlüsseltechnologie

- Erhöhte Verkehrssicherheit
- Optimierter Verkehrsfluss
- Intelligente Transportsysteme



**Carolo-Cup**

[https://www.team-cdlc.de/  
media/Carolo\\_Cup\\_Logo.jpg](https://www.team-cdlc.de/media/Carolo_Cup_Logo.jpg)

## ► Aktive Forschung und Entwicklung

- DARPA Urban Challenge
- Carolo-Cup
- Automobilindustrie
- Simulationen



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# Fahrzeug-zu-Fahrzeug Kommunikation

Sensoren und  
Umgebungs-  
erfassung

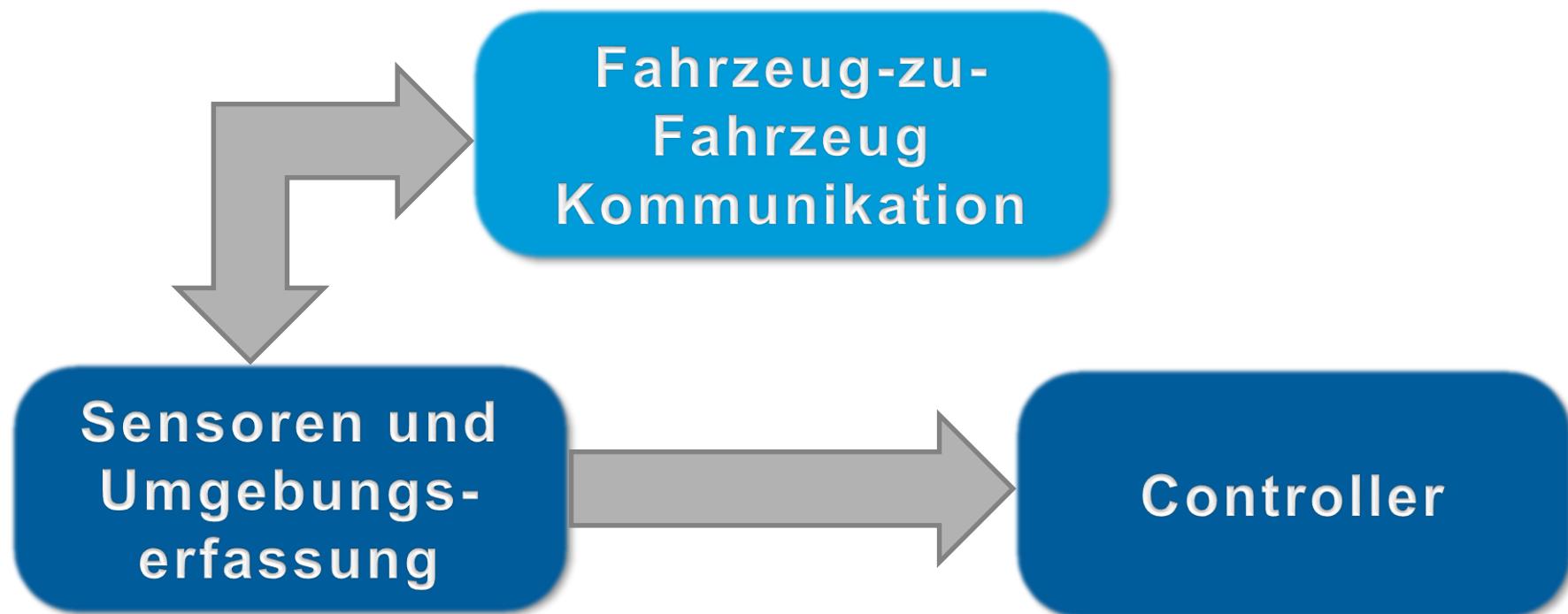


Controller

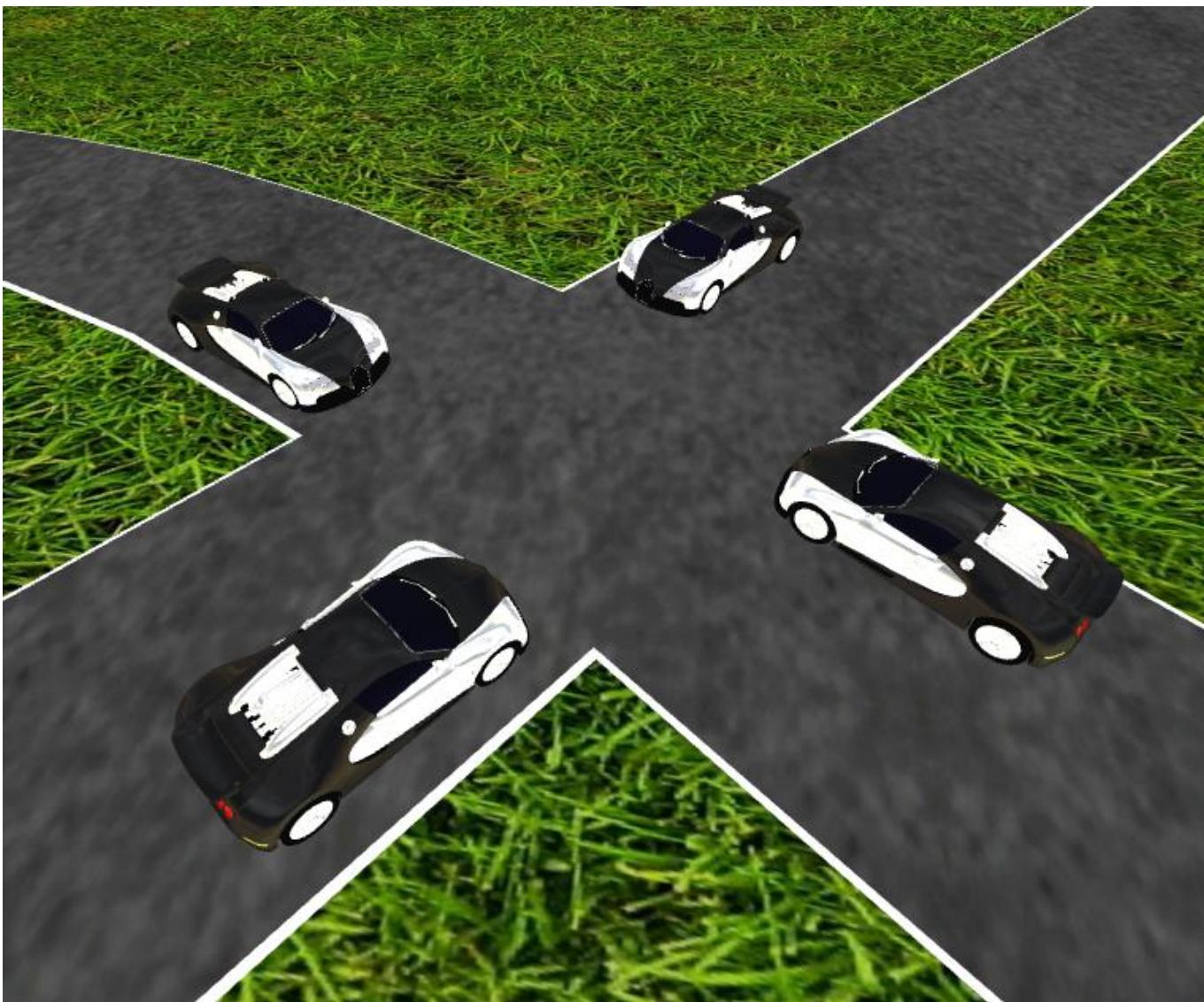
# Fahrzeug-zu-Fahrzeug Kommunikation

## ► Fahrzeug-zu-Fahrzeug Kommunikation

- Zusätzliche Daten zur Erfassung der Umgebung
- Daten: Position, Geschwindigkeit, Trajektorie, ...



# Fahrzeug-zu-Fahrzeug Kommunikation



# Hypothese und Methodik

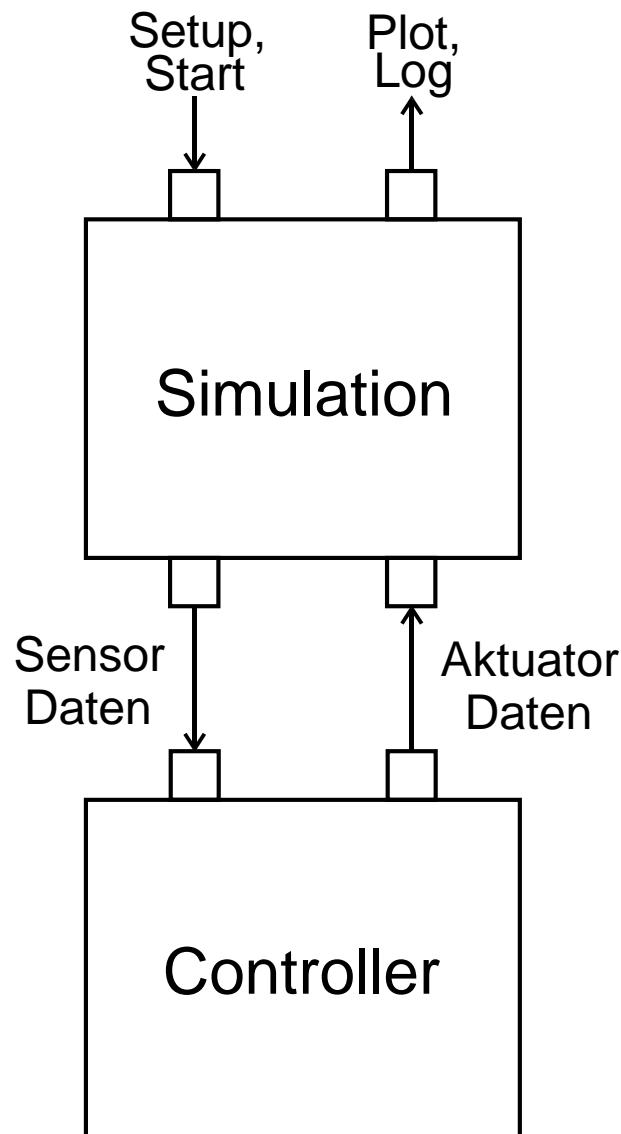
## ► Hypothese

- Gekoppelte Simulation von autonomen Fahrzeugen und Fahrzeug-zu-Fahrzeug Kommunikation mit Modellen
- Resultate für Entwicklung realer autonomer Fahrzeuge

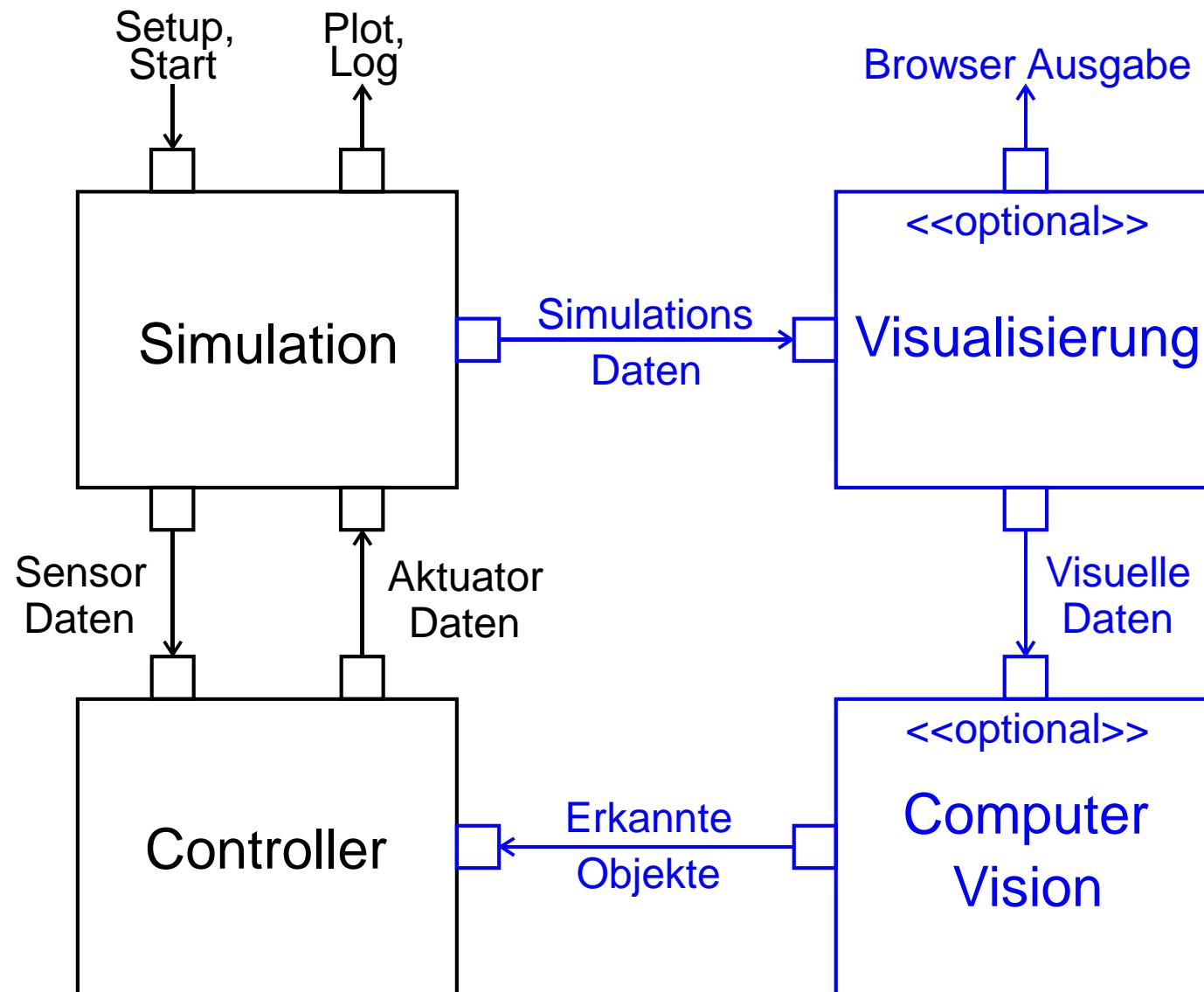
## ► Methodik

- Vorkenntnisse: Fahrzeug-zu-Fahrzeug Kommunikation
- Entwicklung: Prototyp für Netzwerksimulation
- Flexible Kopplung von Simulations-Prototypen
- Evaluation der experimentellen Daten

