Network-Assisted Resource Allocation with Quality and Conflict Constraints for V2V Communications

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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] 3GPP: The 3rd Generation Partnership Project
[2] C-V2X: Cellular Vehicle–to–Everything
[3] D2D: Device–to–Device communications

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

- However, in LTE-D2D (introduced for public safety) the ultimate objective is to prolong batteries lifespan (at the expense of compromising on latency).

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- Modifications at MAC layer
  - A novel subchannelization[5] containing

    (i) sidelink control information (e.g. MCS)

    (ii) transport block (data)

    in the same subframe to minimize latency.

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

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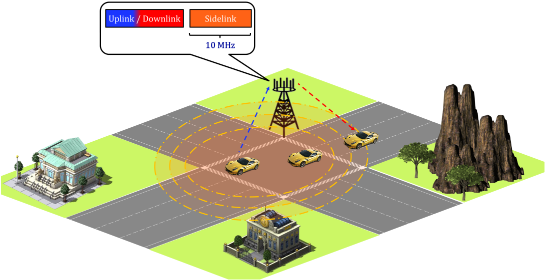
Background

- Besides **uplink** and **downlink** (Uu), vehicles can also communicate via **sidelink** [6]



[6] The sidelink supports direct communications between vehicles.

C-V2X Mode-3

- In **safety** applications, vehicles would typically exchange **cooperative awareness messages (CAMs)**: position, velocity, direction, etc.

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- **Example:** *If two vehicles transmit concurrently, they will not receive the CAM message of the other.*

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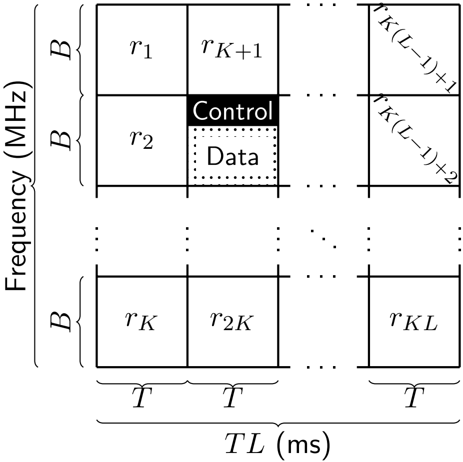
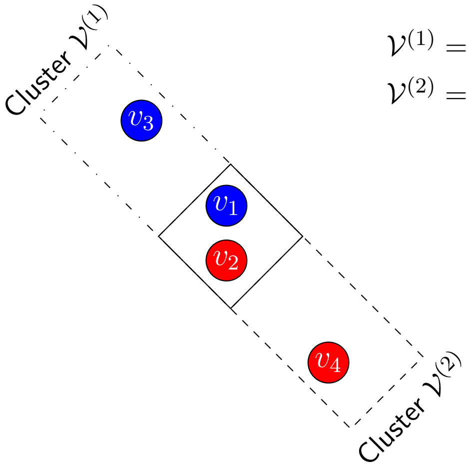
- Conversely to mainstream communications, in **C-V2X mode-3** (centralized scheduling) data traffic from/to vehicles do not traverse the eNodeB.
- **Example:** *If two vehicles transmit concurrently, they will not receive the CAM message of the other.*
- *Four types of conflicts/requirements have been identified.*

Sidelink Subchannelization



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

Motivation: Toy Example



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

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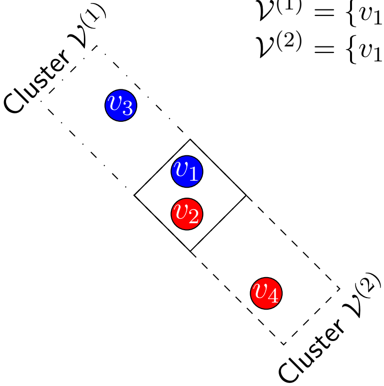
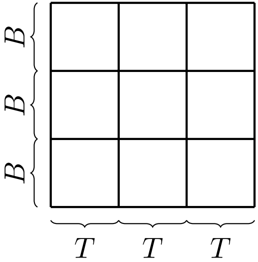
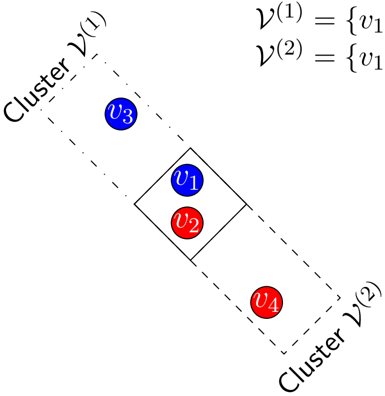


