Subchannel Allocation for Vehicle–to–Vehicle Broadcast Communications in Mode-3

Luis F. Abanto-Leon

Co-authors: Arie Koppelaar
Sonia Heemstra de Groot

Department of Electrical Engineering
Eindhoven University of Technology

IEEE Wireless Communications and Networking Conference
(IEEE WCNC 2018)

Contents

Figure 1: Connected world

Background

- 3GPP[1] proposed in Release 14, two novel schemes to support sidelink vehicular communications
  - C-V2X *mode-3* (centralized)
  - C-V2X[2] *mode-4* (distributed)

---

[1]The 3rd Generation Partnership Project
[2]Cellular Vehicle–to–Everything
[3]Device–to–Device (D2D) communications

Background

- 3GPP[1] proposed in Release 14, two novel schemes to support sidelink vehicular communications
  - C-V2X *mode-3* (centralized)
  - C-V2X[2] *mode-4* (distributed)

- C-V2X *modes* are based on LTE-D2D[3] technology, where similar communication modalities were proposed.

[1] The 3rd Generation Partnership Project
[2] Cellular Vehicle–to–Everything
[3] Device–to–Device (D2D) communications

Background

- 3GPP[1] proposed in Release 14, two novel schemes to support sidelink vehicular communications
  - C-V2X *mode-3* (centralized)
  - C-V2X[2] *mode-4* (distributed)
- C-V2X *modes* are based on LTE-D2D[3] technology, where similar communication modalities were proposed.
- However, in LTE-D2D (initially introduced for PS) the most important criterion was to prolong batteries lifespan (at the expense of compromising latency).

[1]The 3rd Generation Partnership Project
[2]Cellular Vehicle–to–Everything
[3]Device–to–Device (D2D) communications

Background

- To fulfill the low latency and high reliability requirements:

[4] Pilot symbols more closely spaced for channel estimation in high Doppler.
[5] A subchannel is a time-frequency resource chunk.

Background

- To fulfill the low latency and high reliability requirements:
- Modifications at PHY layer
  - Denser distribution of DMRS[4]

[4] Pilot symbols more closely spaced for channel estimation in high Doppler.
[5] A subchannel is a time-frequency resource chunk.

Background

- To fulfill the low latency and high reliability requirements:
- Modifications at PHY layer
  - Denser distribution of DMRS[4]
- Modifications at MAC layer
  - A novel subchannelization[5] containing

    (i) scheduling assignments (SCI)

    (ii) data (TB)

    in the same subframe to minimize latency.

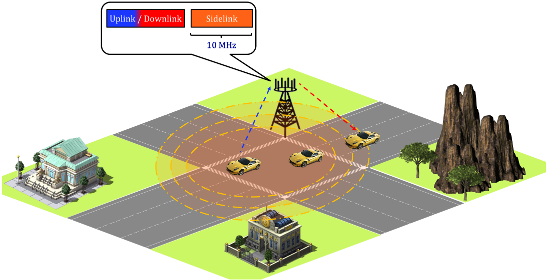
A semi-persistent scheduling was proposed for mode-4. No approach has been specified for mode-3.

[4] Pilot symbols more closely spaced for channel estimation in high Doppler.

[5] A subchannel is a time-frequency resource chunk.

Background

- Besides **uplink** and **downlink** (Uu), vehicles can also communicate via **sidelink** (PC5), which supports direct communications between vehicles.



C-V2X Mode-3

- Conversely to mainstream communications, in **C-V2X mode-3** data traffic from/to vehicles do not traverse the eNodeB.

C-V2X Mode-3

- Conversely to mainstream communications, in **C-V2X mode-3** data traffic from/to vehicles do not traverse the eNodeB.
  - eNodeBs **only** intervene in the **resource allocation** process.

