On Enhancing Semi-Persistent Scheduling in 5G NR V2X to Support Emergency Communication Services in Highly Congested Scenarios

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భారతీయ సాంకేతిక విజ్ఞాన సంస్థ హైదరాబాద్
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Indian Institute of Technology Hyderabad

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Motivation

Ambulances Stuck in Traffic - Song of Life or Death

"At least a dozen people, especially those injured in road accidents, lost their lives in last six months in the city, while on the way to hospitals. Patients died on the way as they could not reach hospital on time because of heavy traffic on the road resulting in the ambulances got stuck in traffic jams." - Oct 2016, The Times of India

"Delay in arrival of '108' ambulance claims one life" - Apr 2019, The Times of India

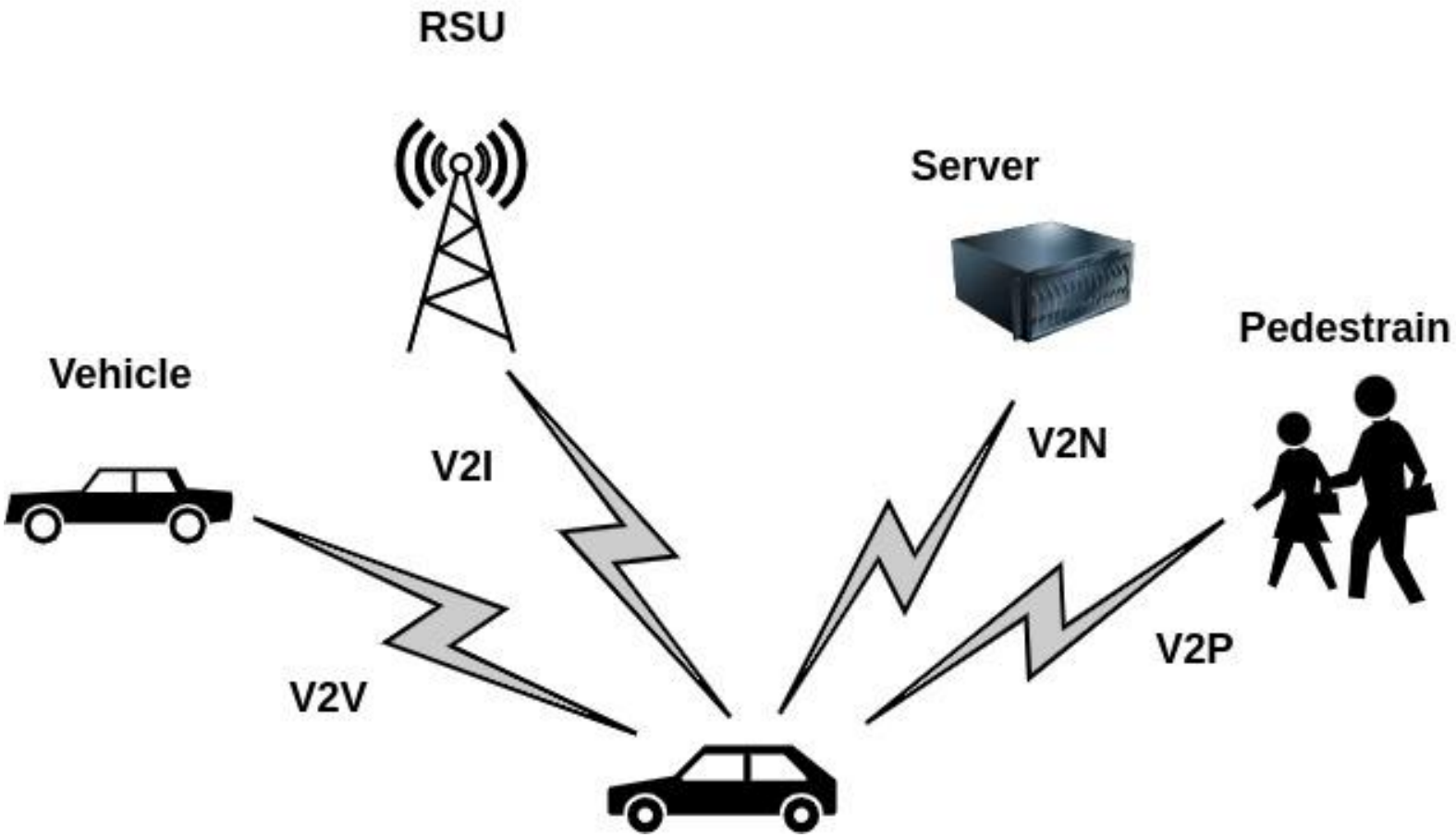
"Ambulances in India fail to arrive on time and are mostly ill-equipped" - Dec 2022, The Economic Times

