Graph-Based Resource Allocation with Conflict Avoidance for V2V Broadcast Communications

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Background

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[2]Initially aimed at supporting proximity services (ProSe).
[3]Pilot symbols more closely spaced for channel estimation in high Doppler.

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- V2V is based on a previously developed technology, namely **device–to–device (D2D) communications**[2]

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- Additional modifications have been applied in order to support more dynamic scenarios
  - Denser distribution of DMRS[3]

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  - Denser distribution of DMRS[3]
  - A novel structure that supports adjacent (i) scheduling assignments and (ii) data resources

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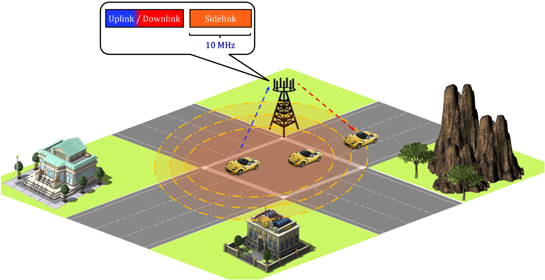
Background

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



V2V Mode-3 Operation

- Conversely to mainstream communications, in **V2V mode-3** data traffic from/to vehicles do not traverse the eNodeB.

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  - Thereupon, **vehicles communicate directly**—with their counterparts via sidelink—in a broadcast manner.

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  - Thereupon, **vehicles communicate directly**—with their counterparts via sidelink—in a broadcast manner.
- In **safety** applications, vehicles would typically exchange **cooperative awareness messages (CAMs)**.

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V2V Mode-3 Operation (cont'd)

- A CAM message contains information such as
  - position,
  - velocity,
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- Due to the one–to–all nature of V2V *mode-3*, the allocation of resources (or subchannels) slightly differs from mainstream communications.

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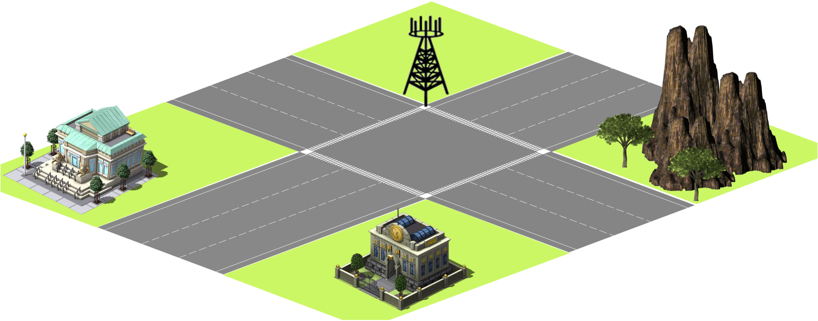
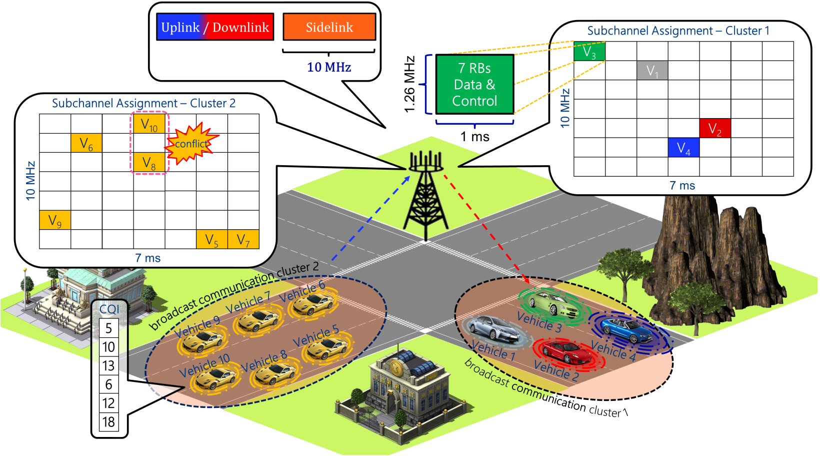
- As these messages transport important information, it is crucial that they are transmitted **reliably**.
- Due to the one–to–all nature of V2V *mode-3*, the allocation of resources (or subchannels) slightly differs from mainstream communications.
- **Example:** *If two vehicles transmit concurrently they will not receive the CAM message of the other.*