C-V2X Mode-3

- Conversely to mainstream communications, in **C-V2X mode-3** data traffic from/to vehicles do not traverse the eNodeB.
  - eNodeBs **only** intervene in the **resource allocation** process.
  - Then **vehicles communicate directly** with their counterparts via sidelink

C-V2X Mode-3

- Conversely to mainstream communications, in **C-V2X mode-3** data traffic from/to vehicles do not traverse the eNodeB.
  - eNodeBs **only** intervene in the **resource allocation** process.
  - Then **vehicles communicate directly** with their counterparts via sidelink
- In **safety** applications, vehicles would typically exchange **cooperative awareness messages (CAMs)**: position, velocity, direction, etc.

C-V2X Mode-3

- As these messages transport important information, it is crucial that they are received **reliably**.

C-V2X Mode-3

- As these messages transport important information, it is crucial that they are received **reliably**.
- Due to the one–to–all broadcast nature, the allocation of resources (or subchannels) slightly differs from mainstream communications.

C-V2X Mode-3

- As these messages transport important information, it is crucial that they are received **reliably**.
- Due to the one–to–all broadcast nature, the allocation of resources (or subchannels) slightly differs from mainstream communications.
- **Example:** *If two vehicles transmit concurrently they will not receive the CAM message of the other.*
- *Four types of conflicts/requirements have been identified.*