# Simulator für autonome Fahrzeuge



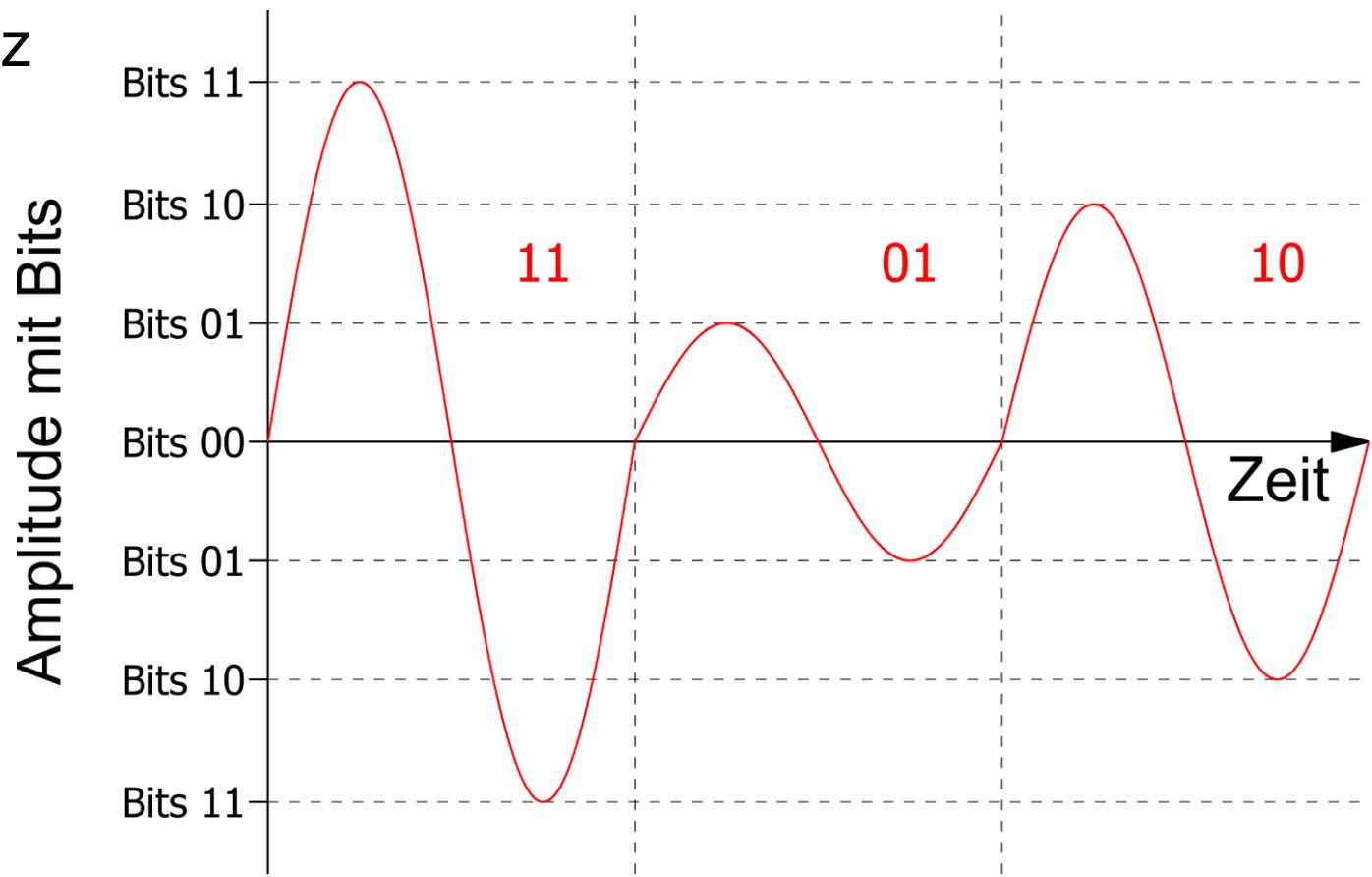
# Simulator für autonome Fahrzeuge



# Elektromagnetische Wellen

## ► Charakteristische Größen

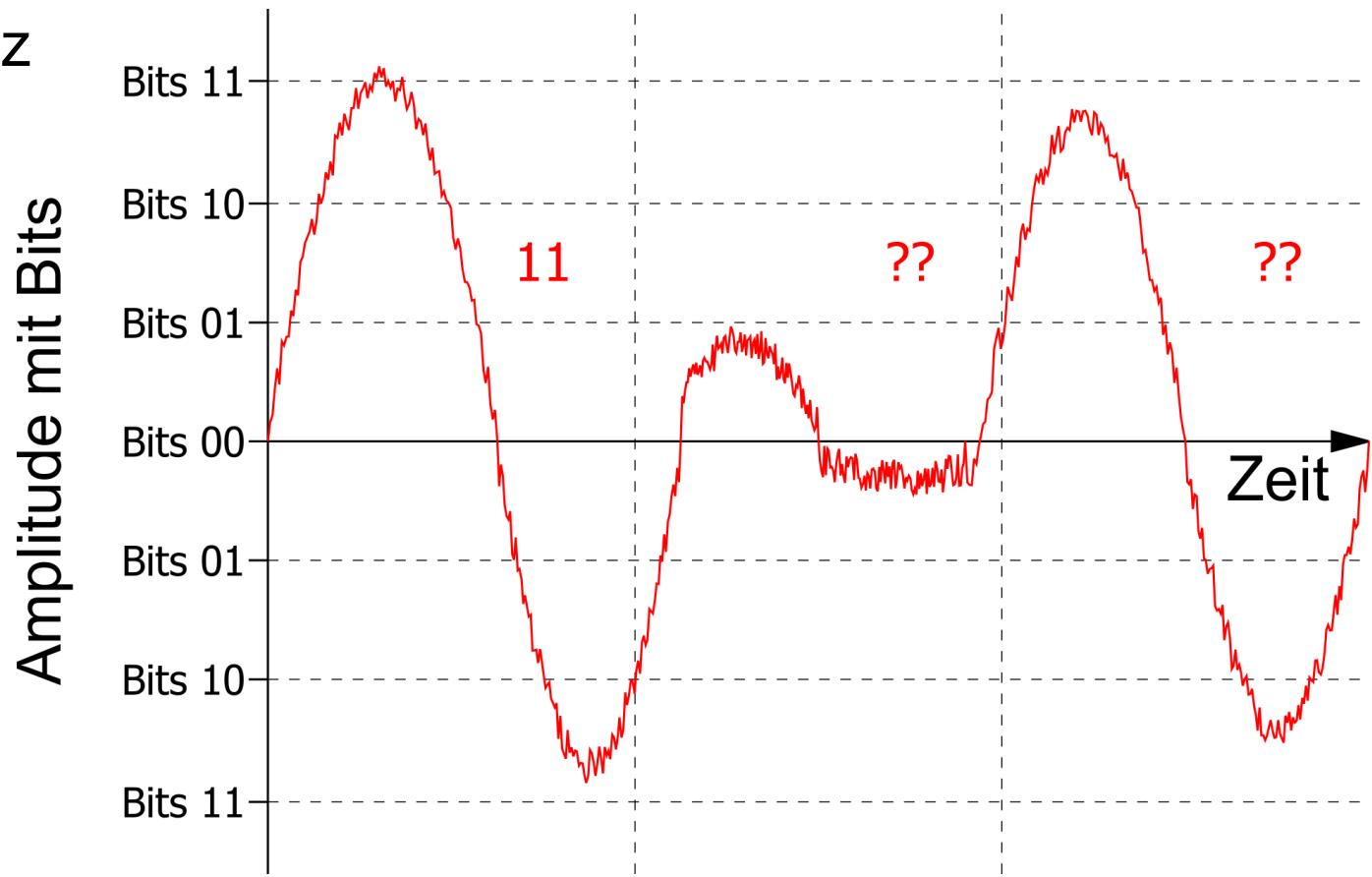
- Amplitude
- Frequenz
- Phase



# Elektromagnetische Wellen

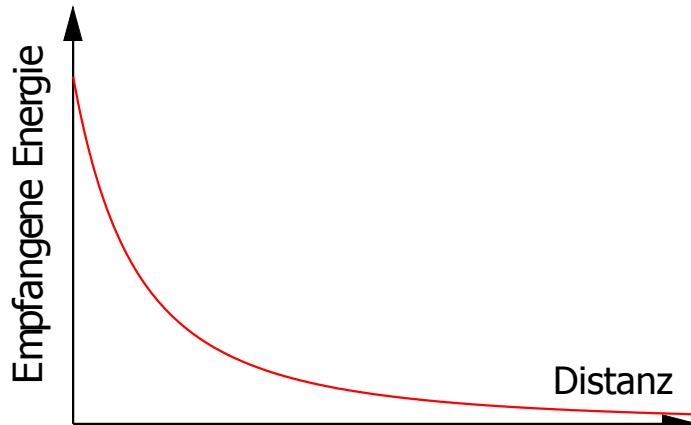
## ► Charakteristische Größen

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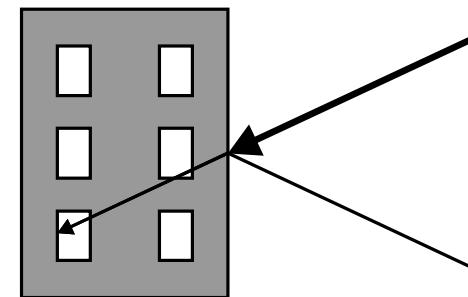


# Elektromagnetische Wellen

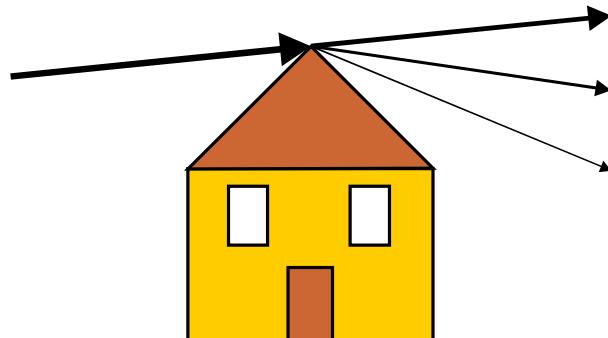
Pfadverlust



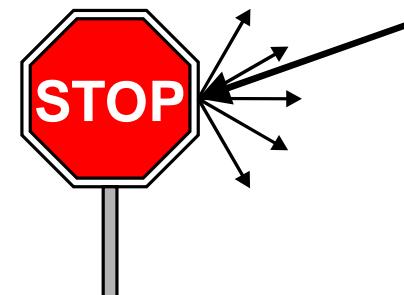
Reflektionen



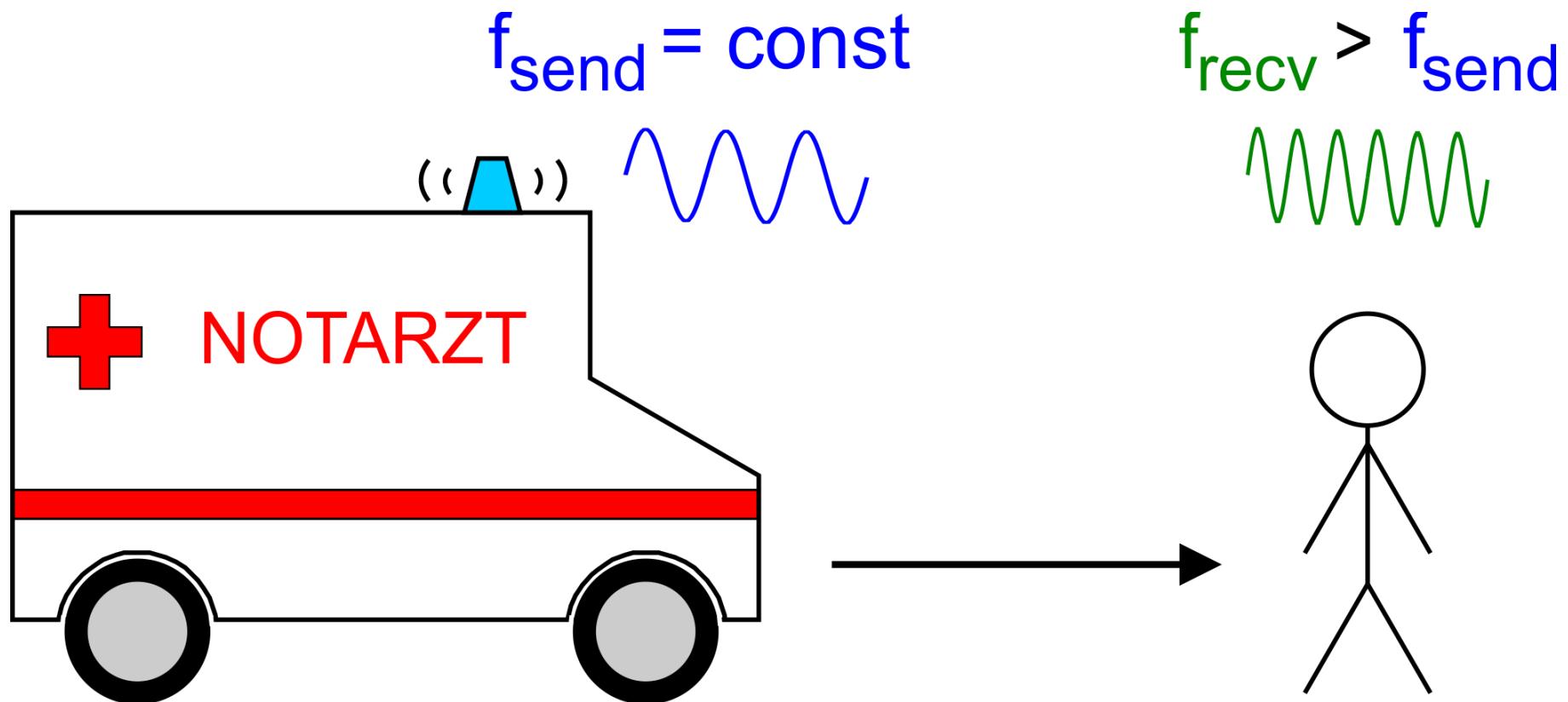
Beugung



Streuung



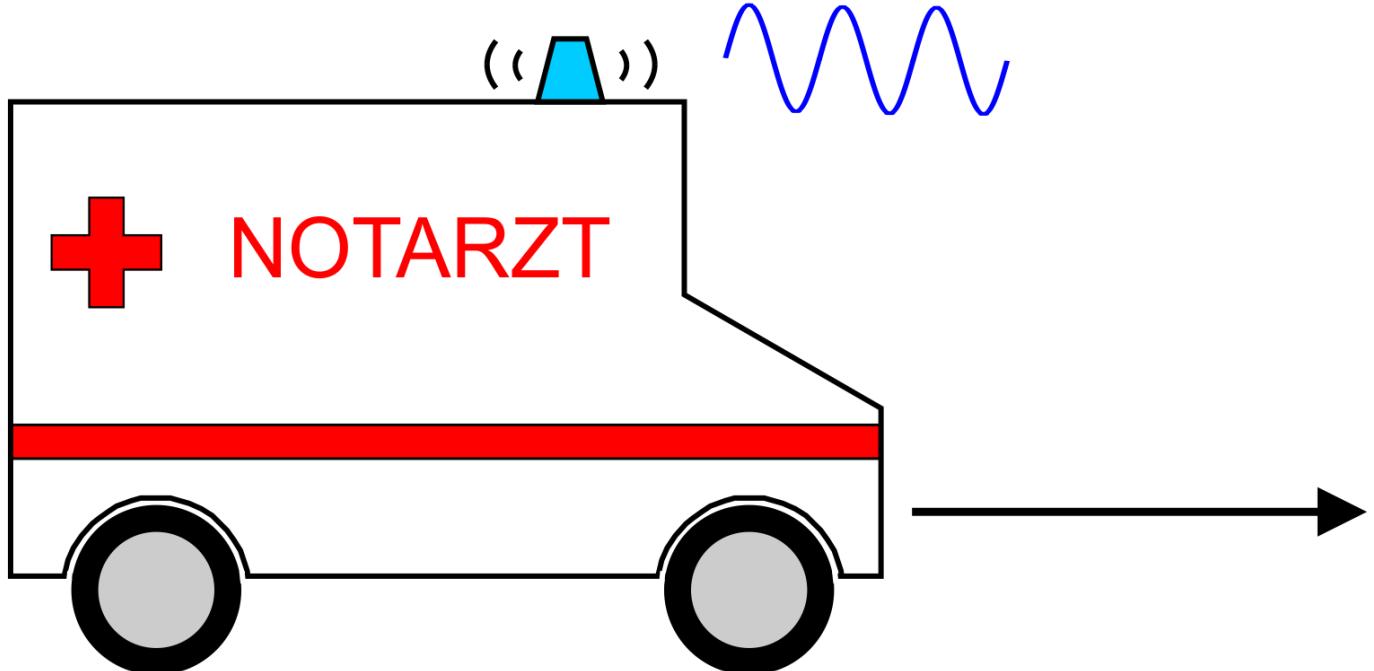
# Doppler Effekt



# Doppler Effekt

$$f_{\text{recv}} < f_{\text{send}}$$

$$f_{\text{send}} = \text{const}$$



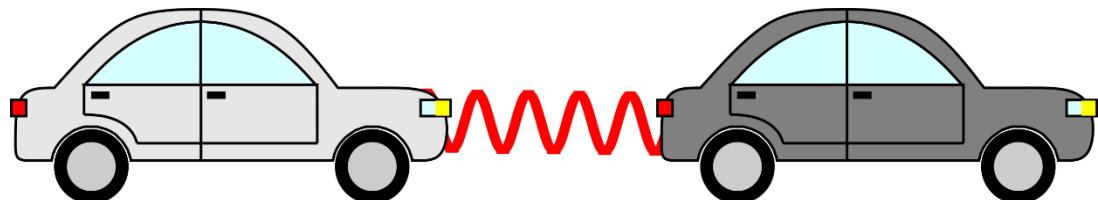
# IEEE 802.11p

## ► IEEE 802.11

- Standard für kabellose Kommunikation
- Ad hoc und Infrastruktur Netzwerke
- Contention-based protocol
- Carrier-sense multiple access (CSMA/CA)

## ► IEEE 802.11p

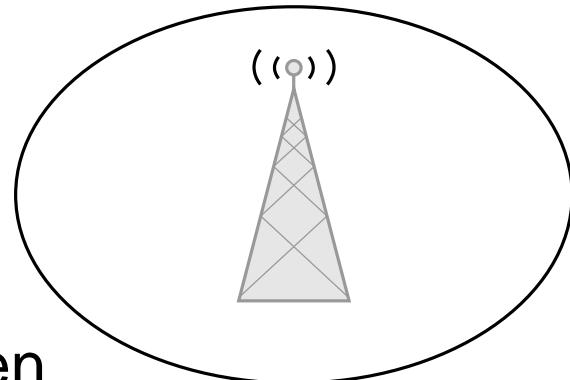
- Standard für Fahrzeug-zu-Fahrzeug Kommunikation
- Beacon messages
- 5.9 GHz



# 3GPP LTE

## ► 3GPP LTE

- Standard für zellulares Netzwerk
- Verschiedene Frequenzbereiche
- Kanäle für Kontrolldaten und Nutzdaten
- Koordination durch Basisstationen



## ► Erweiterte Techniken

- Multiple Input Multiple Output (MIMO) Antennen
- Robust Header Compression (ROHC)
- Hybrid Automatic Repeat Request (HARQ)