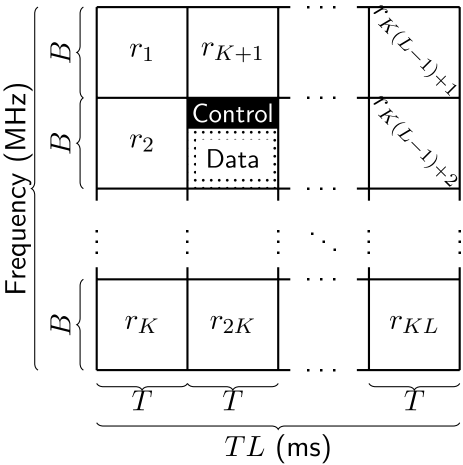
Vehicular Scenario



Vehicular Scenario

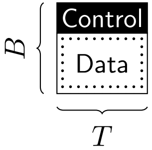


Sidelink Channelization



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

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[5] 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.

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

Problem Formulation

Antecedents

- Vehicles can either transmit or receive at a time[6].
- When two or more vehicles transmit concurrently in subchannels of the same subframe, a **conflict** is generated.

Objectives

- Attain a **conflict-free subchannel assignment**.
- Maximize the sum-capacity of the system

[6]Due to half-duplex PHY assumption

Problem Formulation (cont'd)

Antecedents

- Vehicles can either transmit or receive at a time.
- When two or more vehicles transmit concurrently in subchannels of the same subframe, a **conflict** is generated.

Proposed Solution

- The subchannel allocation problem is approached as a **bipartite graph matching**.
- Additional constraints have been considered in order to **prevent conflicts** from occurring.

General Assumptions

- There are available **spectrum resources** for uplink and downlink.

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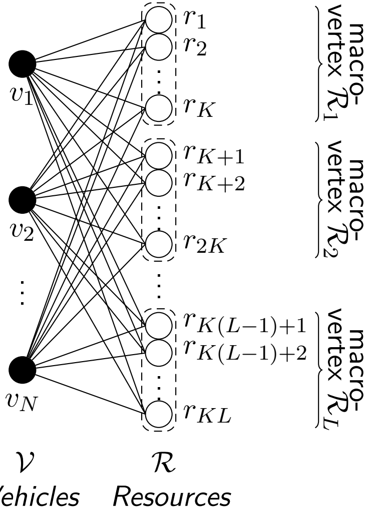
- The eNodeB notifies the vehicles on their assigned subchannel via downlink.
- Then, vehicles start broadcasting CAM messages.

Graph Representation of Subchannel Allocation



$$\max \sum_{i=1}^{N} \sum_{j=1}^{KL} c_{ij} x_{ij}$$

subject to

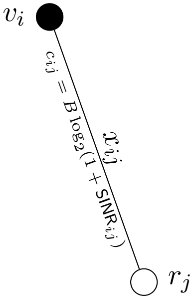
$$\sum_{j=1}^{KL} x_{ij} = 1, \quad i = 1, 2, \ldots, N$$

$$\sum_{i=1}^{N} \sum_{j \in \mathcal{R}_\alpha} x_{ij} = 1, \quad \alpha = 1, 2, \ldots, L$$

$$x_{ij} = \{0, 1\}.$$

Optimization Problem

The optimization problem can be recast as:



$$\max \ \mathbf{c}^T \mathbf{x} \tag{2a}$$

$$\text{subject to} \ \left[\frac{\mathbf{I}_{N\times N} \otimes \mathbf{1}_{1\times N}}{\mathbf{1}_{1\times N} \otimes \mathbf{I}_{N\times N}} \right] \otimes \mathbf{1}_{1\times K} \ \mathbf{x} = \mathbf{1} \tag{2b}$$

Note: For completeness, we have assumed that the number of vehicles is equal to the number of subframes, i.e. $N = L$

This problem structure cannot be exploited to be approached by known matching algorithms. So we proceed as follows

Optimization Problem

Objective Function

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

Because $\mathbf{x} \in \mathbb{B}^{MK}$, then the objective function can be recast as

$$\mathbf{c}^T\mathbf{x} \equiv \mathbf{x}^T diag(\mathbf{c})\mathbf{x}$$

without affecting optimality.
Note that $M = N^2$.