Problem Identification: Condition Type I

Condition Type I: Differentiated QoS Requirements per Vehicle

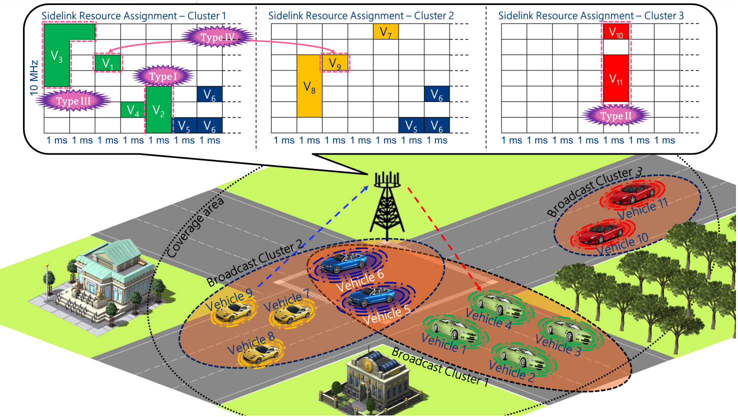


Figure 2: Different types of allocation conflicts

Problem Identification: Condition Type II

Condition Type II: Intra-cluster Subframe Allocation Conflicts

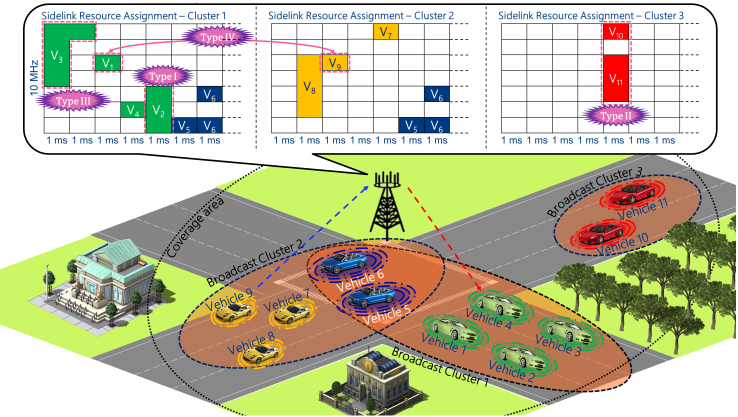


Figure 3: Different types of allocation conflicts

Problem Identification: Condition Type III

Condition Type III: Minimal Time Dispersion of Subchannels

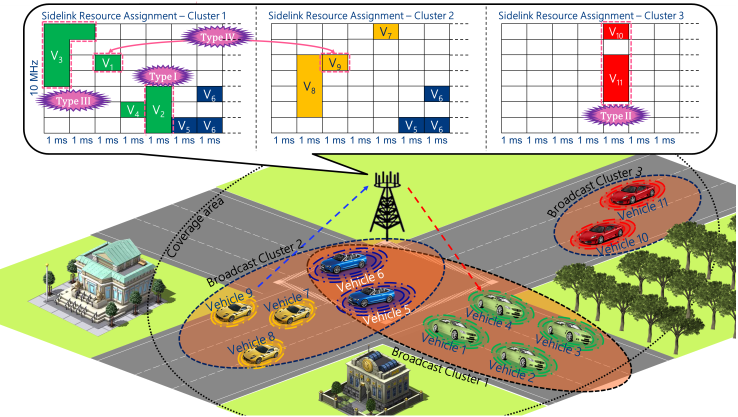


Figure 4: Different types of allocation conflicts

Problem Identification: Condition Type IV

Condition Type IV: One-hop Inter-cluster Subchannel Conflicts

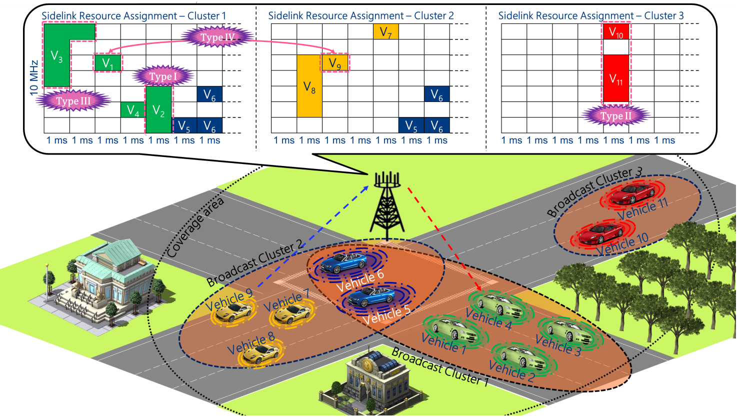
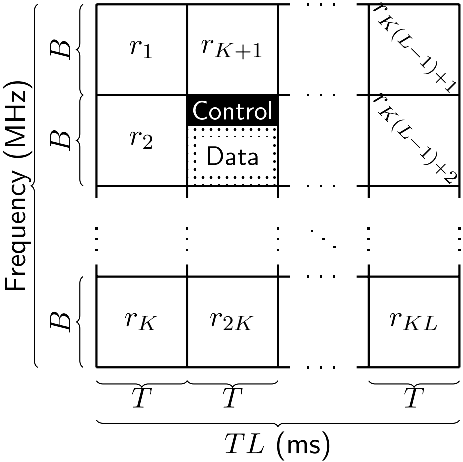


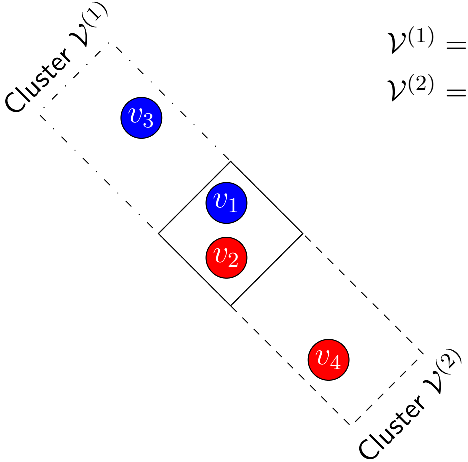
Figure 5: Different types of allocation conflicts

Sidelink Channelization



- T: duration of a subframe
- K: number of subchannels per subframe
- L: total number of subframes for allocation
- B: subchannel bandwidth

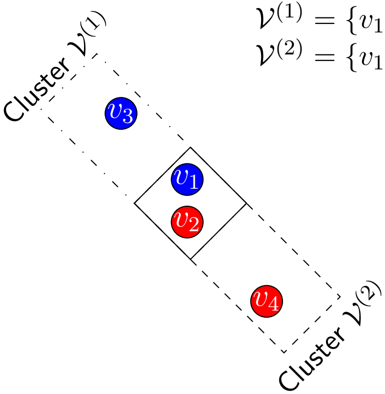
Motivation: Toy Example

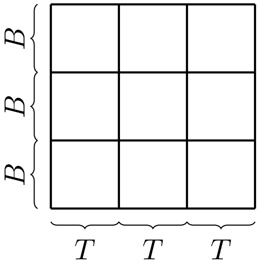


$$\mathcal{V}^{(1)} = \{v_1, v_2, v_3\}$$
$$\mathcal{V}^{(2)} = \{v_1, v_2, v_4\}$$