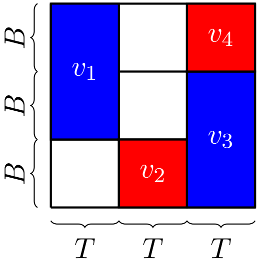


Motivation: Toy Example

Condition Type I: Differentiated QoS Requirements per Vehicle

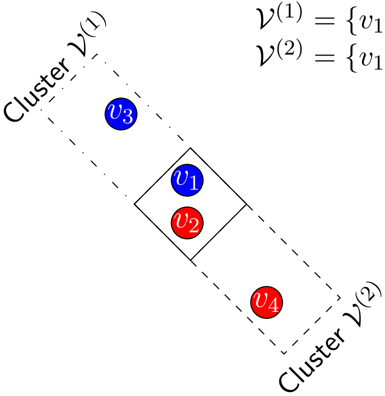
$$\mathcal{V}^{(1)} = \{v_1, v_2, v_3\}$$
$$\mathcal{V}^{(2)} = \{v_1, v_2, v_4\}$$





Motivation: Toy Example

Condition Type II: Intra-cluster Subframe Allocation Conflicts

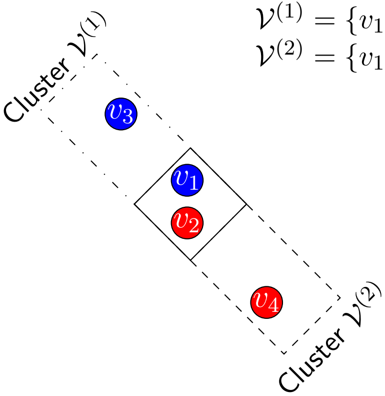


$$\mathcal{V}^{(1)} = \{v_1, v_2, v_3\}$$
$$\mathcal{V}^{(2)} = \{v_1, v_2, v_4\}$$

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

Motivation: Toy Example

Condition Type III: Minimal Time Dispersion of Subchannels



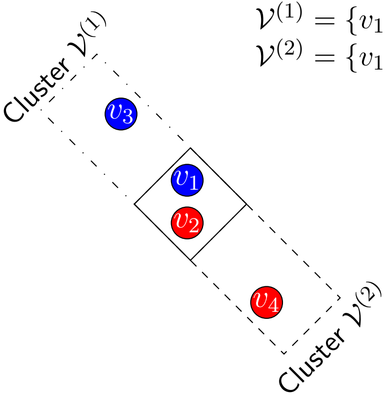
$$\mathcal{V}^{(1)} = \{v_1, v_2, v_3\}$$
$$\mathcal{V}^{(2)} = \{v_1, v_2, v_4\}$$

$$\widetilde{\mathbf{Q}} = \begin{array}{c} \begin{array}{ccc} sf_1 & sf_2 & sf_3 \end{array} \\ \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \end{bmatrix} \end{array} \begin{array}{c} \\ sf_1 \\ sf_2 \\ sf_3 \end{array}$$

Motivation: Toy Example

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

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



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

Problem Formulation

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

subject to

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

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

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

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

$\otimes$: Kronecker product

$\circ$: Hadamard product

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

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

Equivalent Formulation

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

subject to

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

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

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

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

Subchannel Allocation based on MIKPs

Algorithm 1: Subchannel Allocation Algorithm based on Multiple Independent Knapsack Problems (MIKPs)

begin

Stage 1: Sort the clusters in descending order of cardinality.

for $j = 1 : J$ **do**

Stage 2: Assign randomly to each vehicle $v_i \in \mathcal{V}^{(j)}$ some subframe l_{k_i} without placing more than one vehicle in each subframe.

Stage 3: Solve a knapsack problem for each vehicle $v_i \in \mathcal{V}^{(j)}$

$$\max \sum_{s=\{a|r_a \in \mathcal{R}_{k_i}\}} c_{is}$$

$$\text{subject to} \sum_{s=\{a|r_a \in \mathcal{R}_{k_i}\}} c_{is} \leq q_i$$

where $\mathcal{R}_{k_i}$ is the set of subchannels in subframe l_{k_i} .

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, 9 Mbps, 6 Mbps or 3 Mbps.
- There are 10 vehicles for each kind of QoS value.

Scenario: Required QoS = 12 Mbps

The number of subframes is $L = 16$.
The number of subchannels per subframe is $K = 3$.
$\epsilon = 1.6$ *Mbps and therefore the range of rates are*
$[10.4 - 13.6]$ *Mbps*, $[7.4 - 10.6]$ *Mbps*, $[4.4 - 7.6]$ *Mbps and* $[1.4 - 4.6]$ *Mbps*.