Optimization Problem

Objective Function

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

For any vehicle v_i,

$$x_{ij} x_{ik} = 0, \; r_j, r_k \in \mathcal{R}_\alpha.$$

Moreover,

$$c_{ij} x_{ij} x_{ik} = 0, \; r_j, r_k \in \mathcal{R}_\alpha.$$

In general, for N vehicles

$$\mathbf{x}^T \left(\mathbf{I}_{M \times M} \otimes [\mathbf{1}_{K \times K} - \mathbf{I}_{K \times K}] \right) diag(\mathbf{c}) \mathbf{x} = 0.$$

Optimization Problem

Objective Function

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

As long as $\mathbf{x}^T\left(\mathbf{I}_{M\times M}\otimes[\mathbf{1}_{K\times K}-\mathbf{I}_{K\times K}]\right)diag(\mathbf{c})\mathbf{x}=0$ holds, conflicts will be prevented.

We can aggregate this condition to the objective function. Hence,

$$\mathbf{c}^T\mathbf{x}=\mathbf{x}^T diag(\mathbf{c})\mathbf{x}+\mathbf{x}^T\left(\mathbf{I}_{M\times M}\otimes[\mathbf{1}_{K\times K}-\mathbf{I}_{K\times K}]\right)diag(\mathbf{c})\mathbf{x}$$

Further manipulation leads to

$$\mathbf{c}^T\mathbf{x}=\mathbf{x}^T(\mathbf{I}_{M\times M}\otimes\mathbf{1}_{K\times K})diag(\mathbf{c})\mathbf{x}$$

Optimization Problem

Objective Function

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

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

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

$$\begin{aligned}
\mathbf{c}^T\mathbf{x} &= \mathbf{x}^T(\mathbf{I}_{M\times M} \otimes \mathbf{1}_{K\times K})diag(\mathbf{c})\mathbf{x} \\
&= \mathbf{x}^T(\mathbf{I}_{M\times M}\mathbf{I}_{M\times M} \otimes \mathbf{1}_{K\times 1}\mathbf{1}_{1\times K})diag(\mathbf{c})\mathbf{x} \\
&= \underbrace{\mathbf{x}^T(\mathbf{I}_{M\times M} \otimes \mathbf{1}_{K\times 1})}_{\mathbf{y}^T}\underbrace{(\mathbf{I}_{M\times M} \otimes \mathbf{1}_{1\times K})diag(\mathbf{c})\mathbf{x}}_{\mathbf{d}}
\end{aligned}$$

Optimization Problem

Constraints

$$\text{subject to } \left[\frac{\mathbf{I}_{N\times N}\otimes \mathbf{1}_{1\times N}}{\mathbf{1}_{1\times N}\otimes \mathbf{I}_{N\times N}}\right]\otimes \mathbf{1}_{1\times K}\ \mathbf{x} = \mathbf{1}$$

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

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

Optimization Problem

Constraints

$$\text{subject to} \begin{bmatrix} \mathbf{I}_{N\times N} \otimes \mathbf{1}_{1\times N} \\ \hline \mathbf{1}_{1\times N} \otimes \mathbf{I}_{N\times N} \end{bmatrix} \otimes \mathbf{1}_{1\times K}\, \mathbf{x} = \mathbf{1}$$

$$\left(\begin{bmatrix} \mathbf{I}_{N\times N} \otimes \mathbf{1}_{1\times N} \\ \hline \mathbf{1}_{1\times N} \otimes \mathbf{I}_{N\times N} \end{bmatrix} \otimes \mathbf{1}_{1\times K} \right) \left(\mathbf{I}_{M\times M} \otimes \mathbf{1}^{\dagger}_{1\times K} \right) \mathbf{y} = \mathbf{1}$$