Motivation: Toy Example

$$\mathcal{V}^{(1)} = \{v_1, v_2, v_3\}$$
$$\mathcal{V}^{(2)} = \{v_1, v_2, v_4\}$$

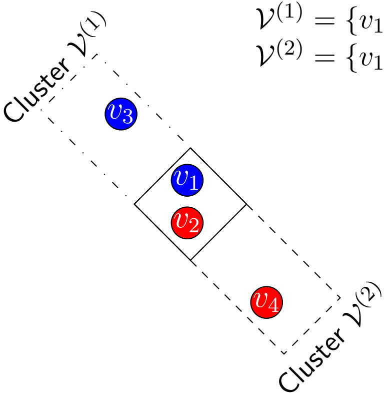


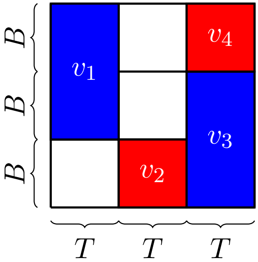


Motivation: Toy Example

Condition Type I: Differentiated QoS Requirements per Vehicle

$$\mathcal{V}^{(1)} = \{v_1, v_2, v_3\}$$
$$\mathcal{V}^{(2)} = \{v_1, v_2, v_4\}$$

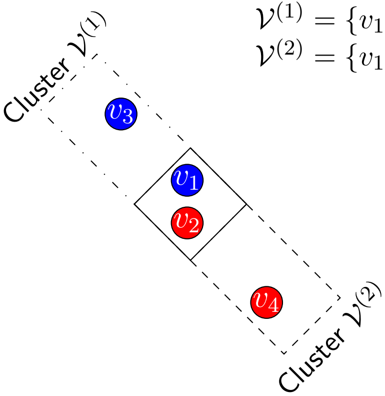




Motivation: Toy Example

Condition Type II: Intra-cluster Subframe Allocation Conflicts

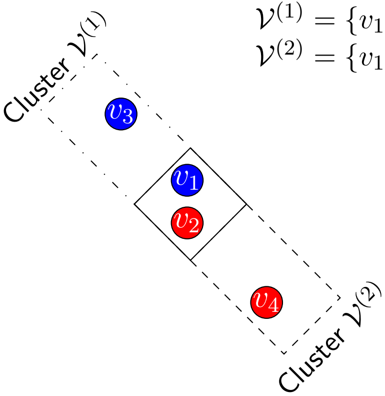
$$\mathcal{V}^{(1)} = \{v_1, v_2, v_3\}$$
$$\mathcal{V}^{(2)} = \{v_1, v_2, v_4\}$$



$$\widetilde{\mathbf{G}} = \begin{array}{cc} \begin{matrix} v_1 & v_2 & v_3 & v_4 \end{matrix} & \\ \begin{bmatrix} 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} & \begin{matrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{matrix} \end{array}$$

Motivation: Toy Example

Condition Type III: Minimal Time Dispersion of Subchannels

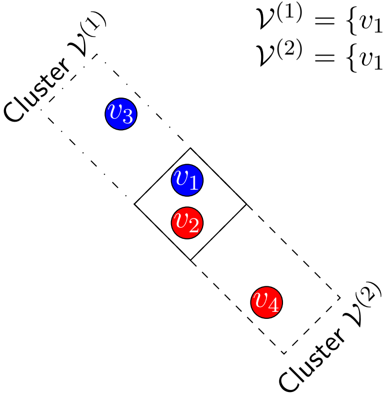


$$\mathcal{V}^{(1)} = \{v_1, v_2, v_3\}$$
$$\mathcal{V}^{(2)} = \{v_1, v_2, v_4\}$$

$$\widetilde{\mathbf{Q}} = \begin{array}{c} \\ \\ \\ \end{array} \begin{array}{cccc} sf_1 & sf_2 & sf_3 & \\ \left[\begin{array}{c} 0 \\ 1 \\ 1 \end{array}\right. \!\!\!\!\! & \begin{array}{c} 0 \\ 0 \\ 1 \end{array} & \left.\begin{array}{c} 0 \\ 0 \\ 0 \end{array}\right] & \begin{array}{c} sf_1 \\ sf_2 \\ sf_3 \end{array} \end{array}$$