Out of people killed in road accidents, about 30% of deaths are caused due to delayed ambulance -- Times of India

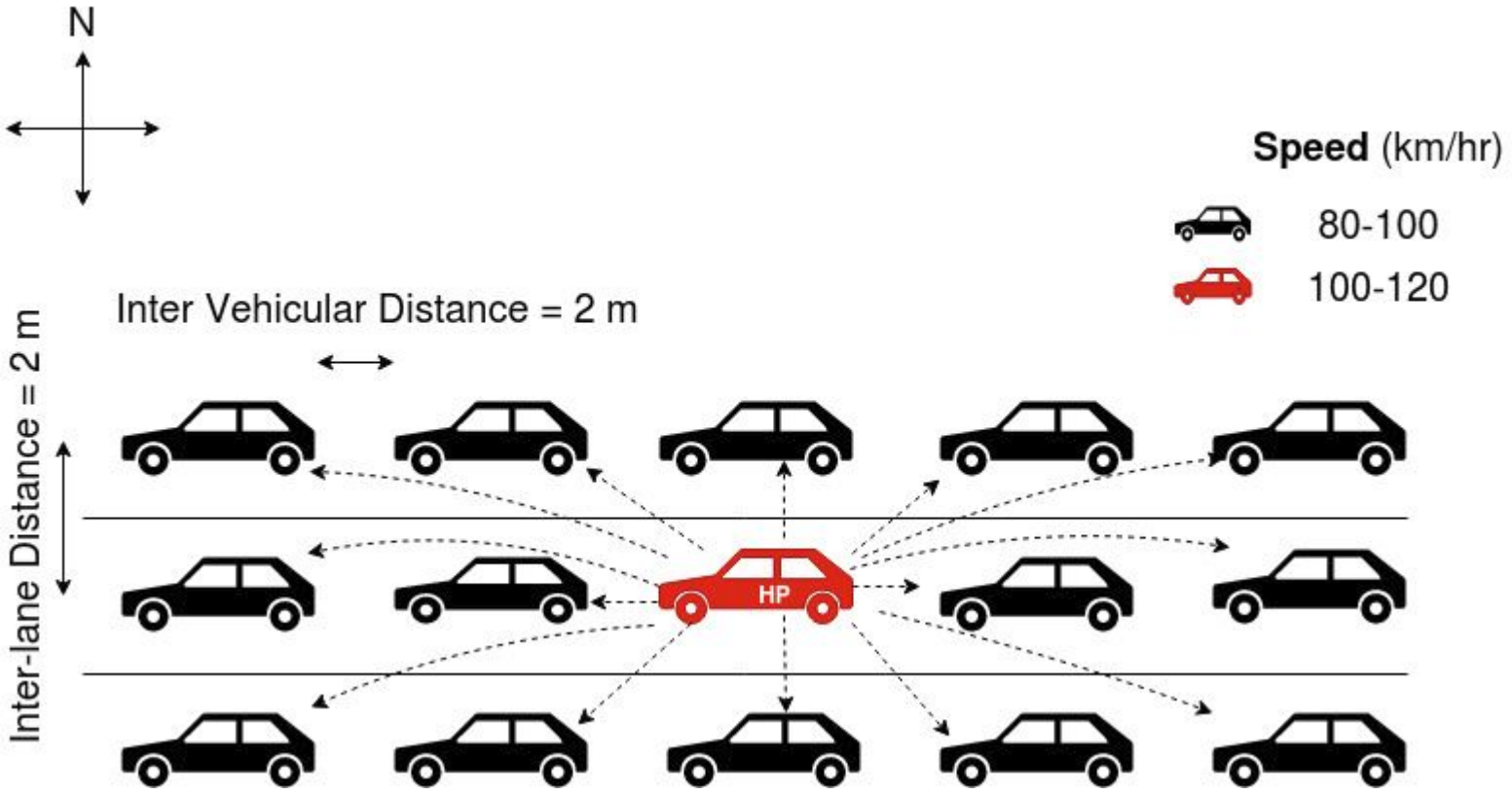
Reference :