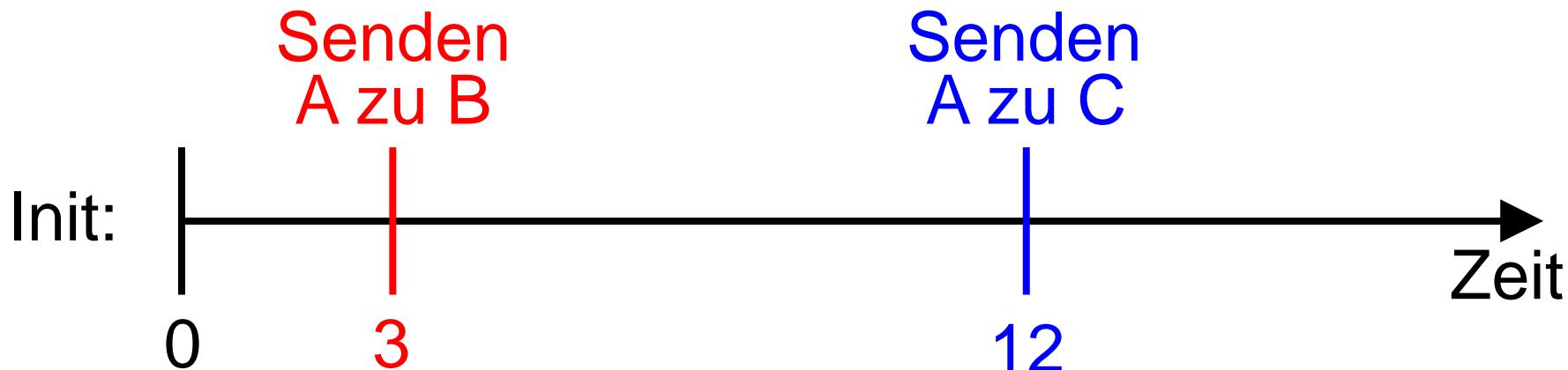
# Netzwerksimulation

## ► Discrete Event Simulation

- ns-3
- OMNeT++



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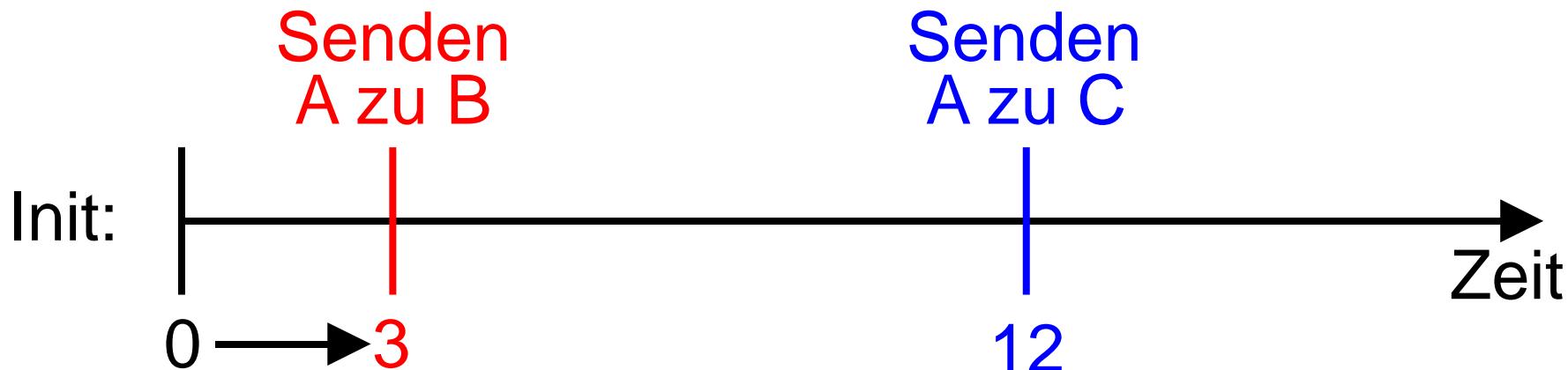
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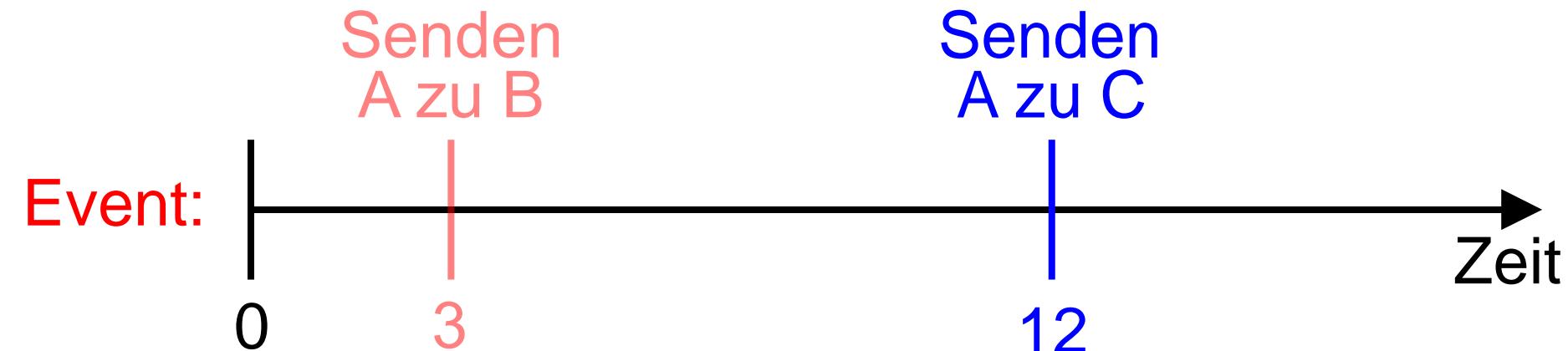
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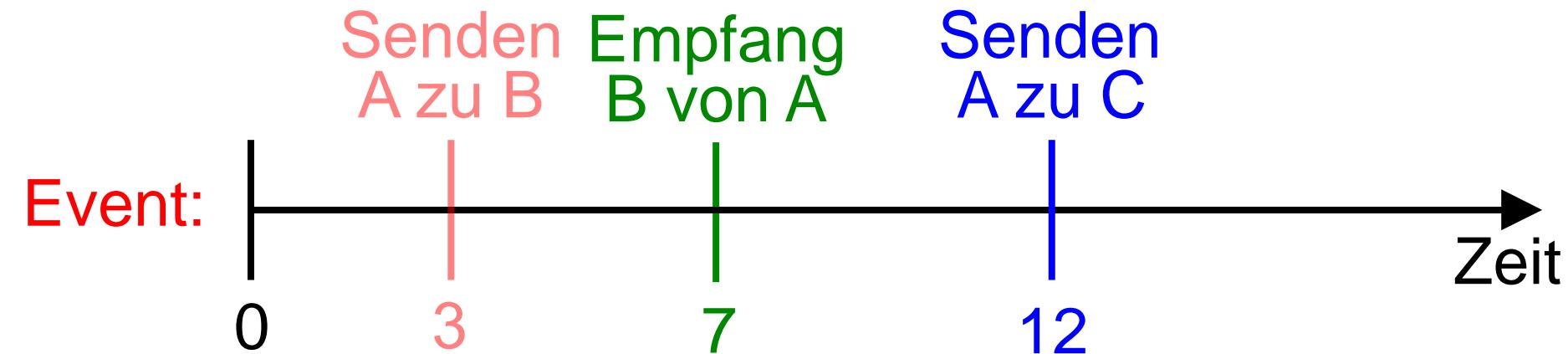
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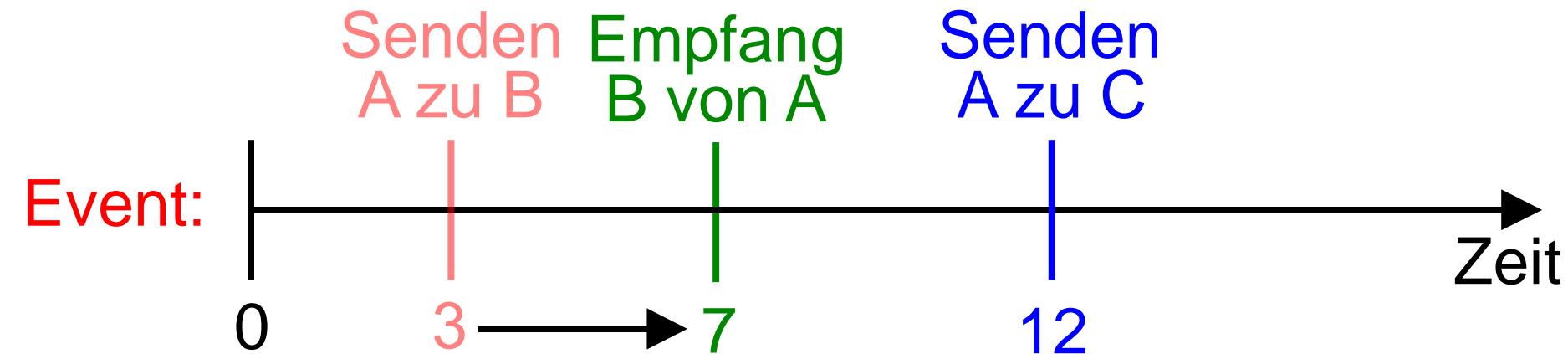
# Netzwerksimulation

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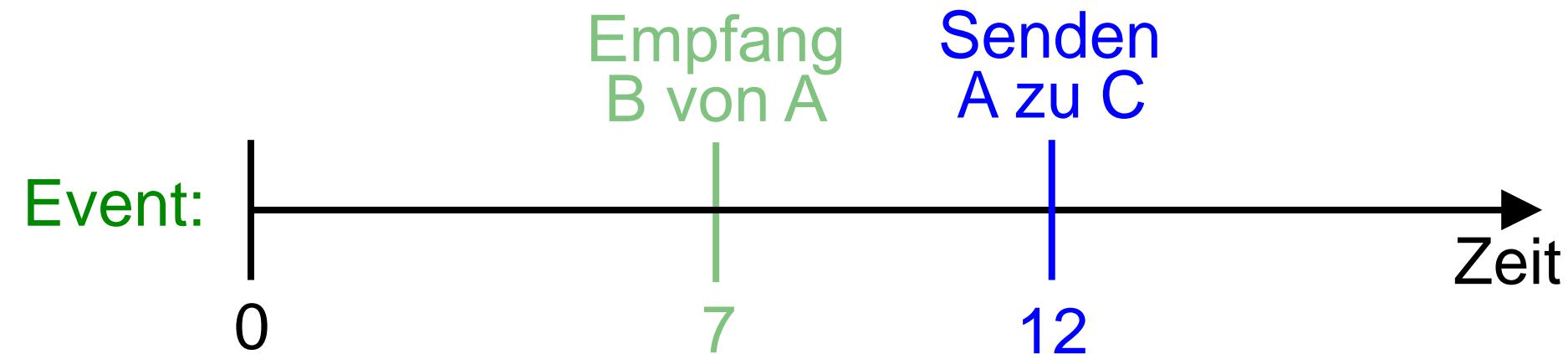
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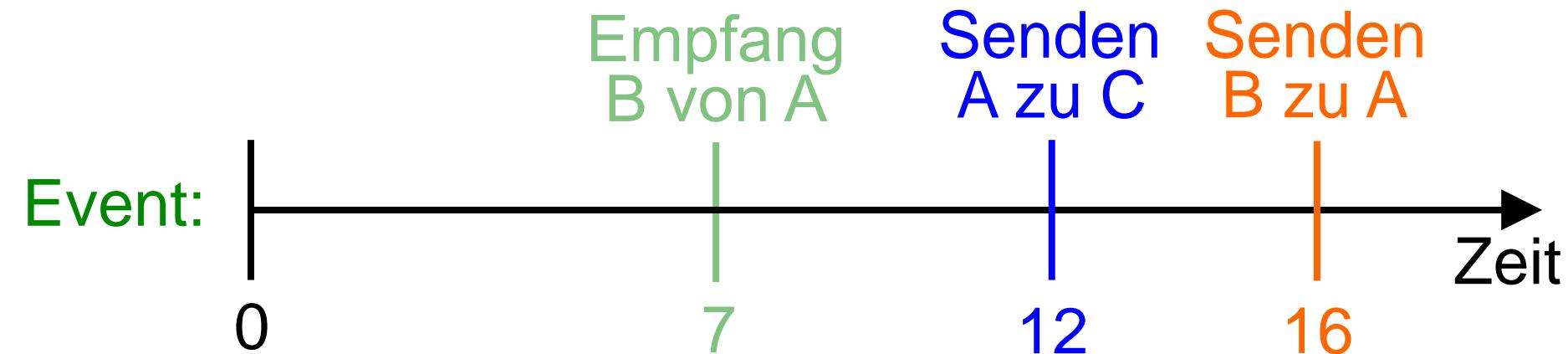
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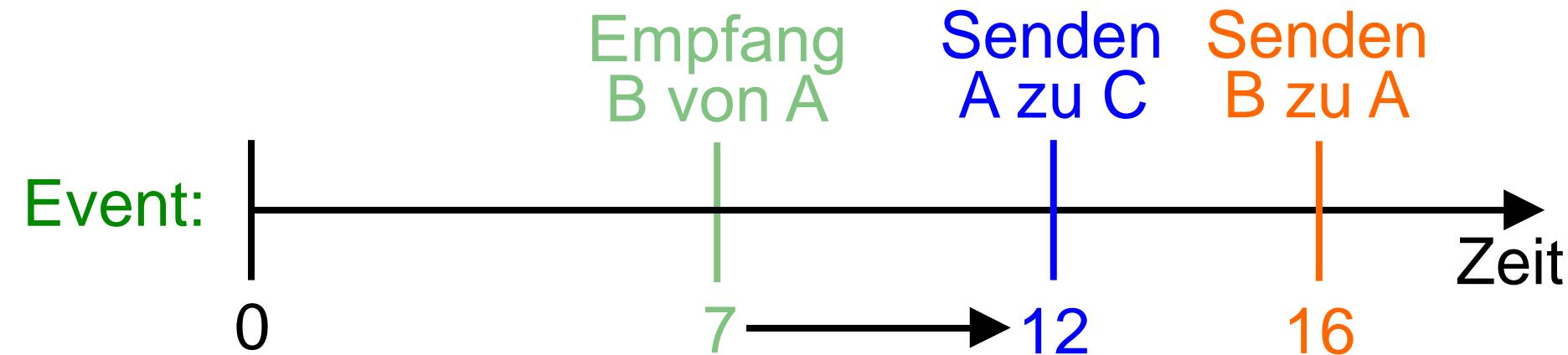
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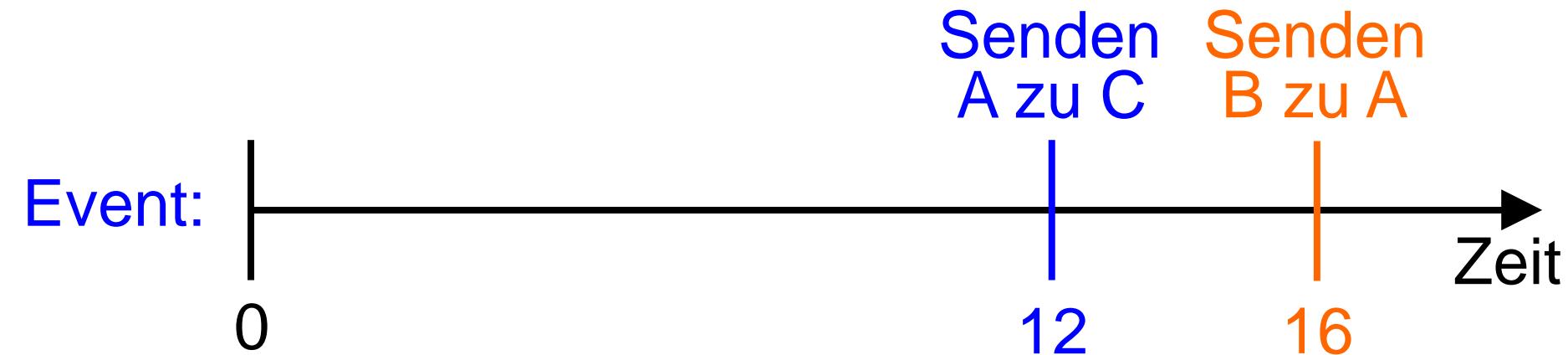
# Netzwerksimulation

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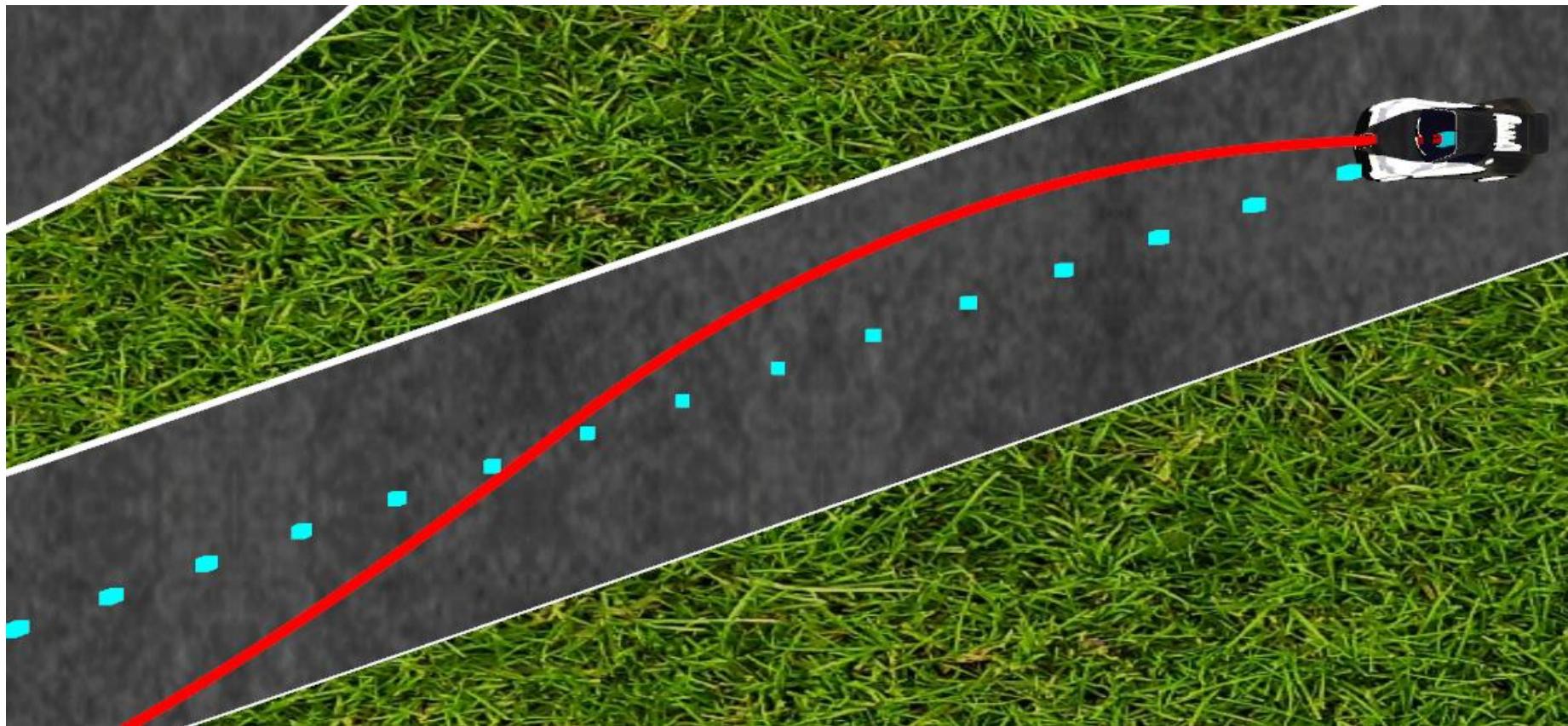


# Anforderungsanalyse

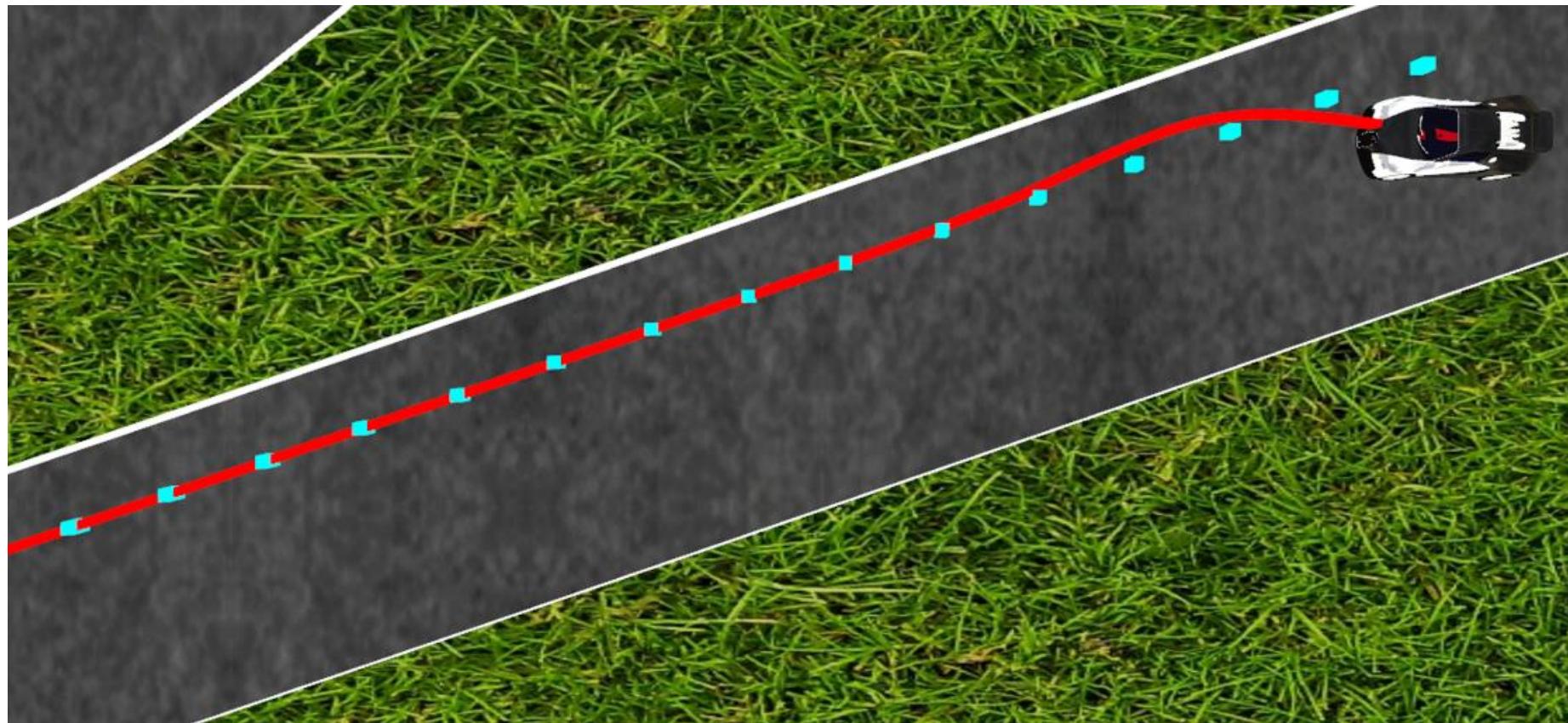
## ► Simulator für Fahrzeug-zu-Fahrzeug Kommunikation