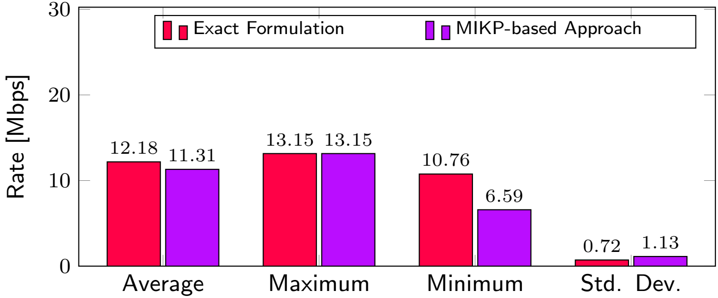


Figure 3: Group of vehicles with target QoS = 12 Mbps and admissible range [10.4 - 13.6] Mbps

Scenario: Required QoS = 9 Mbps

The number of subframes is $L = 16$.
The number of subchannels per subframe is $K = 3$.
$\epsilon = 1.6$ *Mbps and therefore the range of rates are*
$[10.4 - 13.6]$ *Mbps*, $[7.4 - 10.6]$ *Mbps*, $[4.4 - 7.6]$ *Mbps and* $[1.4 - 4.6]$ *Mbps*.

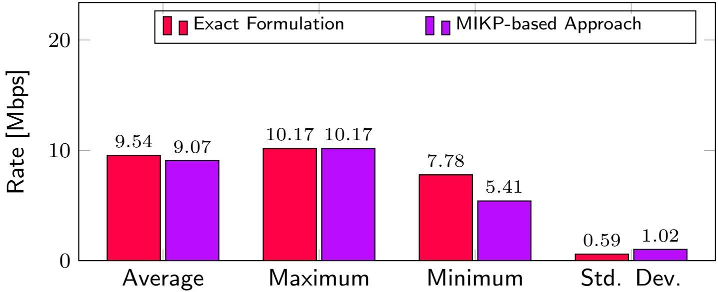


Figure 4: Group of vehicles with target QoS = 9 Mbps and admissible range [7.4 - 10.6] Mbps

Scenario: Required QoS = 6 Mbps

The number of subframes is $L = 16$.
The number of subchannels per subframe is $K = 3$.
$\epsilon = 1.6$ *Mbps and therefore the range of rates are*
$[10.4 - 13.6]$ *Mbps*, $[7.4 - 10.6]$ *Mbps*, $[4.4 - 7.6]$ *Mbps and* $[1.4 - 4.6]$ *Mbps*.

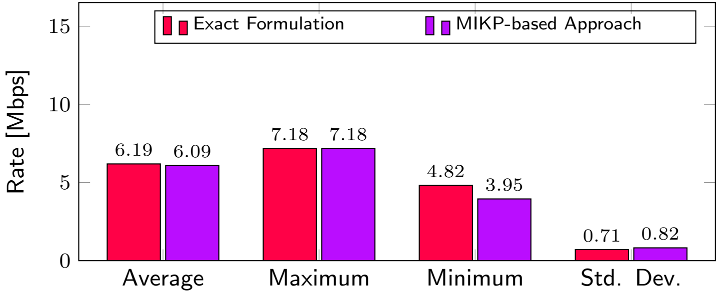


Figure 5: Group of vehicles with target QoS = 6 Mbps and admissible range [4.4 - 7.6] Mbps

Scenario: Required QoS = 3 Mbps

The number of subframes is $L = 16$.
The number of subchannels per subframe is $K = 3$.
$\epsilon = 1.6$ *Mbps and therefore the range of rates are*
$[10.4 - 13.6]$ *Mbps*, $[7.4 - 10.6]$ *Mbps*, $[4.4 - 7.6]$ *Mbps and* $[1.4 - 4.6]$ *Mbps*.

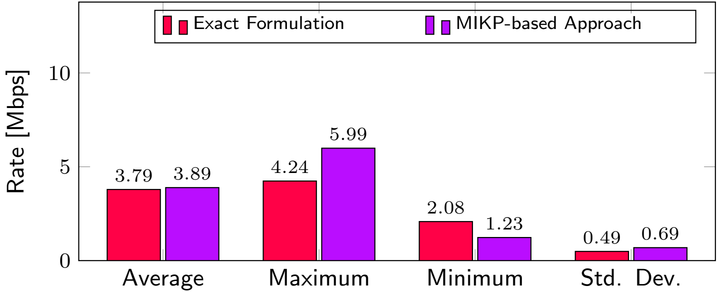


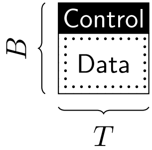
Figure 6: Group of vehicles with target QoS = 3 Mbps and admissible range [1.4 - 4.6] Mbps

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 formulation based on multiple independent knapsack problems was proposed.
- Although the latter scheme is suboptimal, it is computationally less expensive and could become a viable alternative for the derived formulation.

Questions

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[7] 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.

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