- Choking life: 12 on way to hospitals die in traffic jams | Raipur News - Times of India
- 'Ambulances in India fail to arrive on time and are mostly ill-equipped', Health News, ET HealthWorld
- Delay in arrival of '108' ambulance claims one life | Coimbatore News - Times of India

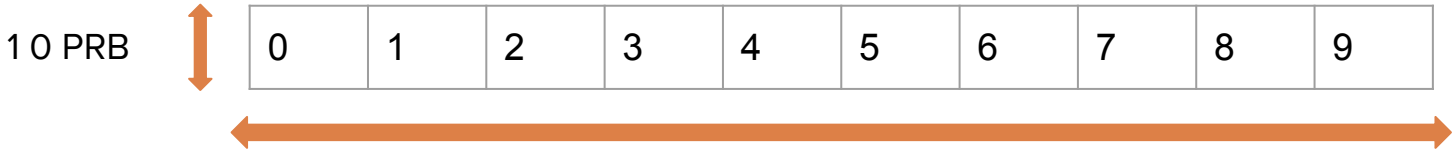
Vehicle-to-Everything (V2X)



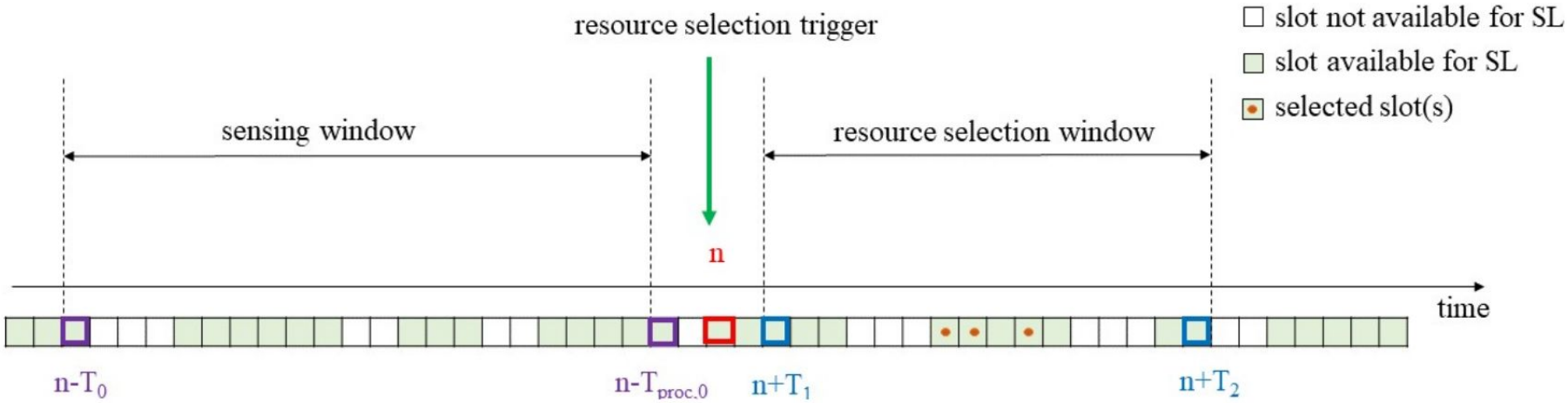
V2X System Model



5G NR V2X Frame Structure and Sensing and Selection Window