Motivation: Toy Example

Condition Type IV: One-hop Inter-cluster Subchannel Conflicts



$$\mathcal{V}^{(1)} = \{v_1, v_2, v_3\}$$
$$\mathcal{V}^{(2)} = \{v_1, v_2, v_4\}$$

$$\widetilde{\mathbf{H}} = \begin{array}{c} \begin{array}{cccc} v_1 & v_2 & v_3 & v_4 \end{array} \\ \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \end{array} \begin{array}{c} v_1 \\ v_2 \\ v_3 \\ v_4 \end{array}$$

Problem Formulation

$$\max \ \mathbf{c}^T \mathbf{x}$$

subject to

$$\mathbf{q}_{N\times 1} - \epsilon \leq (\mathbf{I}_{N\times N} \otimes \mathbf{1}_{1\times KL})(\mathbf{c}_{NKL\times 1} \circ \mathbf{x}_{NKL\times 1}) \leq \mathbf{q}_{N\times 1} + \epsilon$$

$$[(\mathbf{G}^{+}_{P\times N} \otimes \mathbf{I}_{L\times L})(\mathbf{I}_{NL\times NL} \otimes \mathbf{1}_{1\times K})\mathbf{x}] \circ [(\mathbf{G}^{-}_{P\times N} \otimes \mathbf{I}_{L\times L})(\mathbf{I}_{NL\times NL} \otimes \mathbf{1}_{1\times K})\mathbf{x}] = \mathbf{0}_{PL\times 1}$$

$$[(\mathbf{I}_{N\times N} \otimes \mathbf{Q}^{+}_{L\times L})(\mathbf{I}_{NL\times NL} \otimes \mathbf{1}_{1\times K})\mathbf{x}] \circ [(\mathbf{I}_{N\times N} \otimes \mathbf{Q}^{-}_{L\times L})(\mathbf{I}_{NL\times NL} \otimes \mathbf{1}_{1\times K})\mathbf{x}] = \mathbf{0}_{NL\times 1}$$

$$[(\mathbf{H}^{+}_{U\times N} \otimes \mathbf{I}_{KL\times KL})\mathbf{x}] \circ [(\mathbf{H}^{-}_{U\times N} \otimes \mathbf{I}_{KL\times KL})\mathbf{x}] = \mathbf{0}_{U\times 1}.$$

Relaxed Formulation

$$\max \ \mathbf{c}^T\mathbf{x}$$

subject to

$$\mathbf{q}_{N\times 1} - \epsilon \leq (\mathbf{I}_{N\times N} \otimes \mathbf{1}_{1\times KL})(\mathbf{c}_{NKL\times 1} \circ \mathbf{x}_{NKL\times 1}) \leq \mathbf{q}_{N\times 1} + \epsilon$$

$$\mathbf{x}^T(\mathbf{I}_{NL\times NL} \otimes \mathbf{1}_{K\times 1})\{\widetilde{\mathbf{G}}_{N\times N} \otimes \mathbf{I}_{L\times L}\}(\mathbf{I}_{NL\times NL} \otimes \mathbf{1}_{1\times K})\mathbf{x} = 0$$

$$\mathbf{x}^T(\mathbf{I}_{NL\times NL} \otimes \mathbf{1}_{K\times 1})\{\mathbf{I}_{N\times N} \otimes \widetilde{\mathbf{Q}}_{L\times L}\}(\mathbf{I}_{NL\times NL} \otimes \mathbf{1}_{1\times K})\mathbf{x} = 0$$

$$\mathbf{x}^T\{\widetilde{\mathbf{H}}_{N\times N} \otimes \mathbf{I}_{KL\times KL}\}\mathbf{x} = 0.$$