- Basierend auf Discrete Event Simulation
- Verschiedene Modelle und Ansätze für Kommunikation
- Integration mit Simulator für autonome Fahrzeuge
- Kollisionsvermeidung, Rechts vor Links, Stauvermeidung
- Reusability und Extensibility

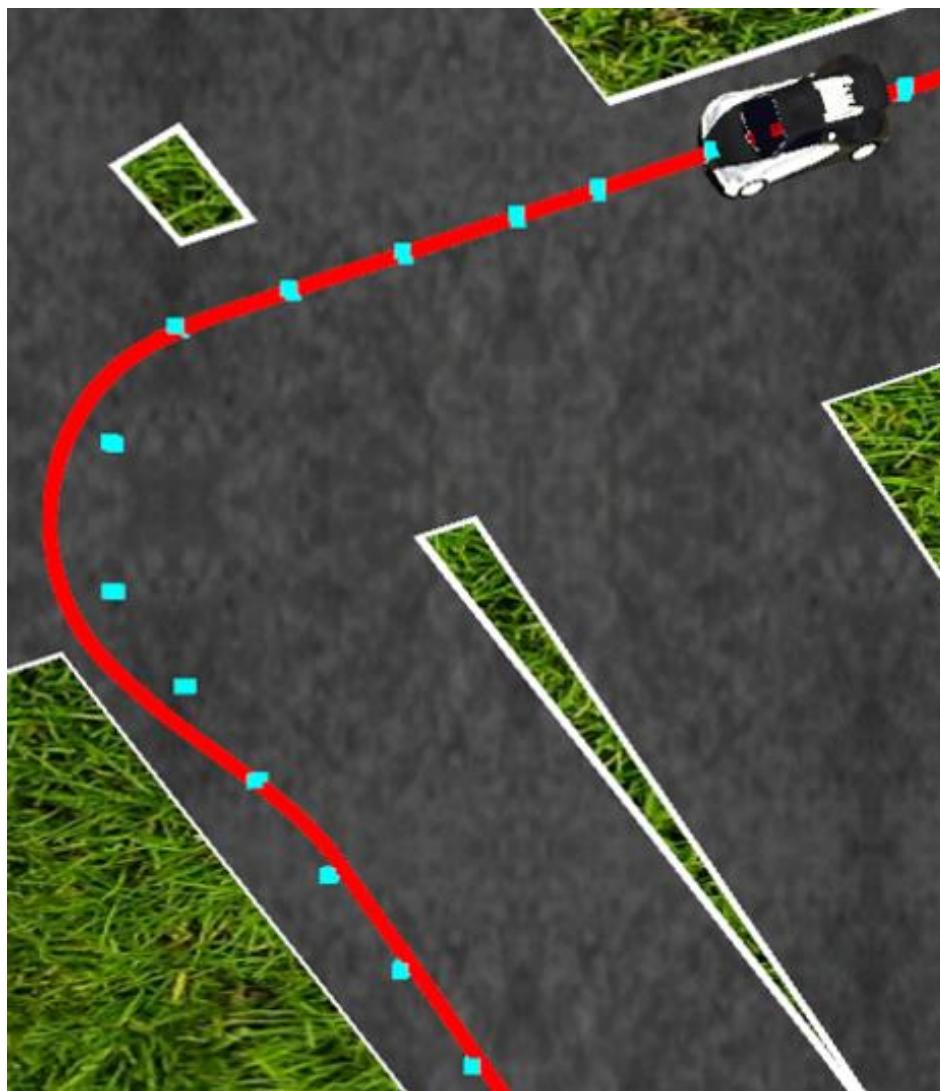
# Simulator für autonome Fahrzeuge



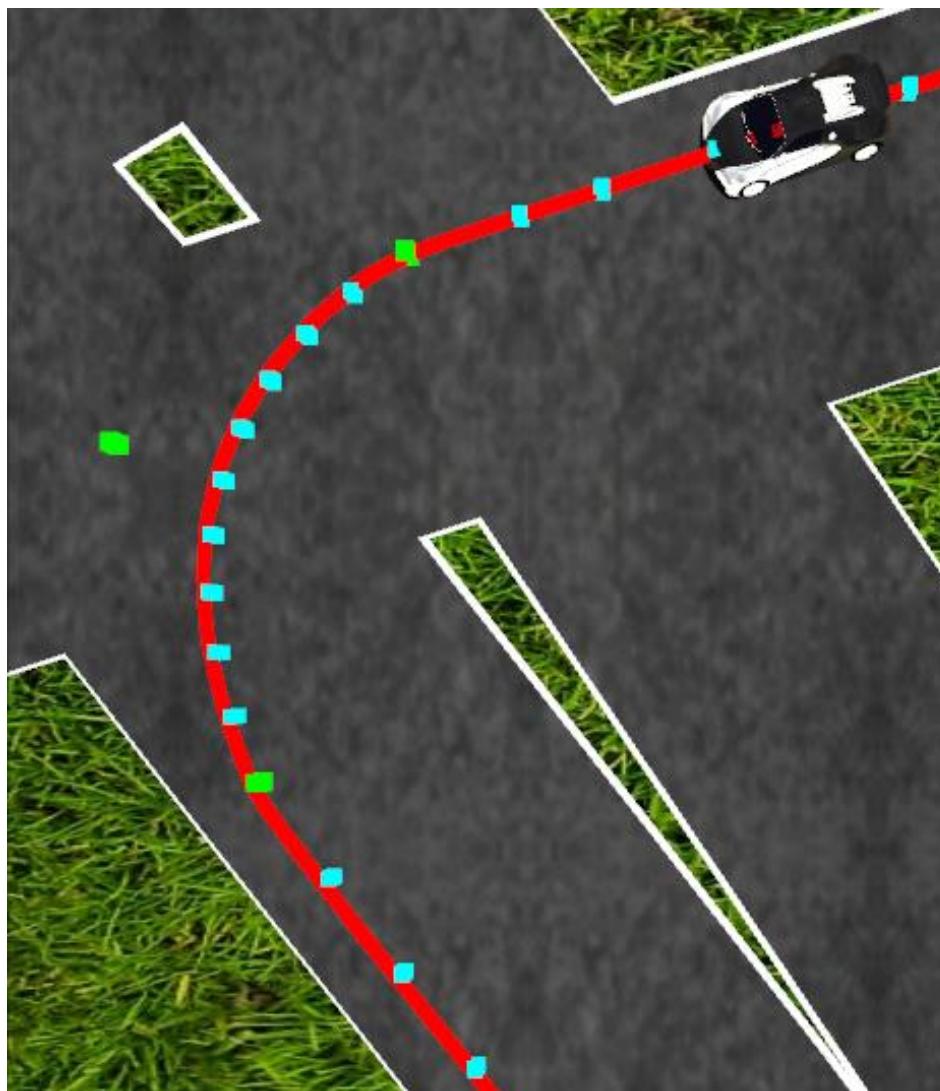
# Simulator für autonome Fahrzeuge



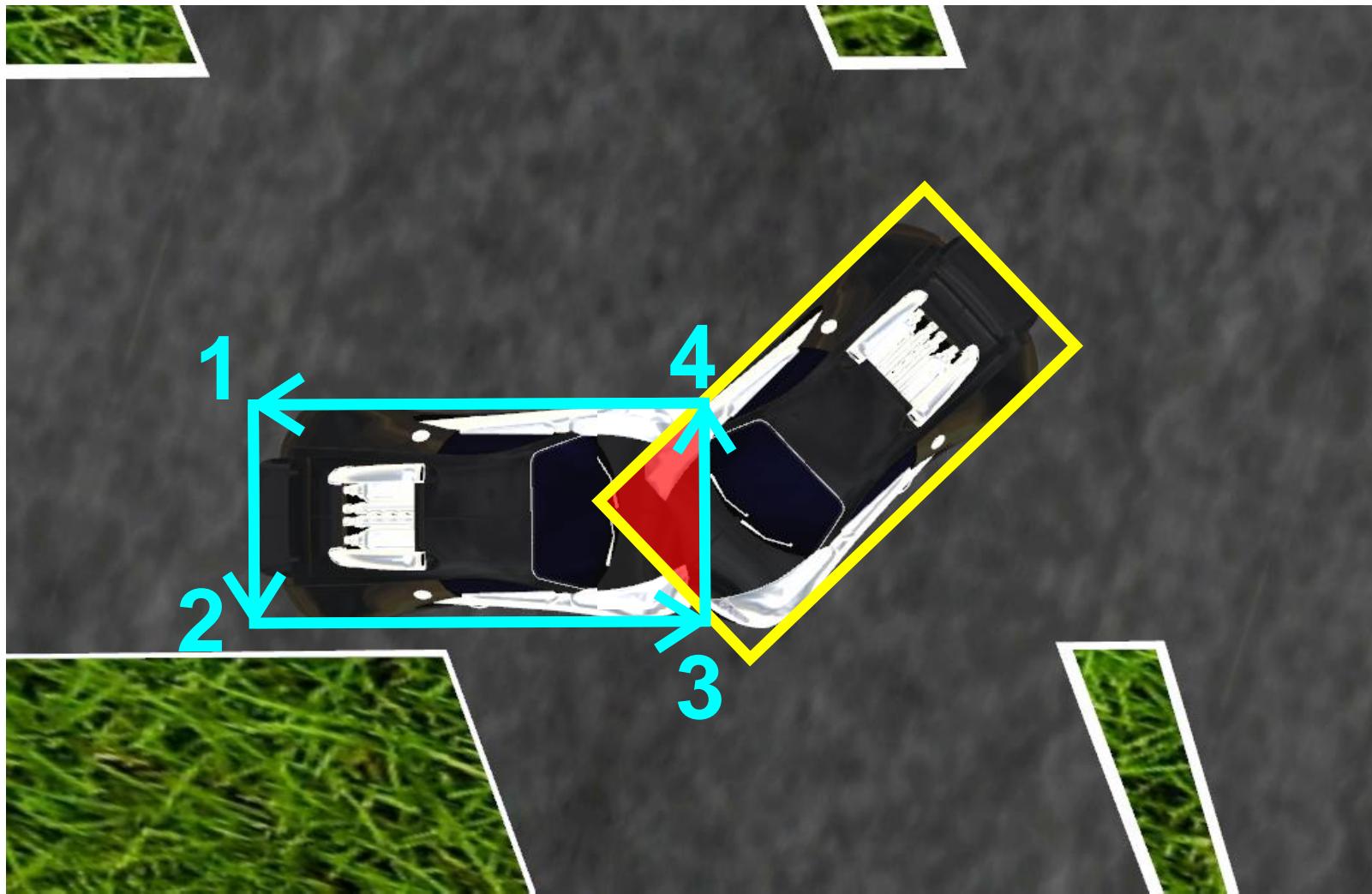
# Simulator für autonome Fahrzeuge



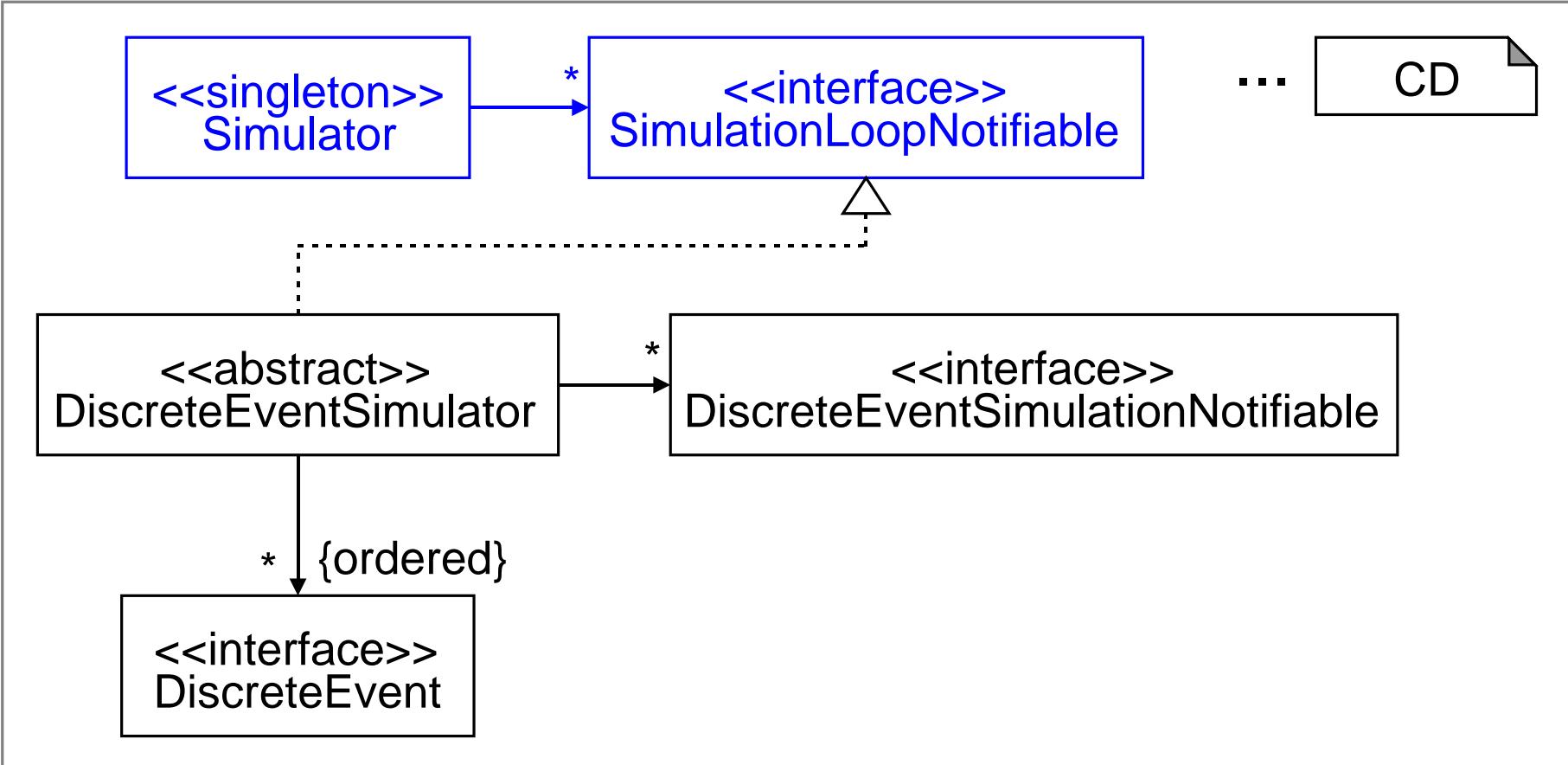
# Simulator für autonome Fahrzeuge



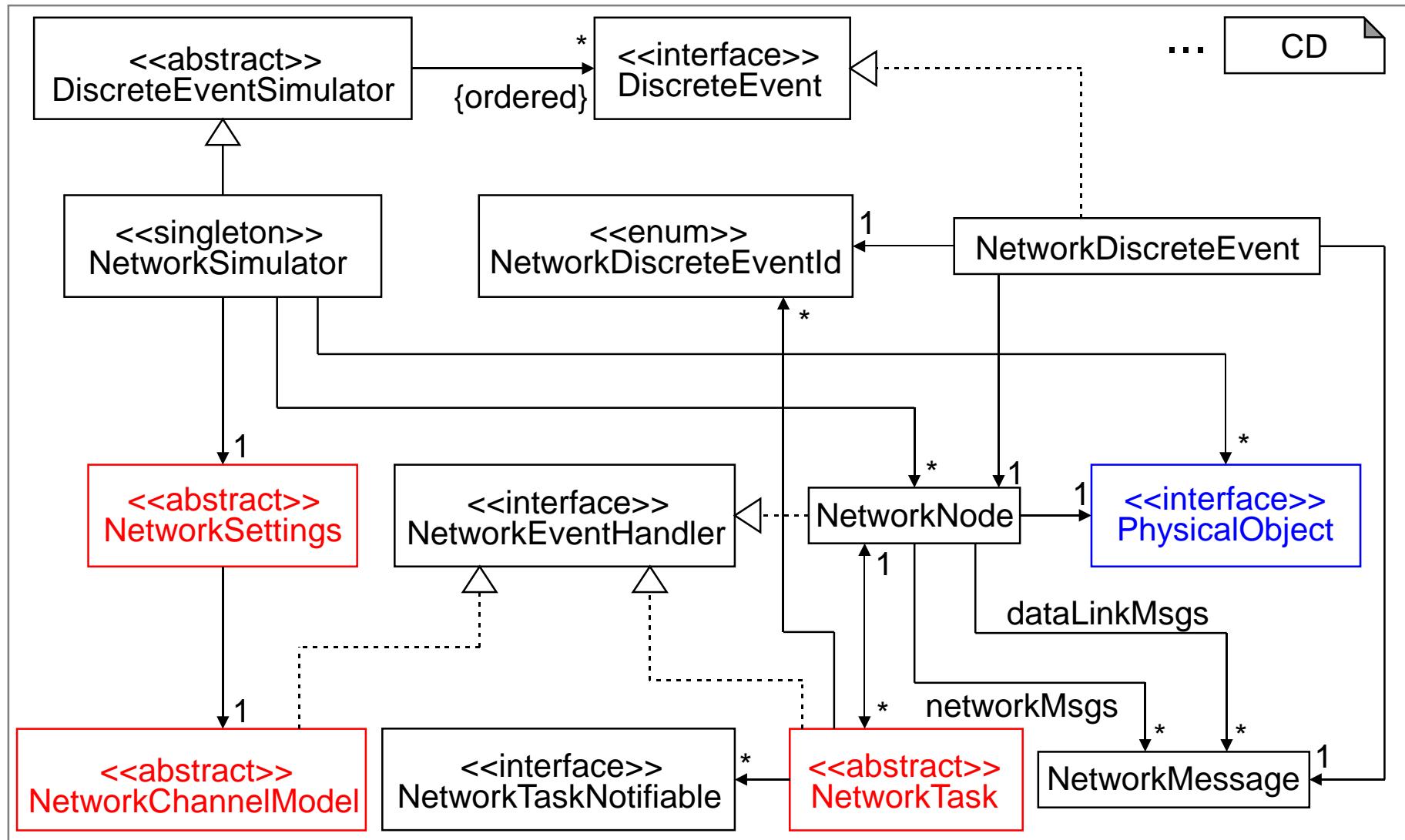
# Simulator für autonome Fahrzeuge



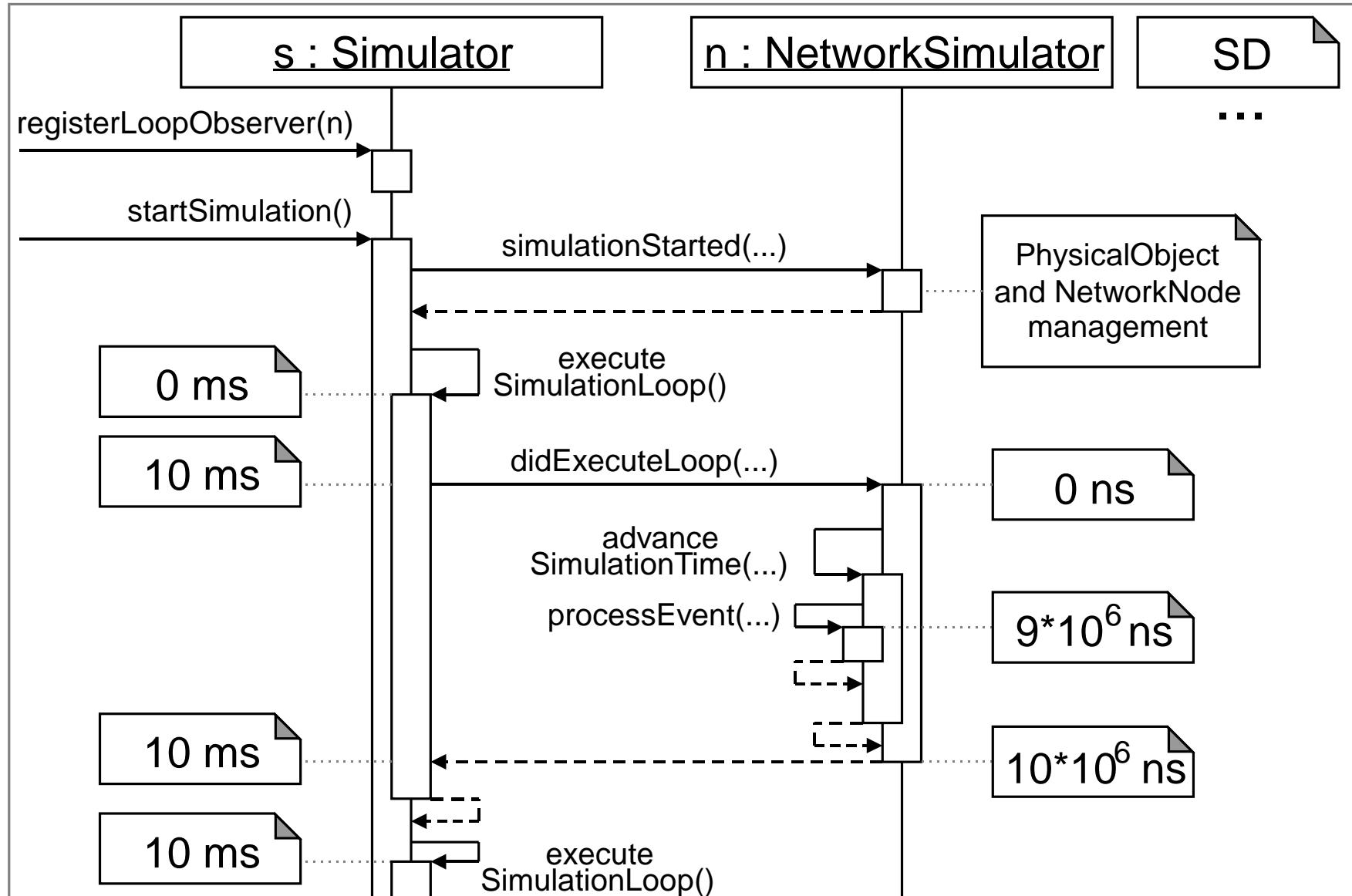
# Software Architektur



# Software Architektur



# Simulatorkopplung

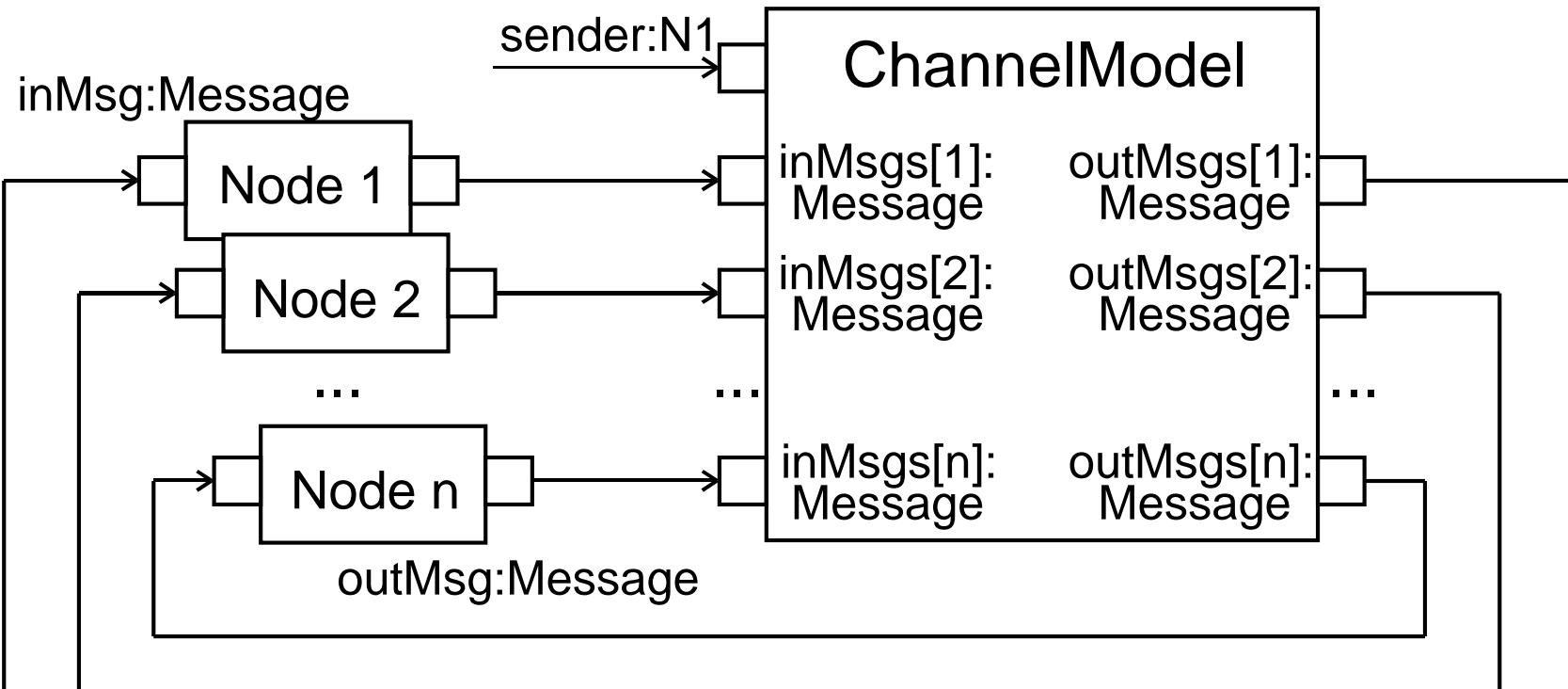


# Kanalmodelle

NetworkSimulator

...

C&C



# Kanalmodelle

## ► Simple / Direct Channel Model:

Index	Data Rate in kbit/s	Modulation: Bits per Signal	Code Rate
0	3000	1 (BPSK)	0.50
1	4500	1 (BPSK)	0.75
2	6000	2 (QPSK)	0.50
3	9000	2 (QPSK)	0.75
4	12000	4 (16QAM)	0.50
5	18000	4 (16QAM)	0.75
6	24000	6 (64QAM)	0.66