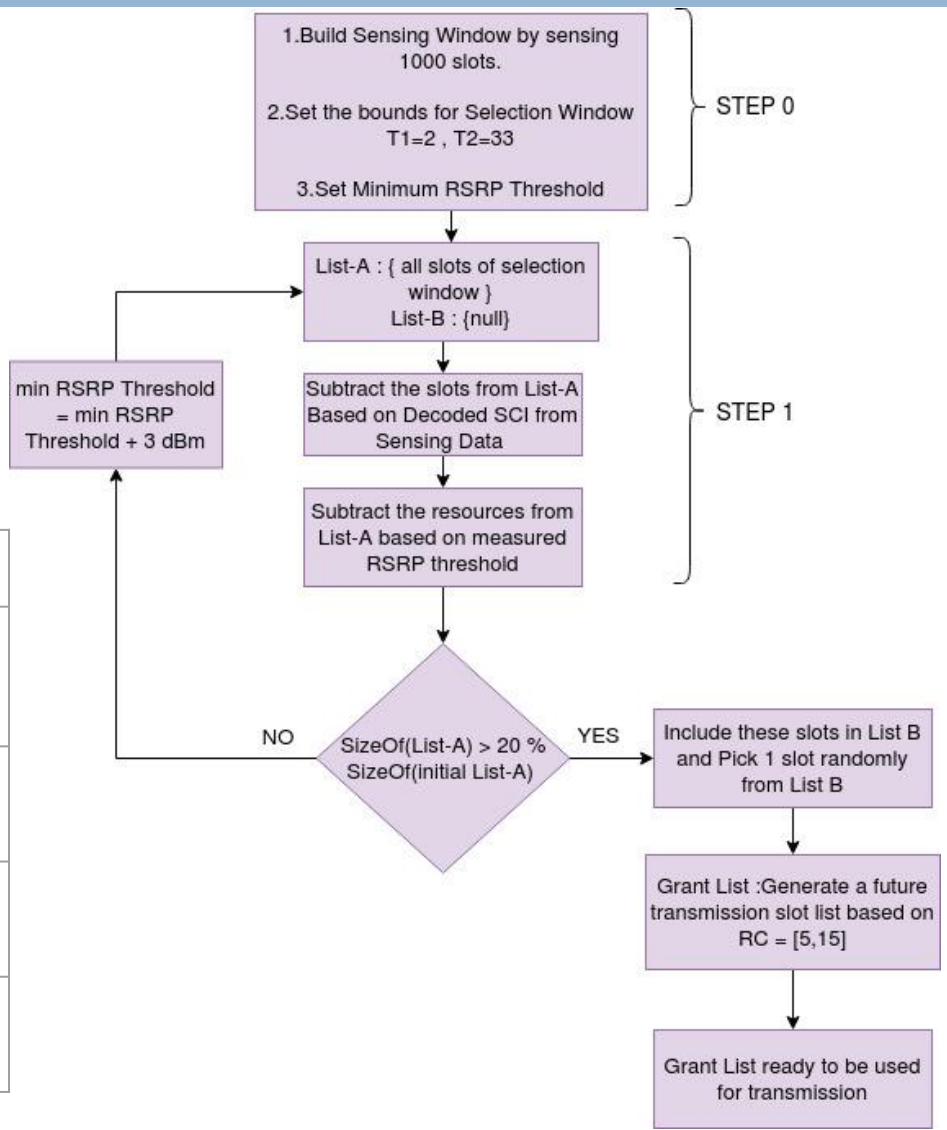


For 5G NR 1 Frame = 10 ms = 10 SubFrames
1 Subframe = 1 ms



Z. Ali, S. Lagén and L. Giupponi, "On the impact of numerology in NR V2X Mode 2 with sensing and random resource selection," 2021 IEEE Vehicular Networking Conference (VNC), 2021, pp. 151-157, doi: 10.1109/VNC52810.2021.9644618.

Semi-Persistent Scheduling (SPS) Algo



Acronyms	
RSRP	Reference Signal Received Power
SCI	Sidelink Control Information
RC	Reselection Counter
PRB	Physical Resource Block