$$= \left(\begin{bmatrix} \mathbf{I}_{N\times N} \otimes \mathbf{1}_{1\times N} \\ \hline \mathbf{1}_{1\times N} \otimes \mathbf{I}_{N\times N} \end{bmatrix} \mathbf{I}_{M\times M} \right) \otimes \underbrace{\left(\mathbf{1}_{1\times K} \mathbf{1}^{\dagger}_{1\times K} \right)}_{1} \mathbf{y} = \mathbf{1}$$

$$= \begin{bmatrix} \mathbf{I}_{N\times N} \otimes \mathbf{1}_{1\times N} \\ \hline \mathbf{1}_{1\times N} \otimes \mathbf{I}_{N\times N} \end{bmatrix} \mathbf{y} = \mathbf{1}$$

Optimization Problem

Original Problem

$$\max \mathbf{c}^T\mathbf{x}, \quad \text{subject to} \left[\frac{\mathbf{I}_{N\times N}\otimes \mathbf{1}_{1\times N}}{\mathbf{1}_{1\times N}\otimes \mathbf{I}_{N\times N}}\right]\otimes \mathbf{1}_{1\times K}\ \mathbf{x} = \mathbf{1}$$

Resultant Problem

$$\max \mathbf{d}^T\mathbf{y}, \qquad \text{subject to} \left[\frac{\mathbf{I}_{N\times N}\otimes \mathbf{1}_{1\times N}}{\mathbf{1}_{1\times N}\otimes \mathbf{I}_{N\times N}}\right]\mathbf{y} = \mathbf{1}.$$

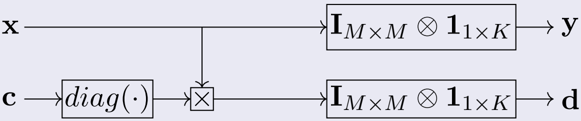
where $\mathbf{d} = (\mathbf{I}_{M\times M}\otimes \mathbf{1}_{1\times K})diag(\mathbf{c})\mathbf{x}$ and $\mathbf{y} = (\mathbf{I}_{M\times M}\otimes \mathbf{1}_{1\times K})\mathbf{x}$

Dimensionality reduction: $\rightarrow |\mathbf{x}| = MK \qquad \rightarrow |\mathbf{y}| = M.$

The resultant problem can now be approached through the Kuhn-Munkres Algorithm.

Optimization Problem

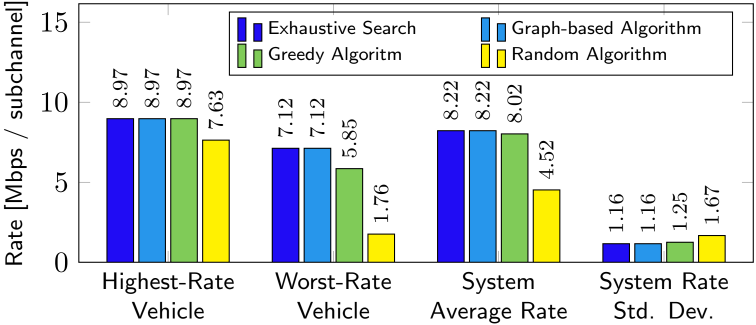
Transformation



$$\mathbf{d} = \lim_{\beta\to\infty} \frac{1}{\beta} \overset{\circ}{\log}\left\{(\mathbf{I}_{M\times M} \otimes \mathbf{1}_{1\times K}) \mathrm{e}^{\circ\beta\mathbf{c}}\right\}$$

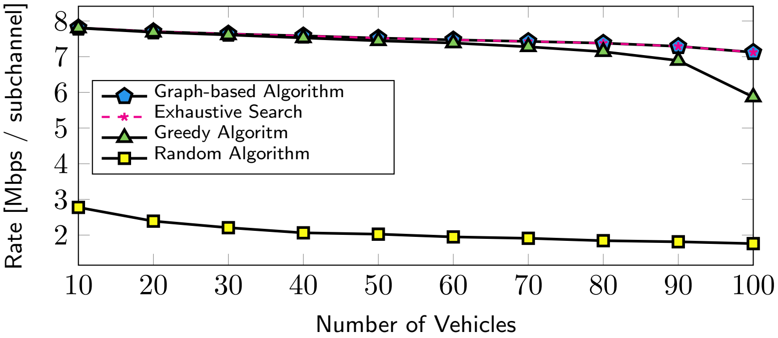
$\overset{\circ}{\log}\{\cdot\}$: Element-wise natural logarithm.
$\mathrm{e}^{\circ\{\cdot\}}$ Hadamard exponential.