7	27000	6 (64QAM)	0.75

# Kanalmodelle

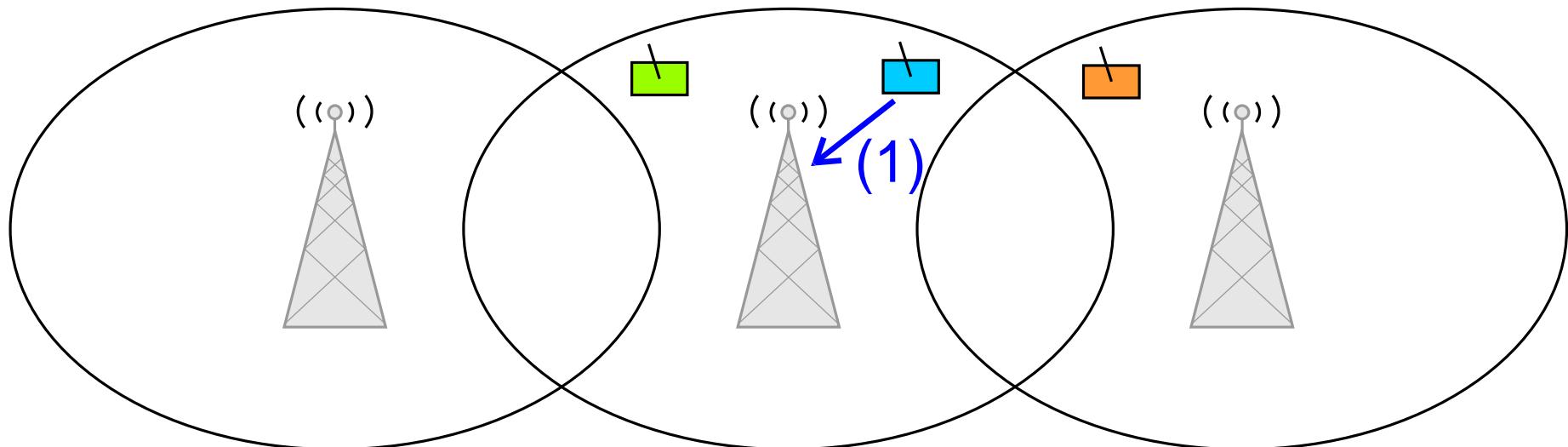
## ► Cellular Channel Model:

Index	Data Rate in kbit/s	Modulation: Bits per Signal	Code Rate
0	Up: 147, Down: 416	2 (QPSK)	0.30
1	Up: 565, Down: 1589	2 (QPSK)	0.44
2	Up: 1679, Down: 4698	2 (QPSK)	0.59
3	Up: 1489, Down: 4192	4 (16QAM)	0.48
4	Up: 3335, Down: 9182	4 (16QAM)	0.60
5	Up: 4517, Down: 12376	6 (64QAM)	0.75
6	Up: 7796, Down: 21702	6 (64QAM)	0.85
7	Up: 12531, Down: 33972	6 (64QAM)	0.93

# Broadcasting: Cellular Model

## ► Lokal begrenztes Broadcasting

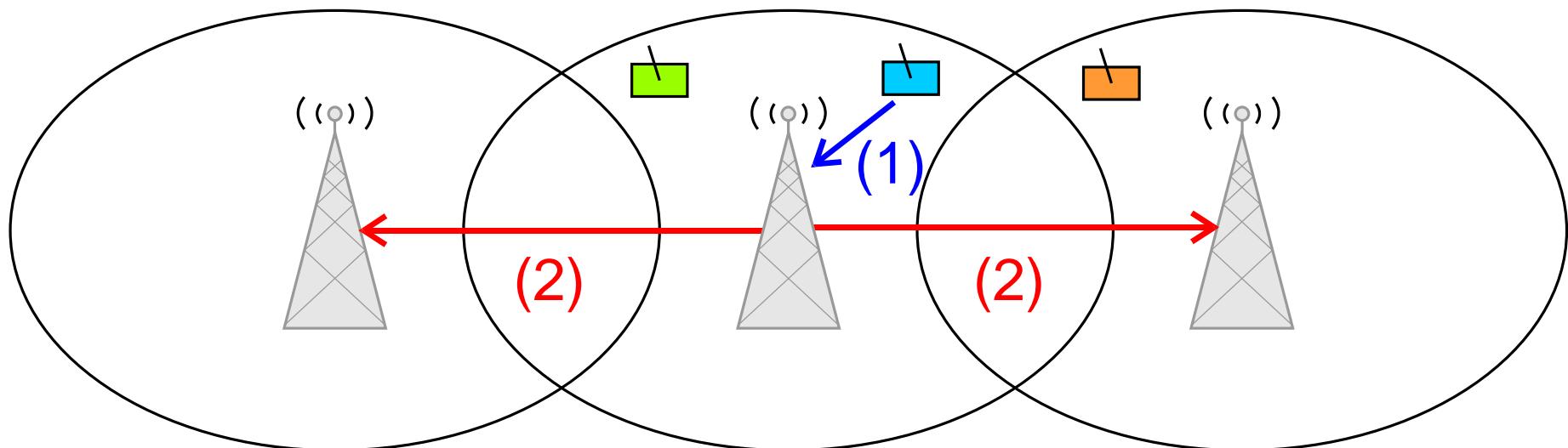
- Übertragung an alle relevanten Fahrzeuge
- Handover zwischen Funkzellen



# Broadcasting: Cellular Model

## ► Lokal begrenztes Broadcasting

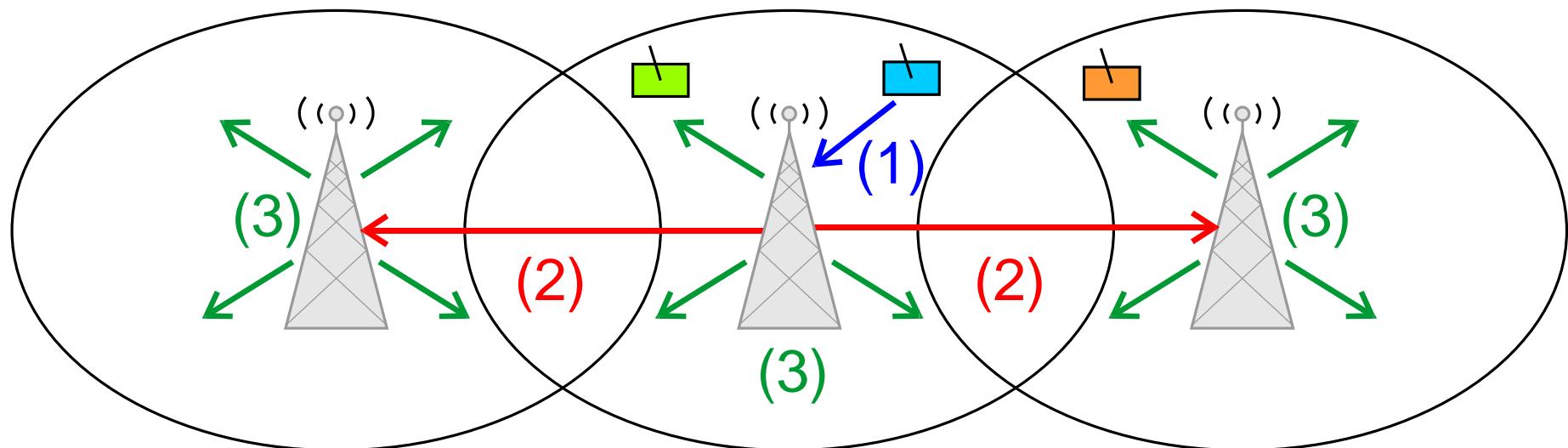
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# Broadcasting: Cellular Model

## ► Lokal begrenztes Broadcasting

- Übertragung an alle relevanten Fahrzeuge
- Handover zwischen Funkzellen

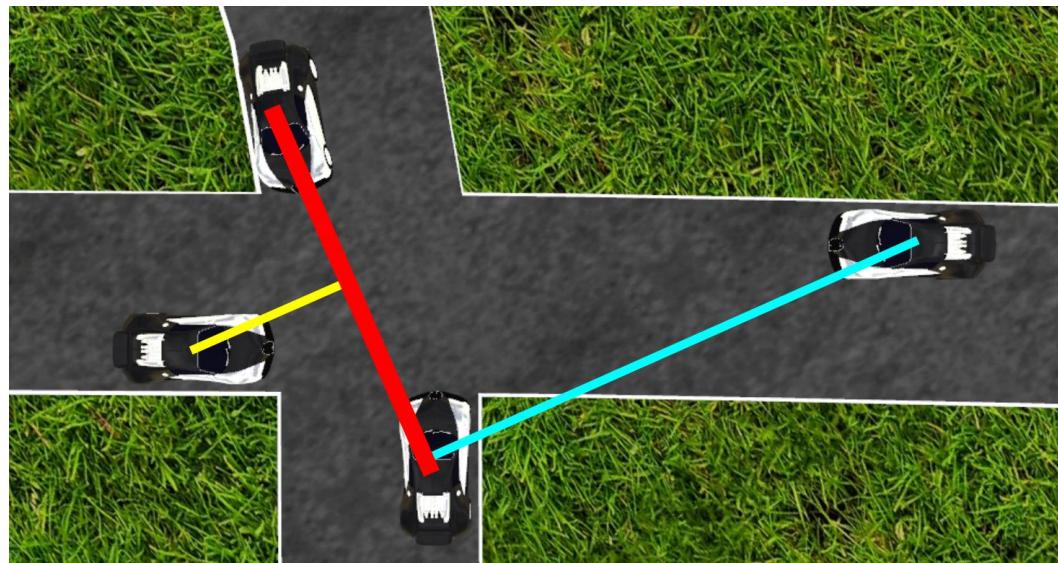


# Ausfallwahrscheinlichkeiten

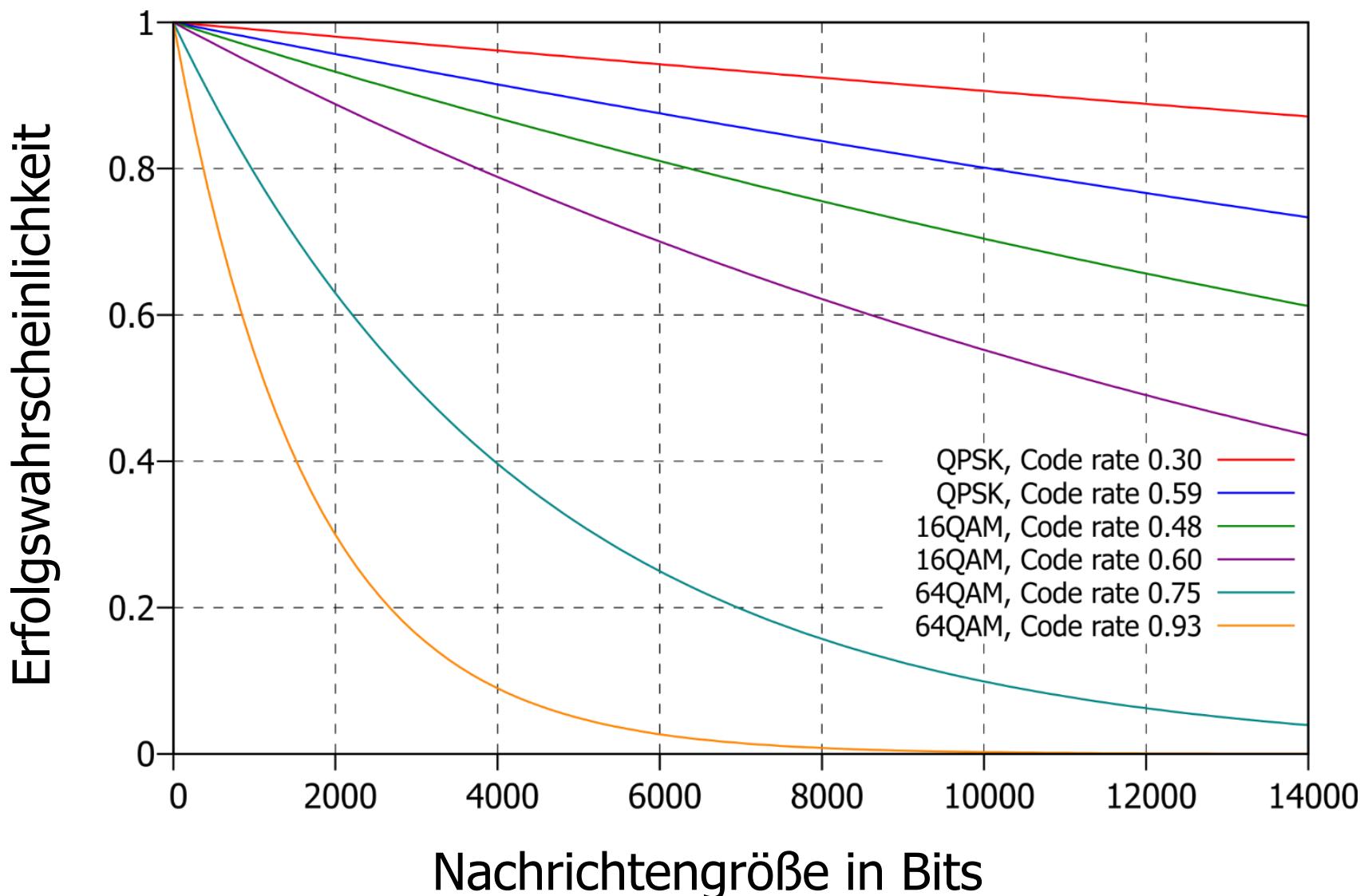
## ► Bit Error Rate / Packet Error Rate:

$$\text{BER}_{\text{total}} = (\text{BER}_{\text{Noise}} + \text{BER}_{\text{PathLoss}} + \text{BER}_{\text{MultiPath}} + \text{BER}_{\text{Doppler}}) * \text{FactorBER}$$

$$\text{PER} = 1 - (1 - \text{BER})^N$$

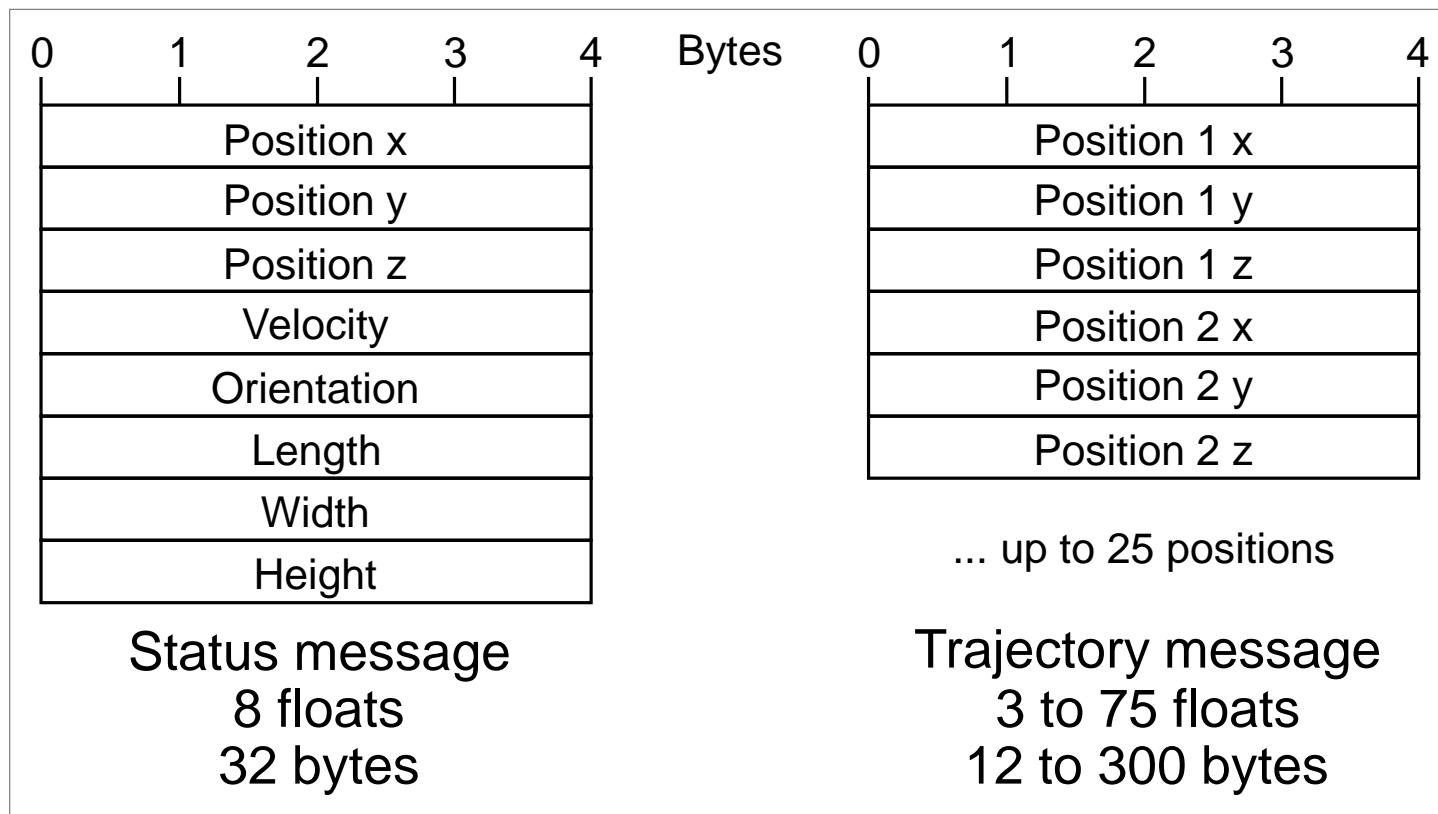


# Beispiel: Cellular Model

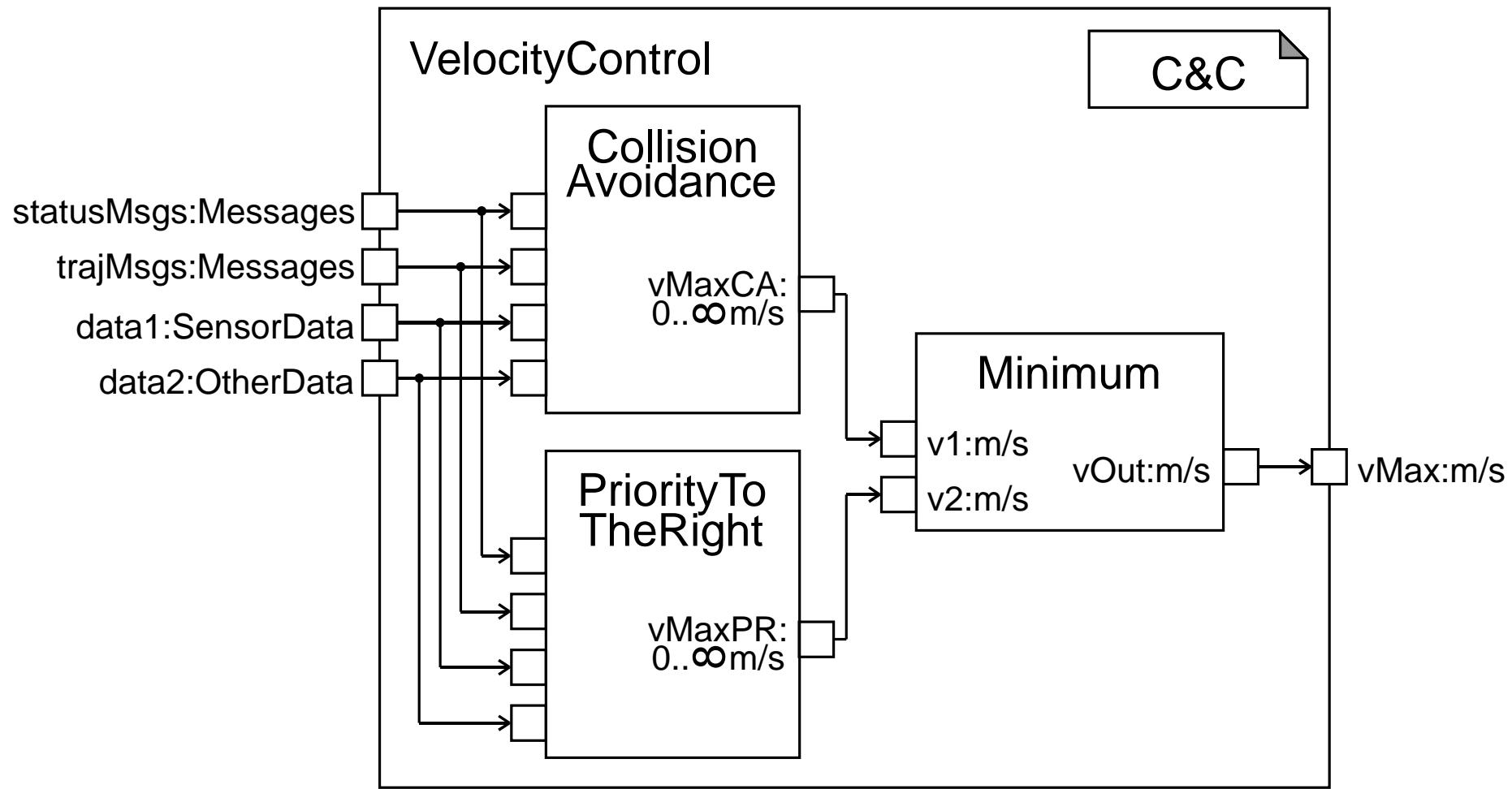


# Beacon Messages

- Zufälliger Start: 0s bis 3s
- Wiederholung: 375ms



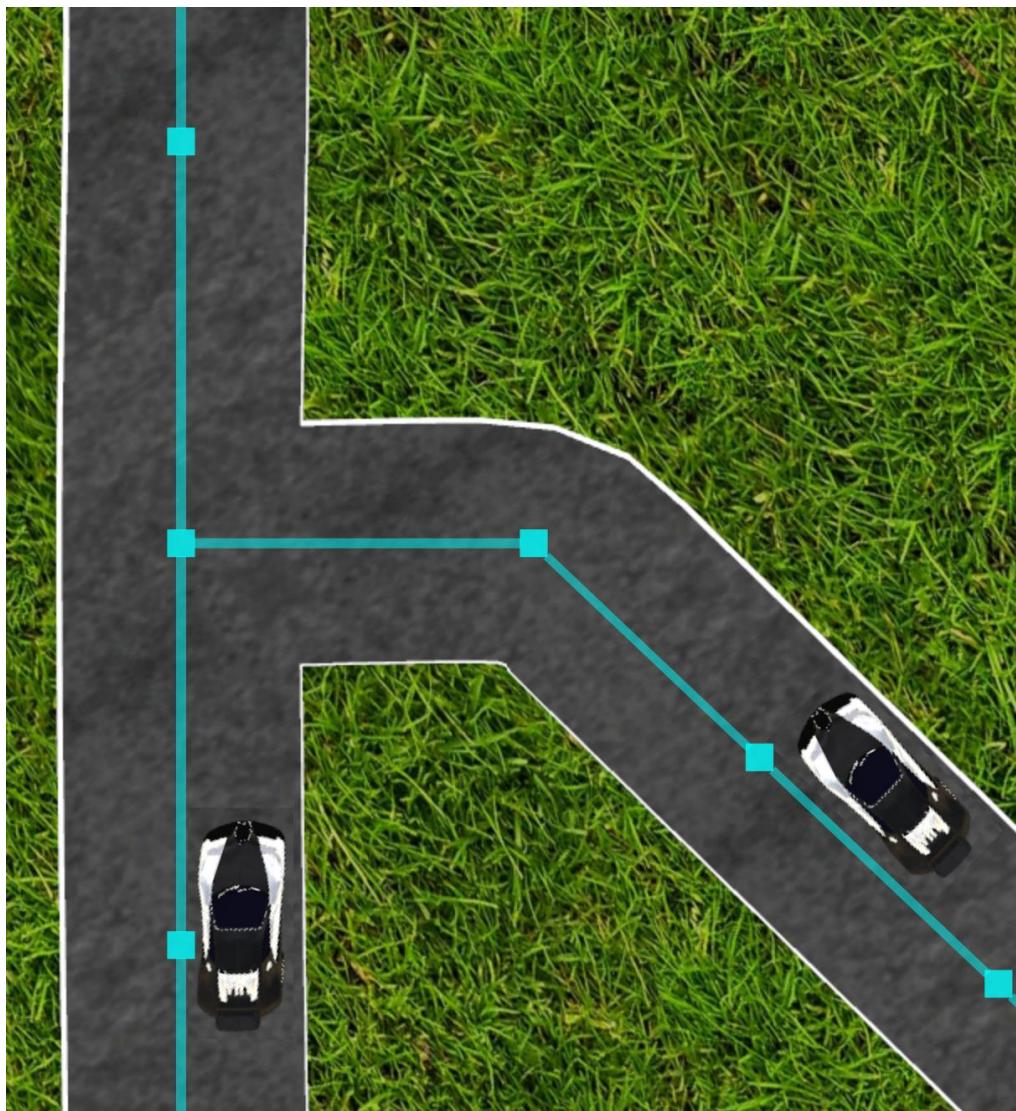
# Geschwindigkeitskontrolle



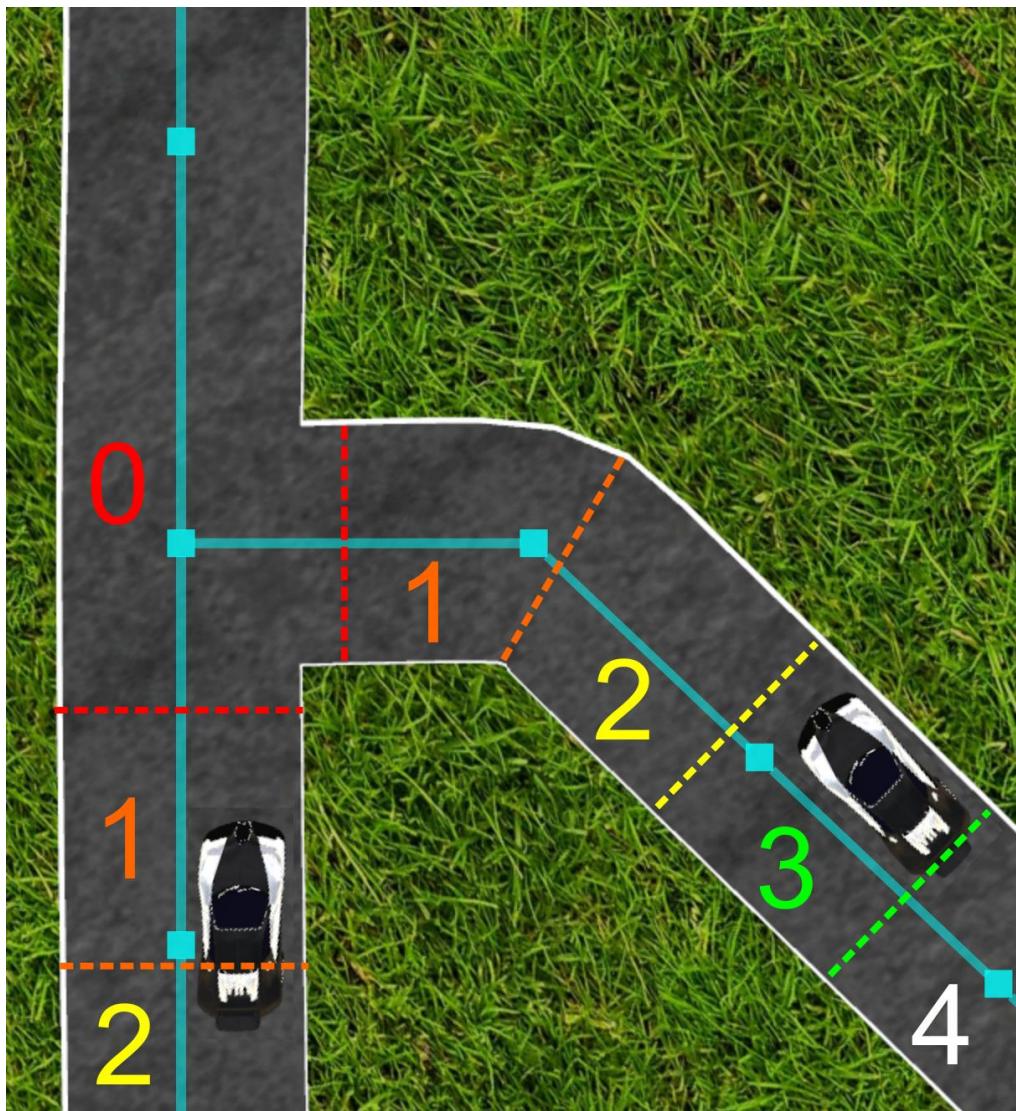