SPS: Illustration

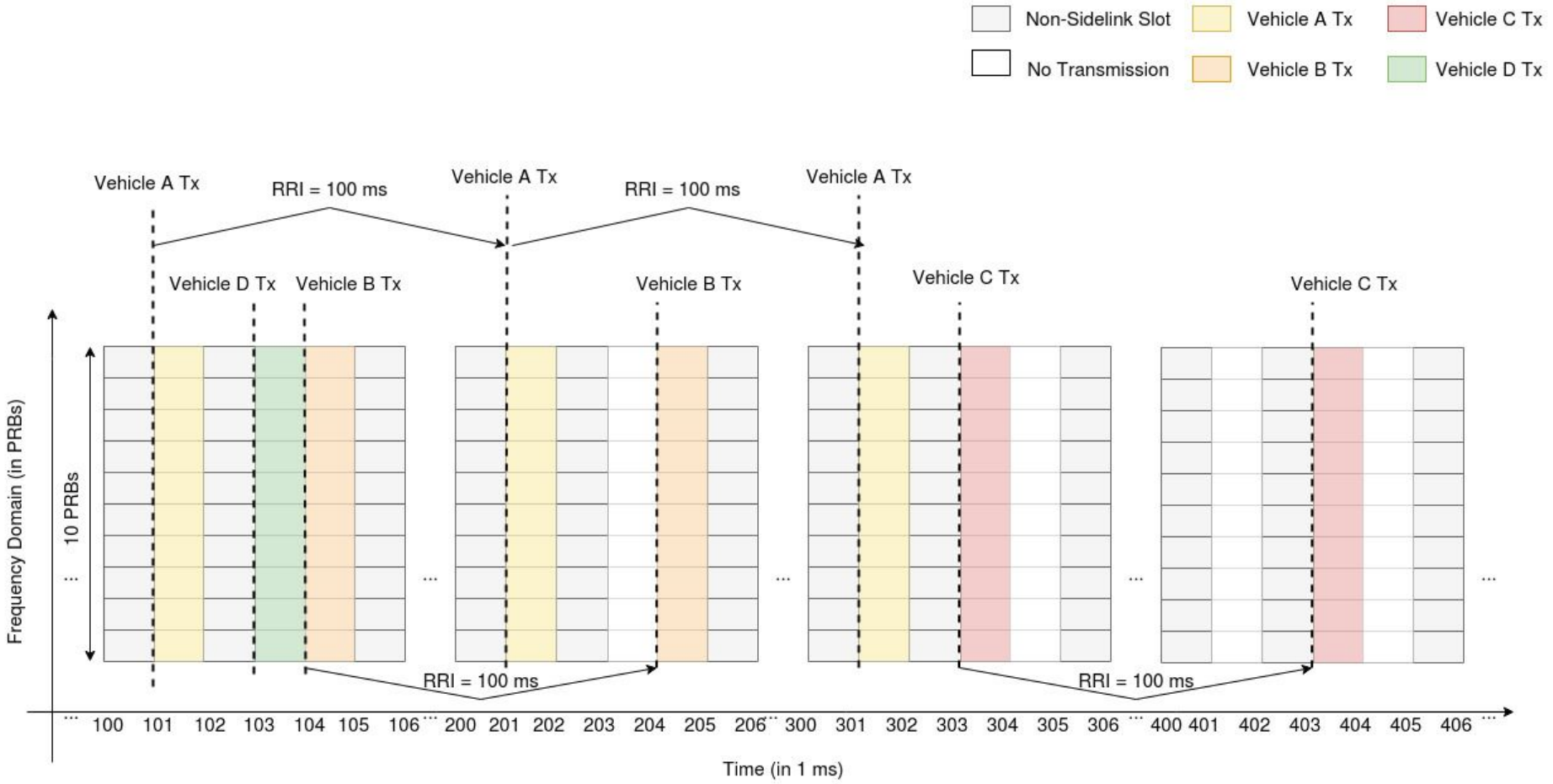


Figure : Representation of Different Vehicles (in different colors) choosing a resource for RC in range [5,15] with an RRI of 100ms at Physical Layer.

Simulation Parameters

Parameter	**Value**
Vehicle Speed	High Priority: [100-120] km/hr Low Priority: [80-100] km/hr
CAM Packet Size	300 Bytes
Selection Window Size	32 Slots
5G Frame Structure	Numerology = 0 (SCS = 15 kHz)
Modulation and Coding Scheme (fixed)	14
RSRP Threshold	Min = -128 dBm Max = -80 dBm
Radio Reservation Interval	100ms
Carrier Frequency	5.89 GHz (ITS Band)
Channel Bandwidth	2 MHz
Sensing Window	1000 ms
Subchannel Size	10 Physical Resource Blocks

Performance Metrics

- **Packet Reception Rate (PRR)**: It is defined as the ratio of number of vehicles which successfully received the CAM packets of a vehicle of interest to the total number of its neighbouring vehicles.

$$PRR_i = \frac{\sum_{j=1}^{M} \frac{No.\ of\ Vehicles\ Successfully\ Received\ CAMs}{Total\ Number\ of\ Neighbors\ of\ Vehicle_i}}{M}$$

where M is the total number of CAM messages transmitted by $vehicle_i$, $1 \leq j \leq M$.