Simulations: Data Rate per Vehicle



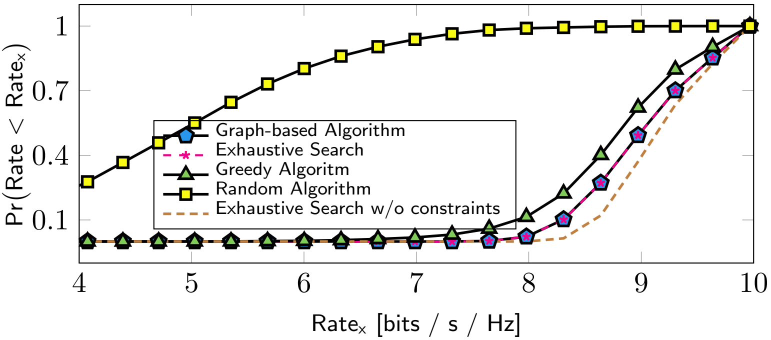
Description	Value
Number of vehicles per cluster	100
Number of clusters	4
Message rate (Hz)	10
Number of allottable subframes	100
Number of resources per subframe	7

Simulations: Least Favored Vehicle



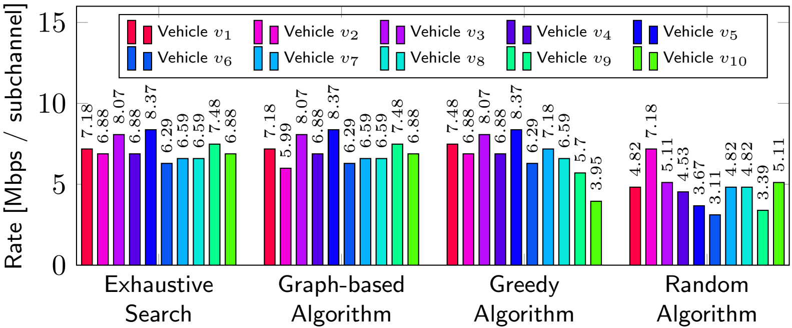
Description	Value
Number of vehicles per cluster	10 - 100
Number of clusters	4
Message rate (Hz)	10
Number of allottable subframes	100
Number of resources per subframe	7

Simulations: CDF of Rate Values



Description	Value
Number of vehicles per cluster	100
Number of clusters	4
Message rate (Hz)	10
Number of allottable subframes	100
Number of resources per subframe	7

Simulations: One-shot simulation



Description	Value
Number of vehicles per cluster	10
Number of clusters	1
Message rate (Hz)	10
Number of allottable subframes	10
Number of resources per subframe	3

Complexity

- Exhaustive search: $\mathcal{O}(|\mathcal{R}|!/(|\mathcal{R}|-|\mathcal{V}|)!)$
- Graph-based approach: $\mathcal{O}(\max\{|\mathcal{V}|, |\mathcal{R}|/K\}^3)$
- Greedy algorithm: $\mathcal{O}(|\mathcal{V}||\mathcal{R}|)$
- Random algorithm: $\mathcal{O}(|\mathcal{V}|)$

$|\mathcal{V}|$: Number of vehicles
$|\mathcal{R}|$: Number of resources
K: Number of subchannels per subframe

Conclusions

- A graph theoretical approach for subchannel allocation in V2V *mode-3* was presented.
- Subchannel conflict avoidance was enforced through graph vertex aggregation.
- For the case of independent vehicular clusters, the **proposed approach attains the same optimality as exhaustive search at lower complexity**.
- Although not explicitly enforced, the proposed scheme is capable of improving the rate fairness between vehicles.

Questions

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