# Rechts vor Links



# Rechts vor Links



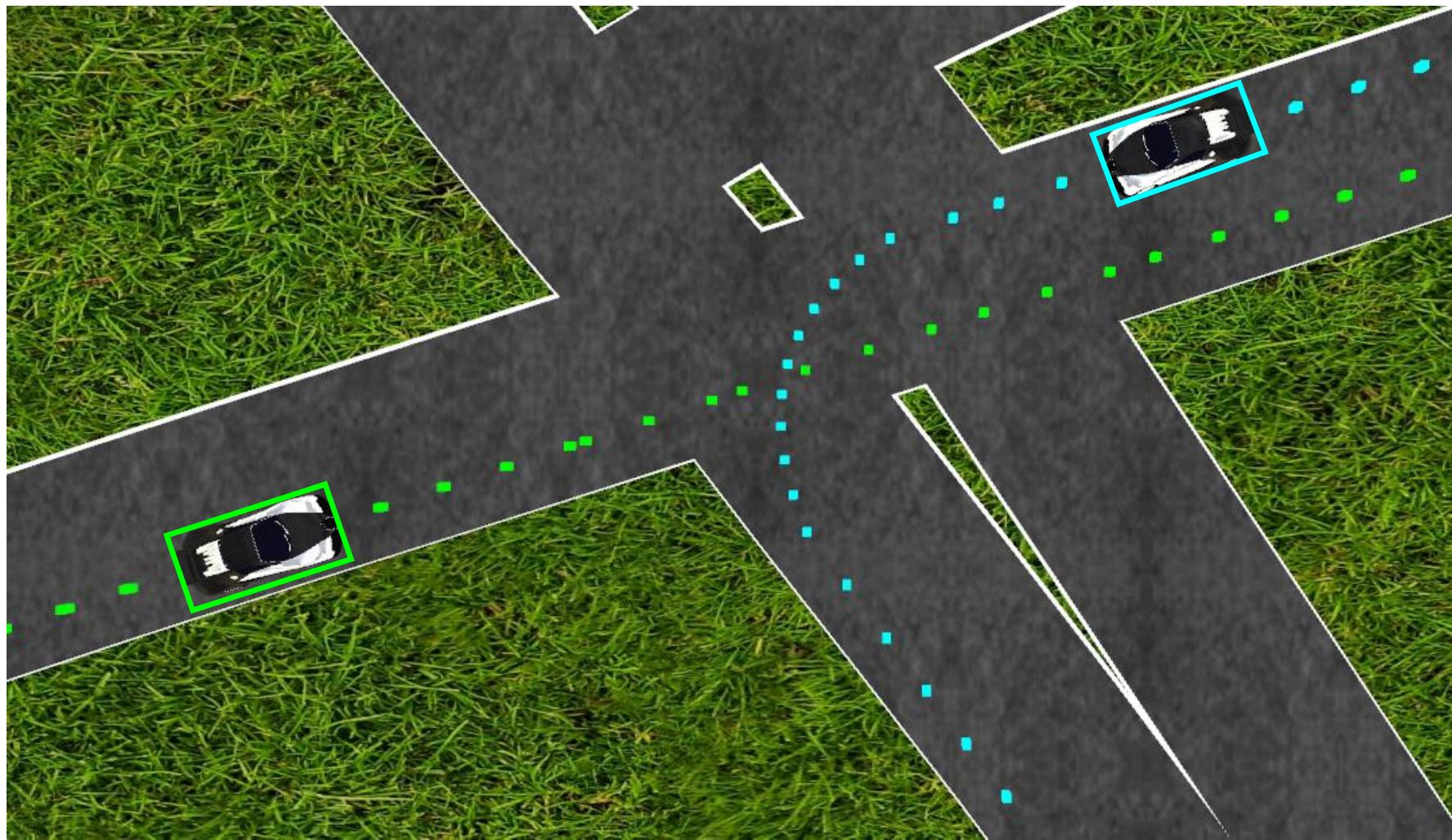
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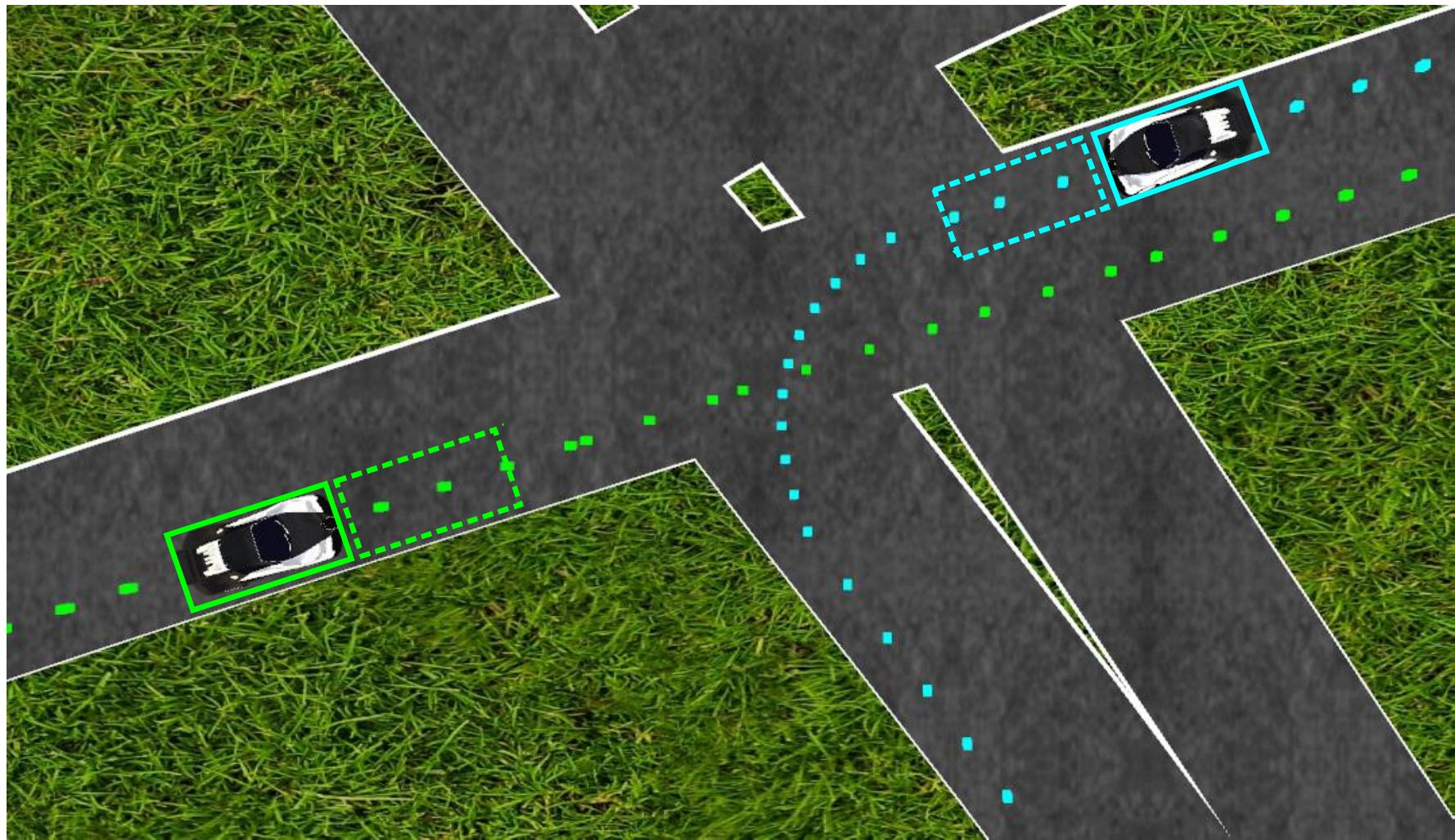
# Rechts vor Links

Note: Video not available in PDF presentation!

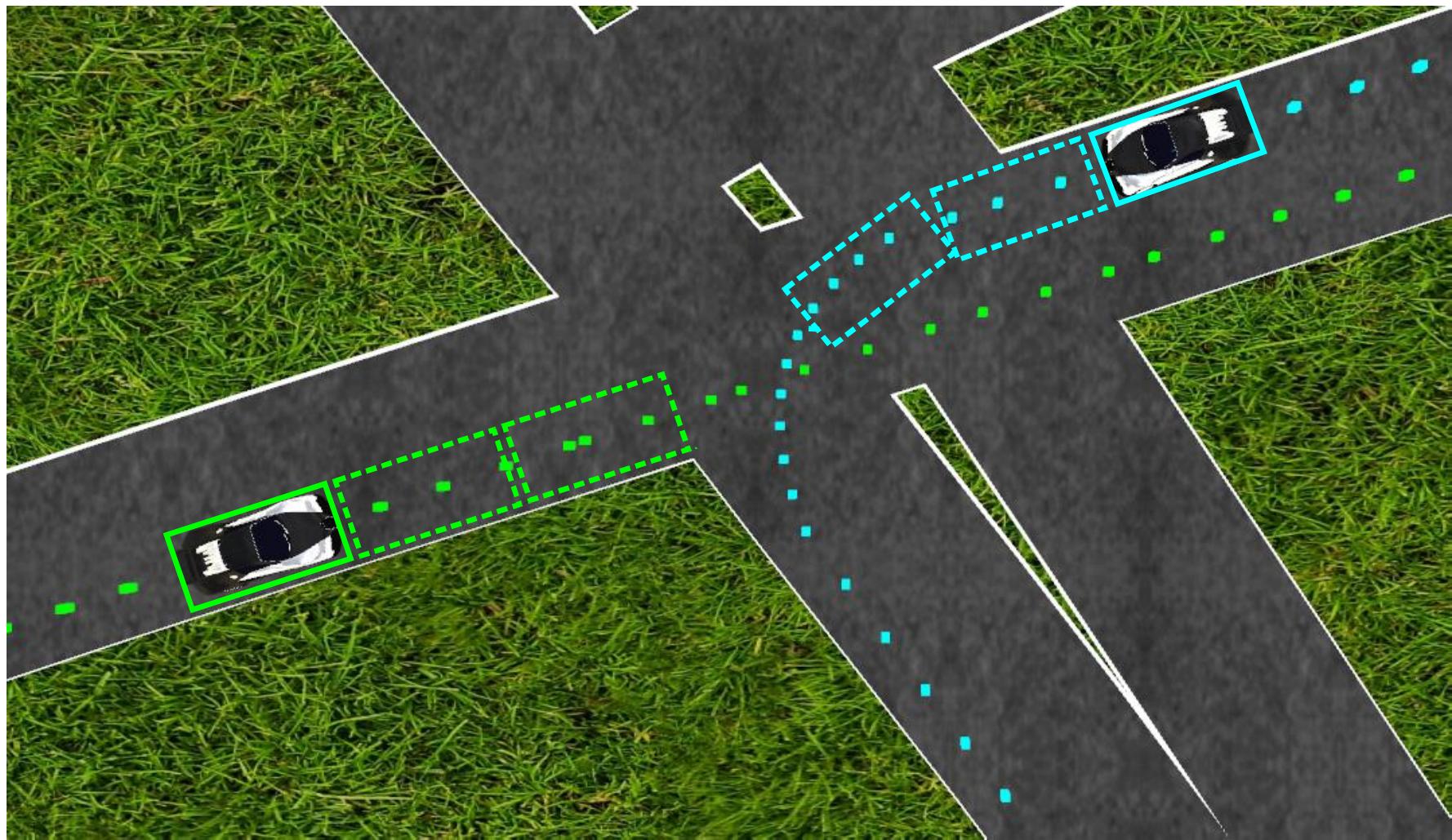
# Kollisionsvermeidung



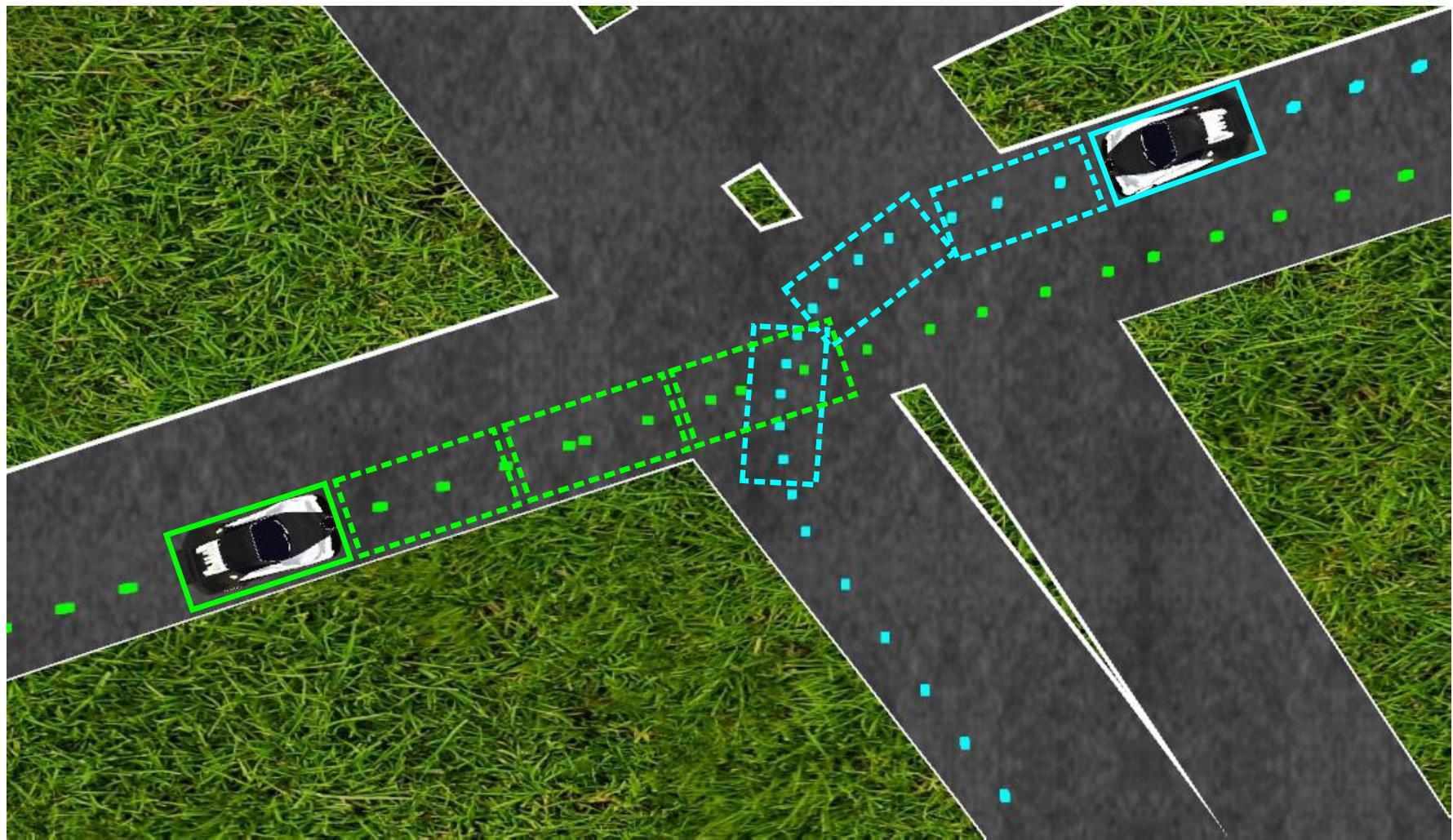
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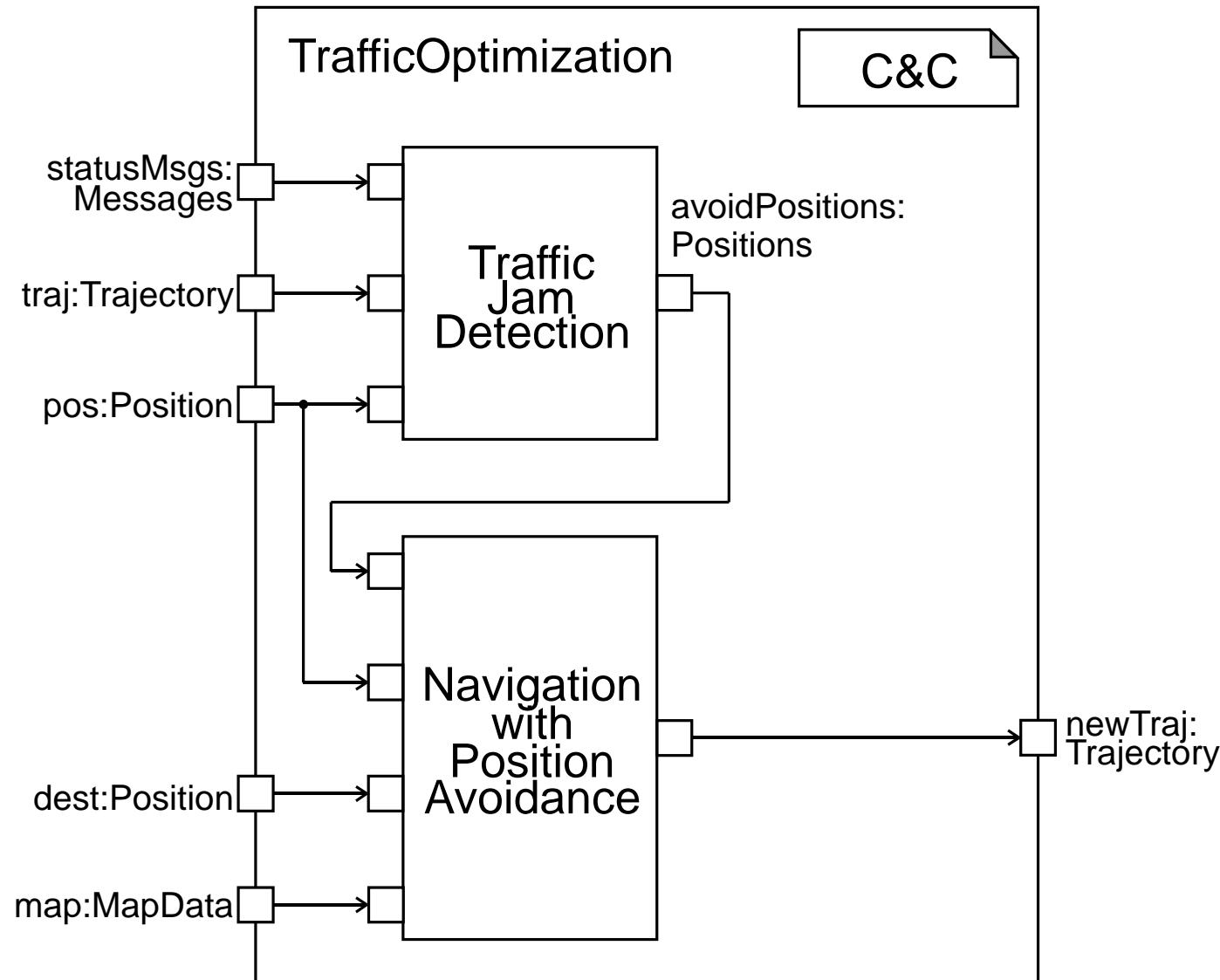
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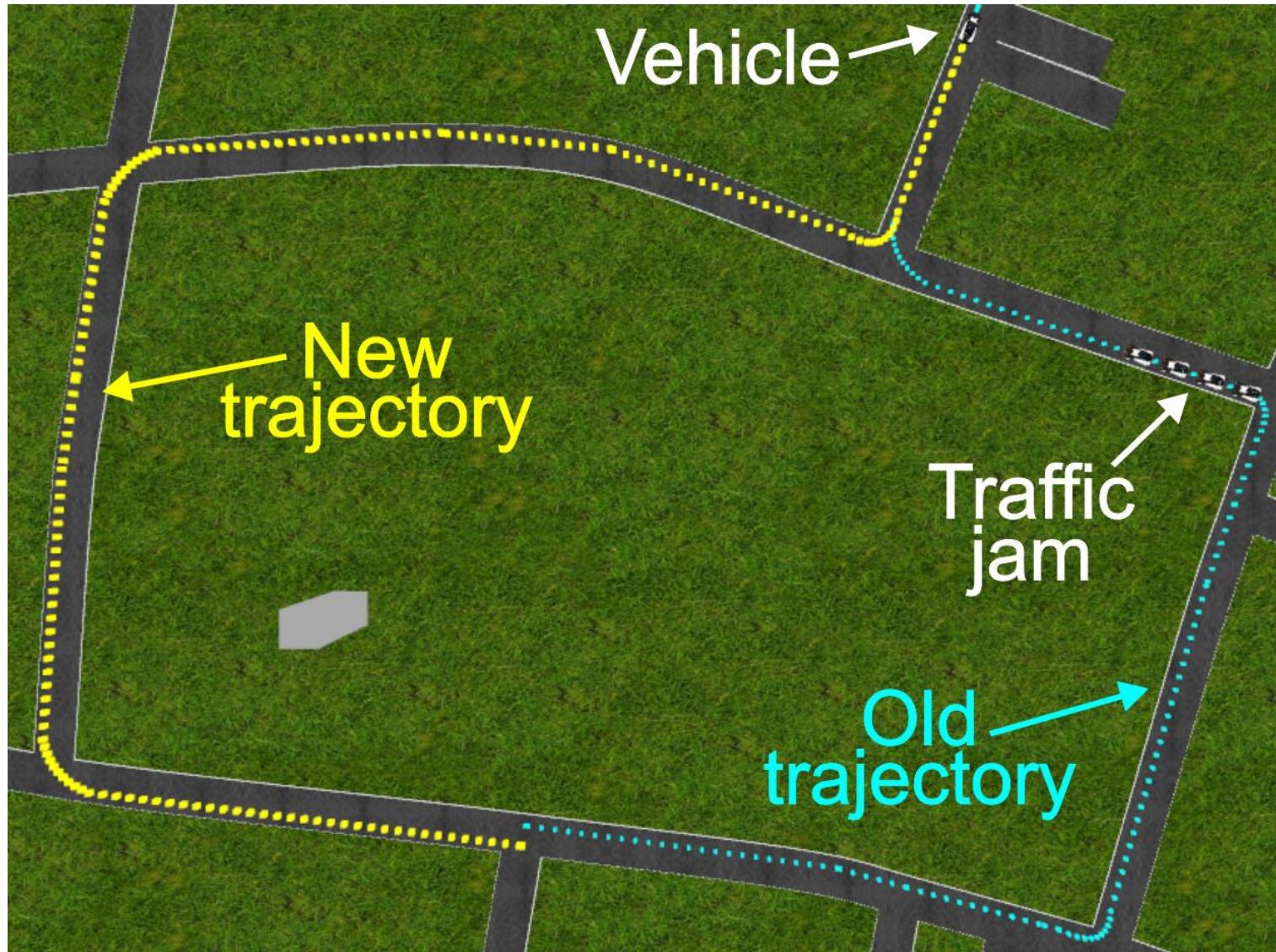
# Stauvermeidung