- **Packet Inter-Reception (PIR)**: It is the time gap between two consecutive successful CAM packet receptions at the neighboring vehicle from a given vehicle of interest.

- The Congestion Level is defined as **Resource Availability Ratio (RAR)**

$$RAR = \frac{Number\ of Resources\ Available}{Total\ Number\ of\ Vehicles}$$

Performance of SPS

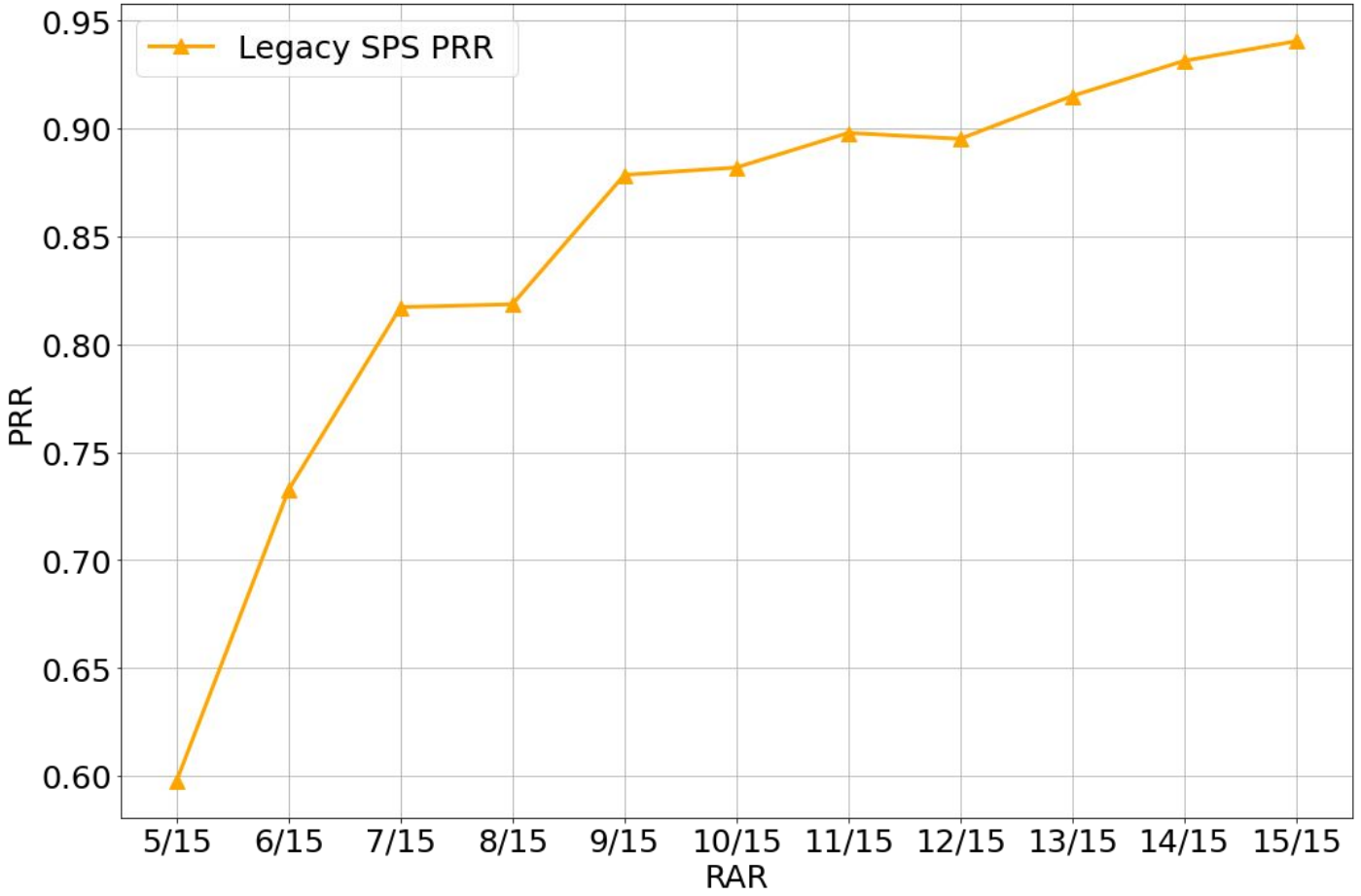


Fig: Variation of PRR vs RAR for Legacy SPS.