Simulation Scenario

Consider the following setting:

- There is a total of $N = 40$ vehicles divided into 4 clusters:
  $|\mathcal{V}^{(1)}| = 16 \quad |\mathcal{V}^{(2)}| = 16 \quad |\mathcal{V}^{(3)}| = 16 \quad |\mathcal{V}^{(4)}| = 8$
  such that:
- $|\mathcal{V}^{(1)} \cap \mathcal{V}^{(2)} \cap \mathcal{V}^{(3)}| = 8$
- $|\mathcal{V}^{(1)} \cap \mathcal{V}^{(4)}| = \emptyset$
- $|\mathcal{V}^{(2)} \cap \mathcal{V}^{(4)}| = \emptyset$
- $|\mathcal{V}^{(3)} \cap \mathcal{V}^{(4)}| = \emptyset$
- QoS requirements: 12 Mbps, 10 Mbps, 5 Mbps or 3 Mbps.
- There are 10 vehicles for each kind of QoS.

Scenario : Required QoS = 12 Mbps

The number of subframes is $L = 16$.
The number of subchannels per subframe is $K = 4$.
$\epsilon = 0.8$ *Mbps and therefore the range of rates are*
$[11.2 - 12.8]$ *Mbps*, $[9.2 - 10.8]$ *Mbps*, $[4.2 - 5.8]$ *Mbps and* $[2.2 - 3.8]$ *Mbps*.

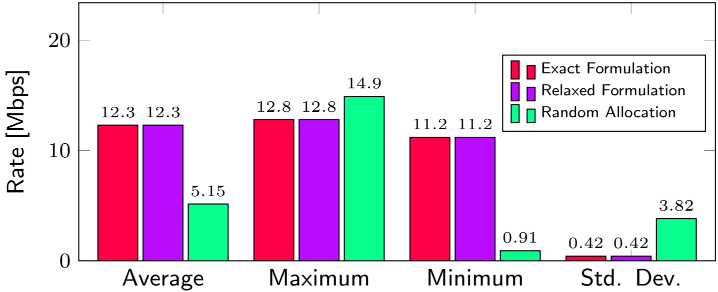


Figure 6: Scenario 1 / Vehicles with QoS = 12 Mbps

Scenario: Required QoS = 10 Mbps

The number of subframes is $L = 16$.
The number of subchannels per subframe is $K = 4$.
$\epsilon = 0.8$ *Mbps and therefore the range of rates are*
$[11.2 - 12.8]$ *Mbps*, $[9.2 - 10.8]$ *Mbps*, $[4.2 - 5.8]$ *Mbps and* $[2.2 - 3.8]$ *Mbps*.

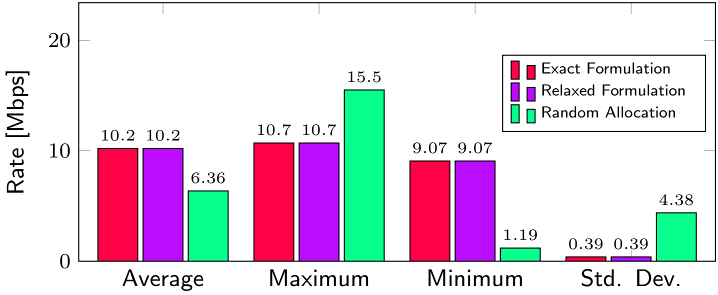


Figure 7: Scenario 1 / Vehicles with QoS = 10 Mbps

Scenario: Required QoS = 5 Mbps

The number of subframes is $L = 16$.
The number of subchannels per subframe is $K = 4$.
$\epsilon = 0.8$ *Mbps and therefore the range of rates are*
$[11.2 - 12.8]$ *Mbps*, $[9.2 - 10.8]$ *Mbps*, $[4.2 - 5.8]$ *Mbps and* $[2.2 - 3.8]$ *Mbps*.