# Stauvermeidung

```
implementation math {
    posResult = [];
    nonMoving = detectNonMovingVehicles(statusMsgs, traj, pos);
    combinations = combntns(nonMoving, 4);
    for i = 1:size(combinations, 1)
        combi = combinations(i,:);
        combinationInRange = true;
        for j = 1:4
            for k = 1:4
                if distanceVehicles(combi(j), combi(k)) > 30.0
                    combinationInRange = false;
            end
        end
    end
    if combinationInRange
        for m = 1:4
            addVehiclePos(combi(m), posResult);
        end
    end
end
avoidPositions = posResult;
}
```

# Stauvermeidung



# Evaluation

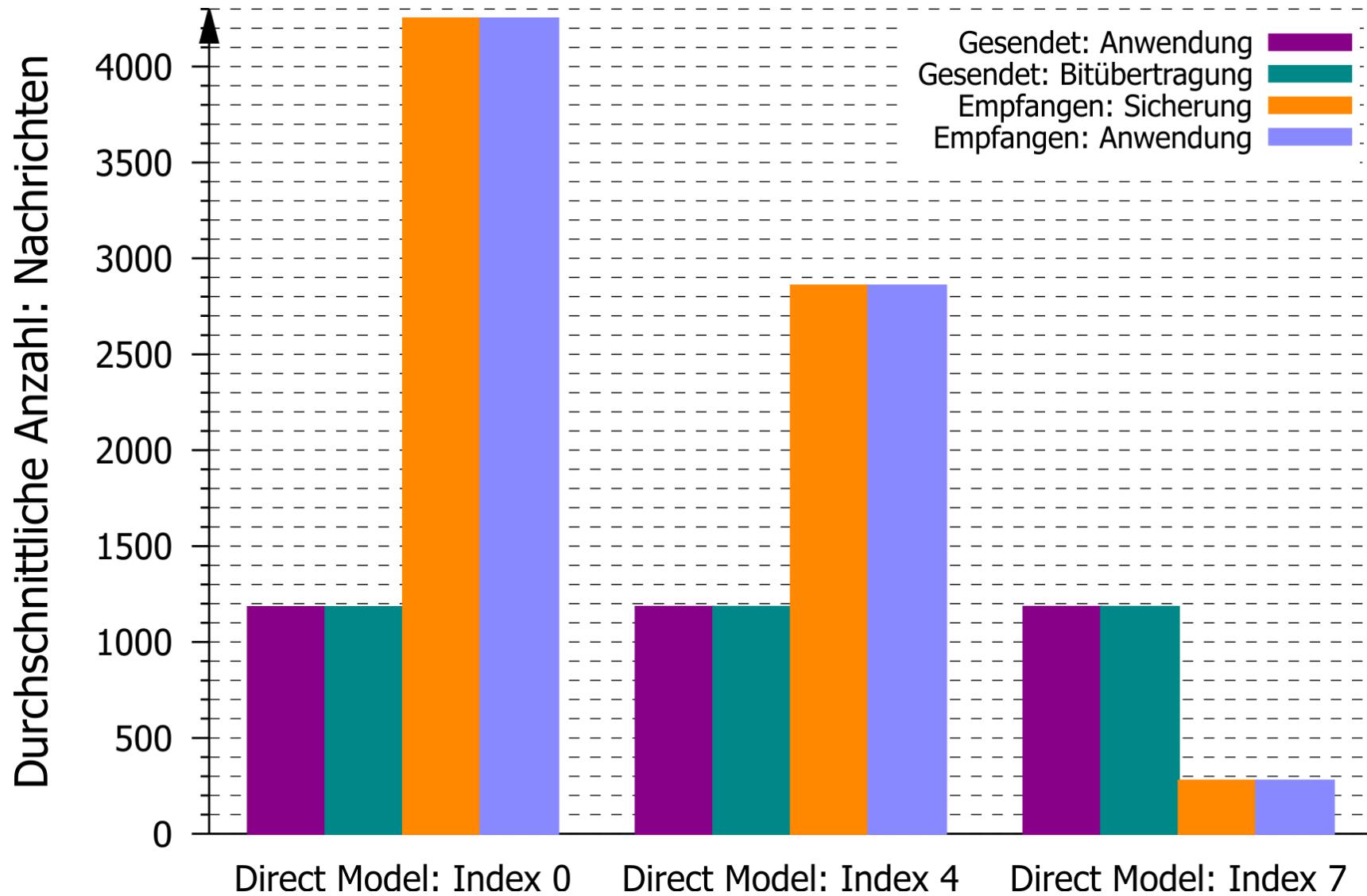
## ► Simulierte Szenarien

- 3 Kanalmodelle
- 3 Modulationseinstellungen
- 5 Fahrsituationen
- => 45 Kombinationen

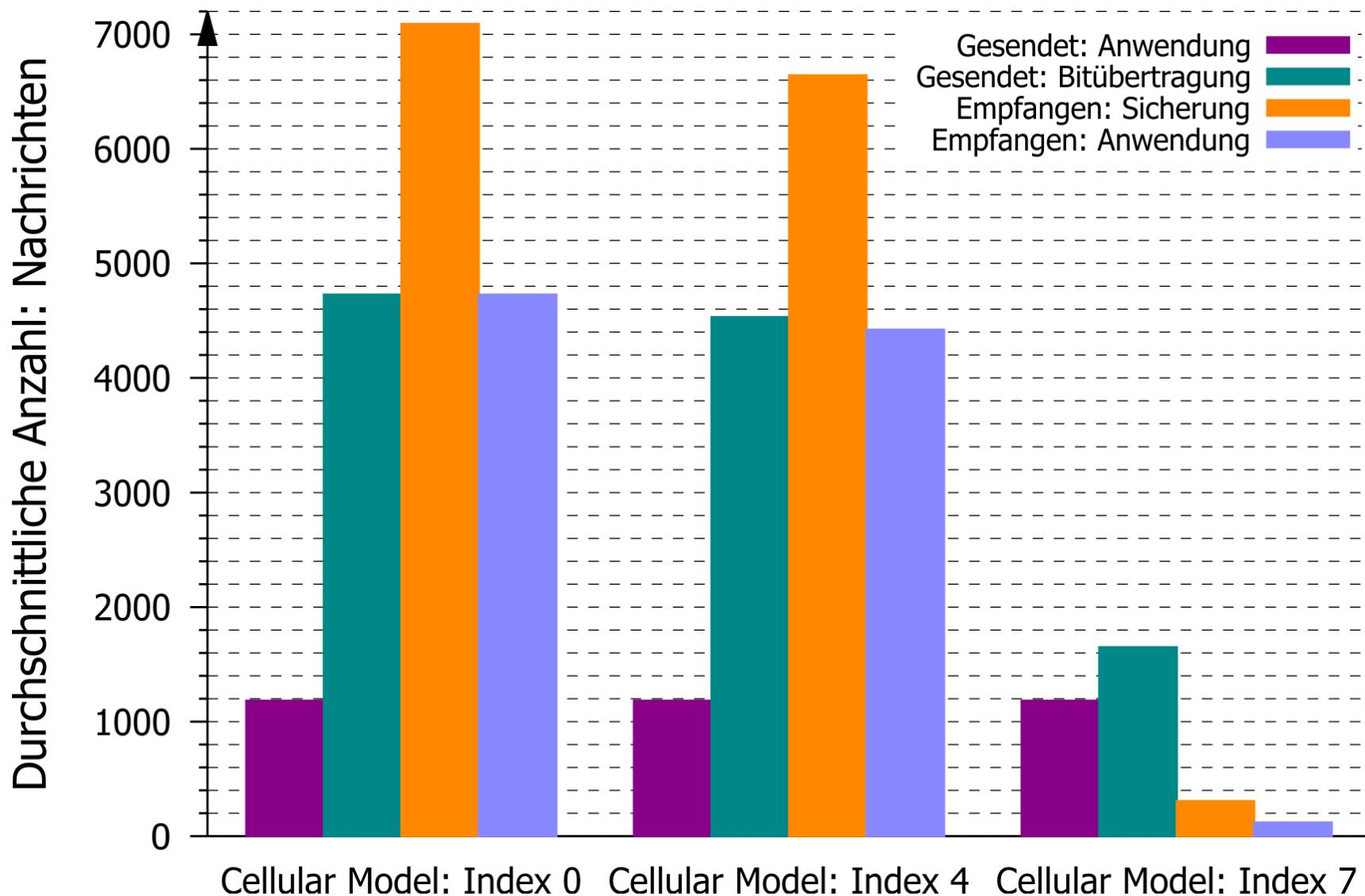
## ► Zufällige Aspekte in Simulation

- 100 Wiederholungen
- Textverarbeitung und MySQL Tabelle
- Durchschnittswerte und Summen

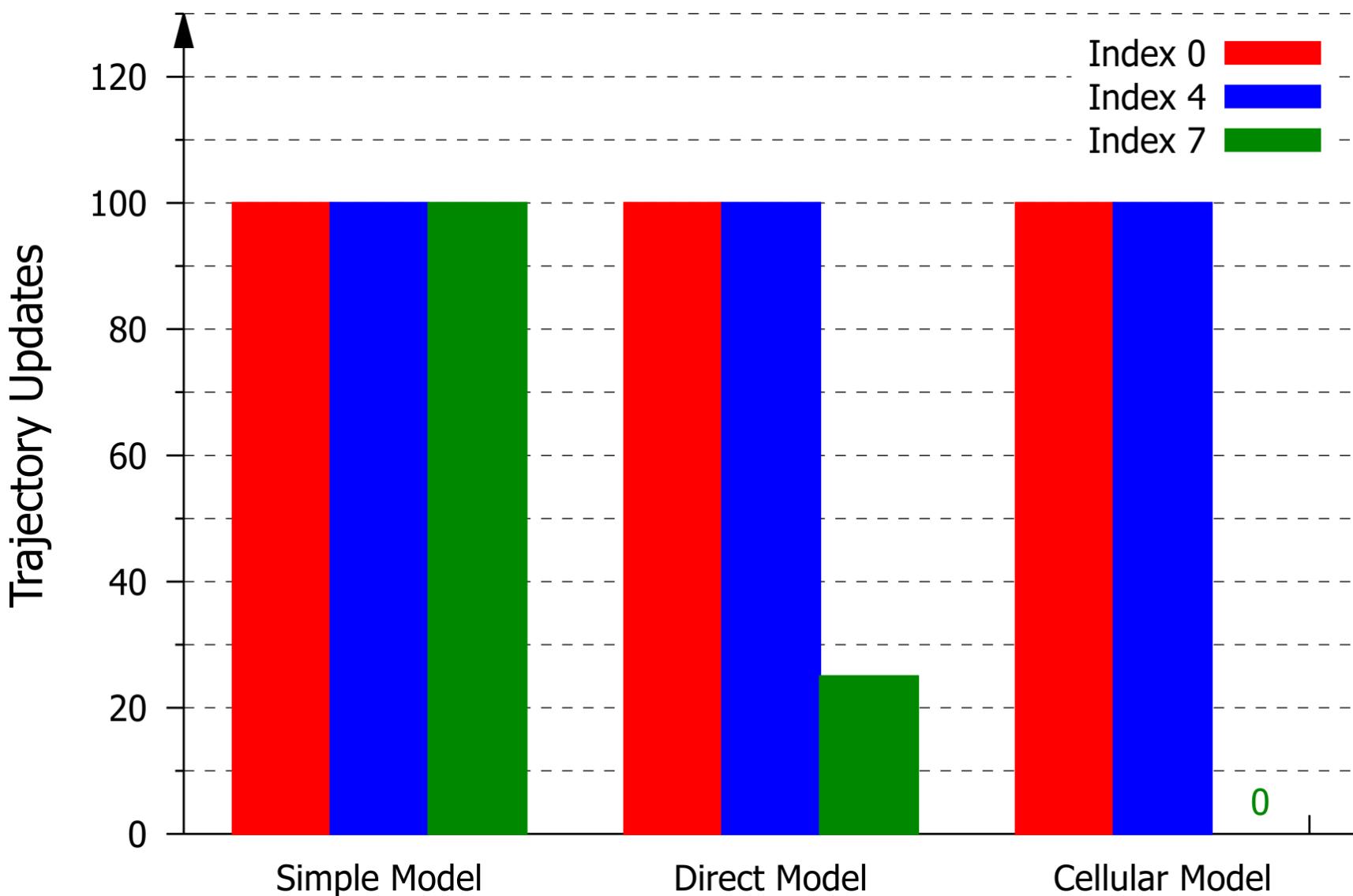
# Evaluation: Stauvermeidung



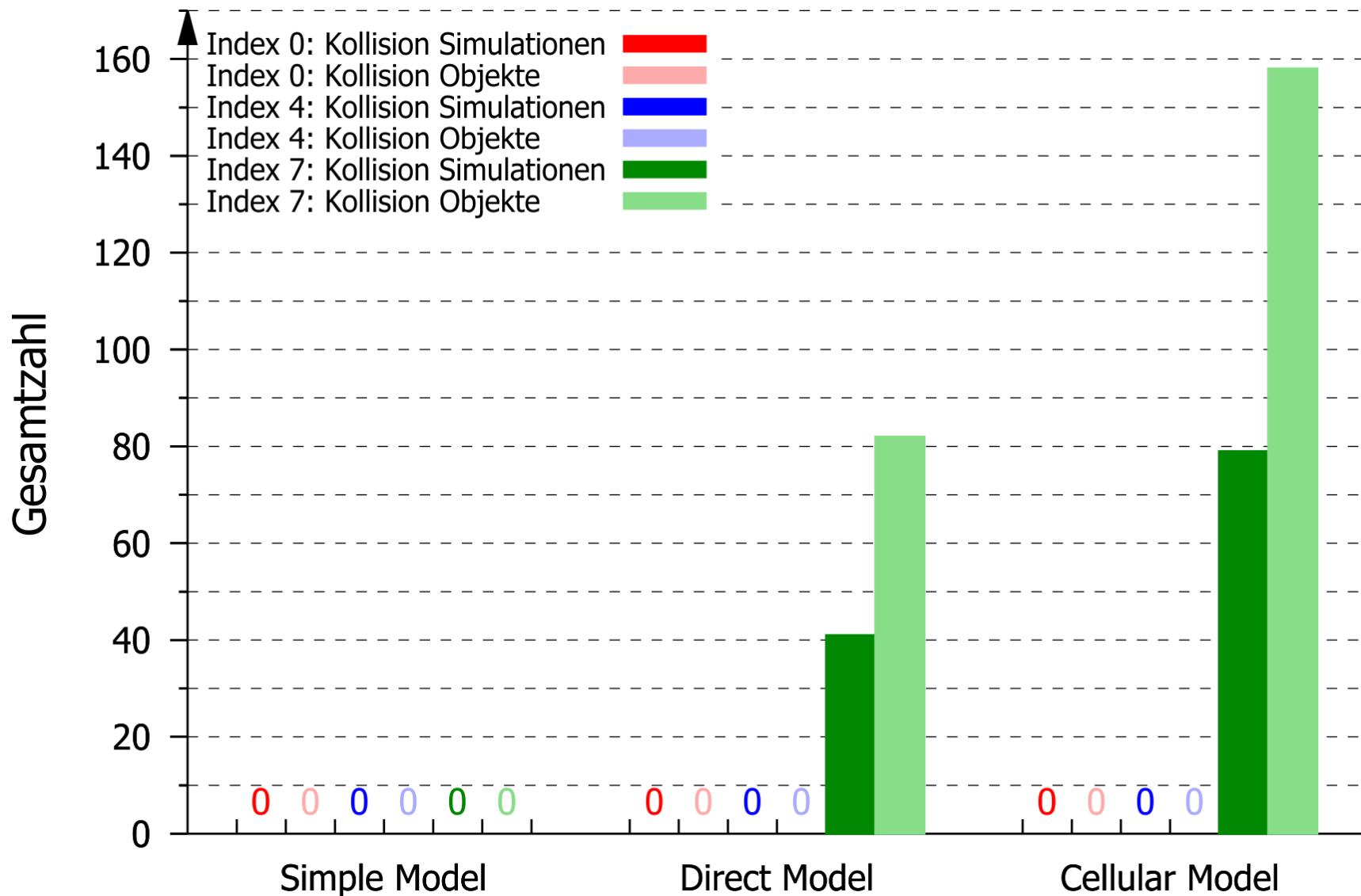
# Evaluation: Stauvermeidung



# Evaluation: Stauvermeidung



# Evaluation: Stauvermeidung



# Fazit

- ▶ Kopplung von Simulatoren
- ▶ Einfache Anpassung der Simulationsparameter
- ▶ Vorhersage von Fahrzeugverhalten
- ▶ Wiederholbarkeit von Szenarien
- ▶ Nützliche Daten für Entwicklung autonomer Fahrzeuge

# Ausblick

- ▶ Realistische Kanalmodelle
- ▶ Routing Algorithmen, Anpassung der Datenrate
- ▶ Sicherheit und Privatsphäre
- ▶ Redundanz: Sensordaten und Kommunikationsdaten
- ▶ Kombination verschiedener Netzwerktypen