P-SPS: Illustration

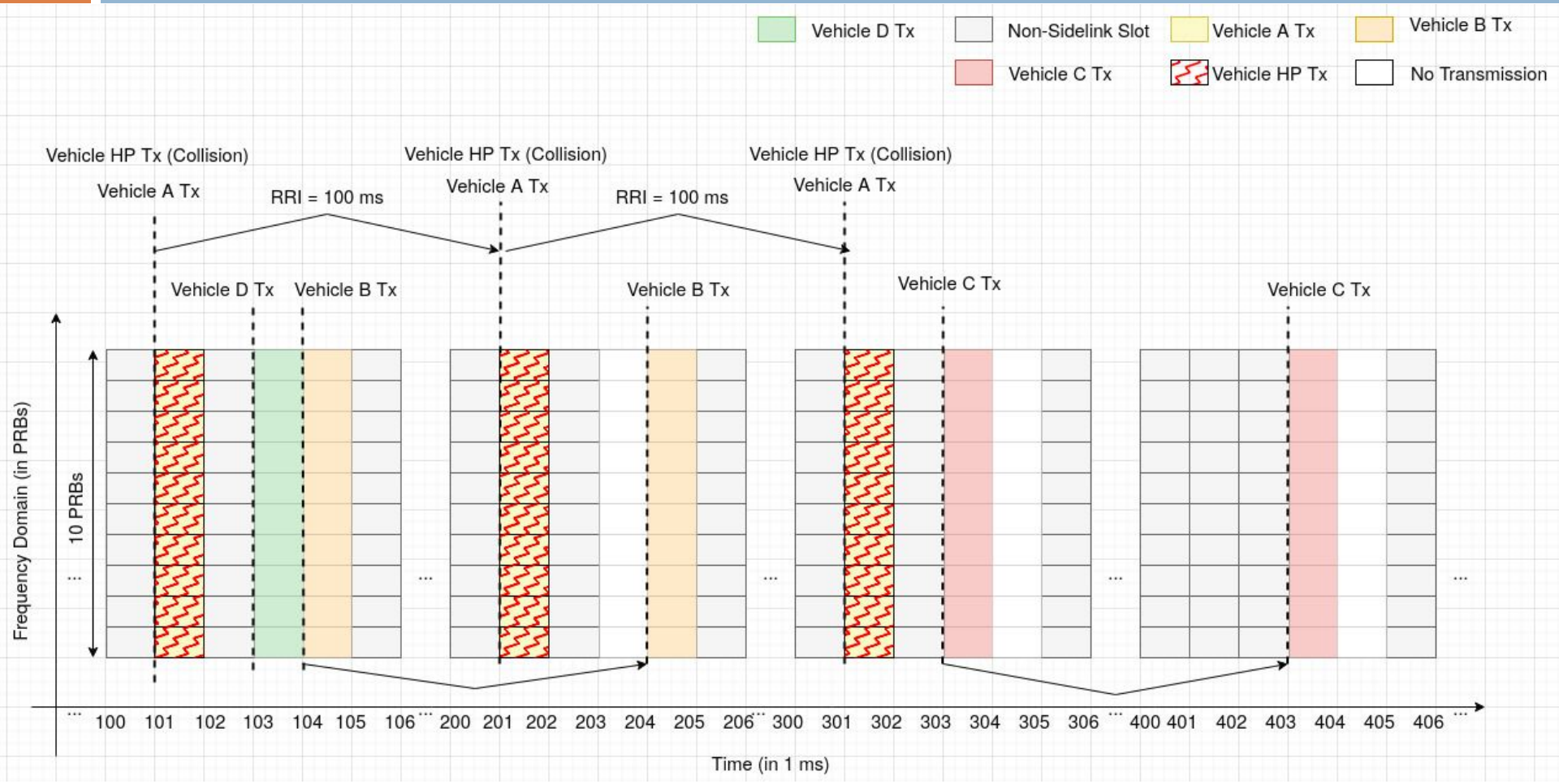


Fig : Representation of a HP Vehicle (red-yellow zig-zag boxes) facing collision caused by forcefully choosing a resource already occupied by a LP Vehicle for RC in range [10,15] with an RRI of 100ms in congested scenarios

P-SPS: Illustration (cond.)