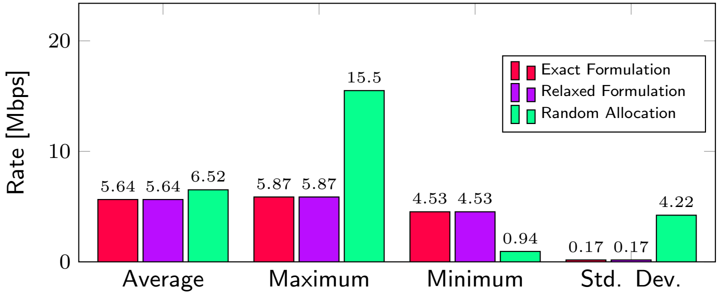


Figure 8: Scenario 1 / Vehicles with QoS = 5 Mbps

Scenario: Required QoS = 3 Mbps

The number of subframes is $L = 16$.
The number of subchannels per subframe is $K = 4$.
$\epsilon = 0.8$ *Mbps and therefore the range of rates are*
$[11.2 - 12.8]$ *Mbps*, $[9.2 - 10.8]$ *Mbps*, $[4.2 - 5.8]$ *Mbps and* $[2.2 - 3.8]$ *Mbps*.

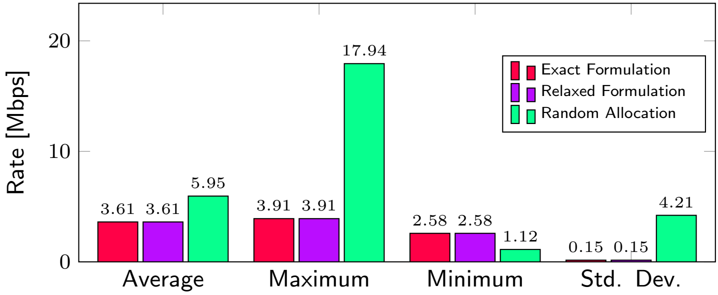


Figure 9: Scenario 1 / Vehicles with QoS = 3 Mbps

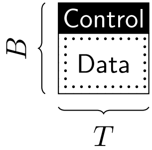
Conclusions

- In this work we have presented a subchannel allocation framework for C-V2X *mode-3*.
- Four types of conditions have been identified and incorporated in order to guarantee a conflict-free allocation that complies with QoS requirements per vehicle.
- In addition, a relaxed formulation (RF) of the original problem that does not impinge on optimality was proposed
- The QoS requirements can be very tightly met—with the exact formulation and the relaxed version—but the random approach introduces noticeable deviation.

Questions

Email: l.f.abanto@tue.nl

Subchannel Structure



Assuming a 10 MHz ITS (Intelligent Transportation Systems) channel, up to 7 subchannels per subframe can be obtained. Thus,

- B: 1.26 MHz
- T: 1 ms (2 slots of 0.5 ms each)
- Control: 2 RBs[6] per slot $\leftarrow$ 24 subcarriers
- Data: 5 RBs per slot $\leftarrow$ 60 subcarriers

Subchannel

A subchannel of 7 RBs is capable of transporting a basic CAM message with a payload of 200 bytes.

[6] RB: A resource block consits of 12 subcarriers

Properties

Property 1 (Product of two tensor products)
Let $\mathbf{X} \in \mathbb{R}^{m \times n}$, $\mathbf{Y} \in \mathbb{R}^{r \times s}$, $\mathbf{W} \in \mathbb{R}^{n \times p}$, and $\mathbf{Z} \in \mathbb{R}^{s \times t}$, then

$$\mathbf{XY} \otimes \mathbf{WZ} = (\mathbf{X} \otimes \mathbf{W})(\mathbf{Y} \otimes \mathbf{Z}) \in \mathbb{R}^{mr \times pt}$$

Property 2 (Pseudo-inverse of a tensor product)
Let $\mathbf{X} \in \mathbb{R}^{m \times n}$ and $\mathbf{Y} \in \mathbb{R}^{r \times s}$, then

$$(\mathbf{X} \otimes \mathbf{Y})^{\dagger} = \mathbf{X}^{\dagger} \otimes \mathbf{Y}^{\dagger} \in \mathbb{R}^{ns \times mr}$$