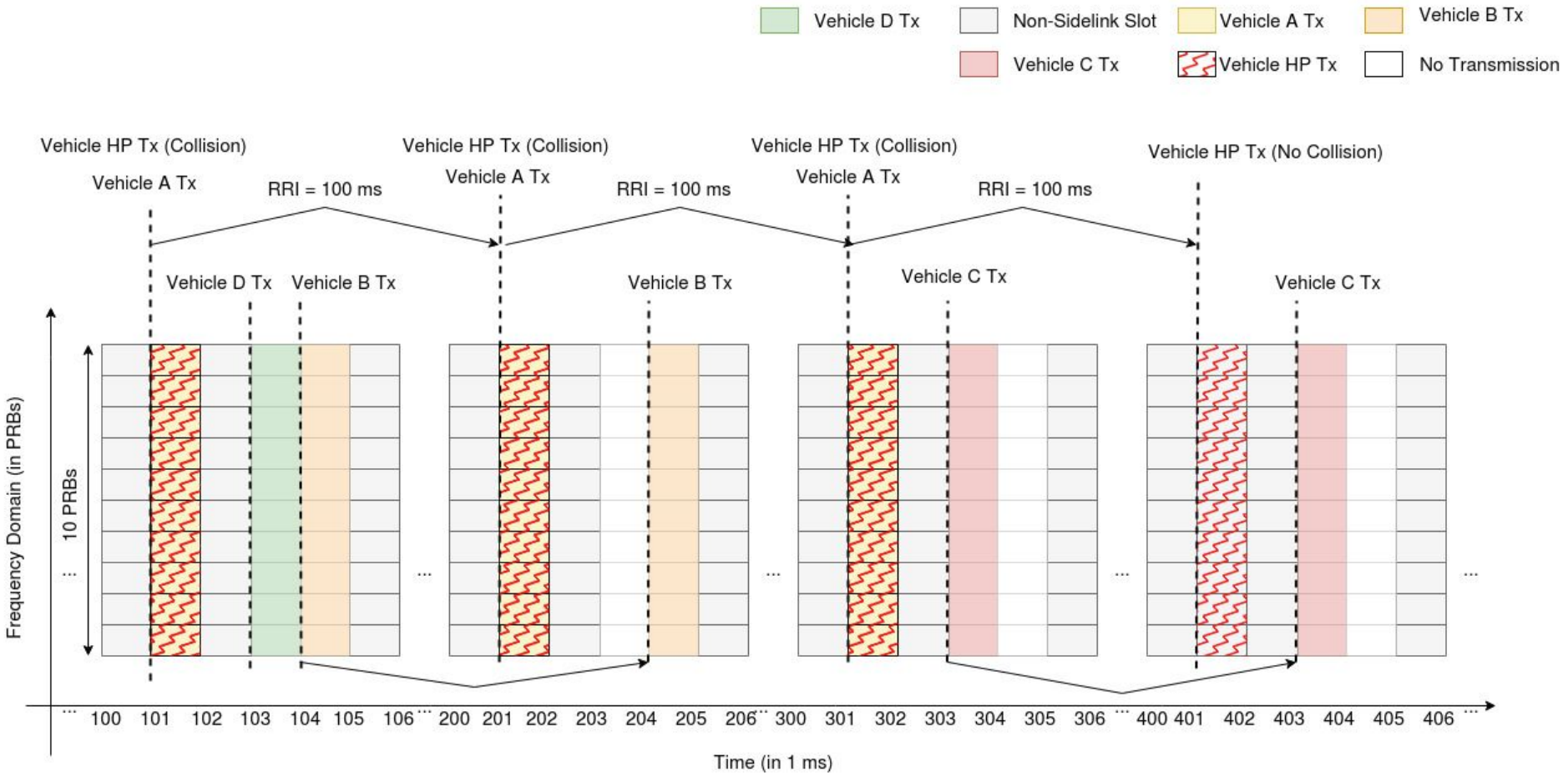
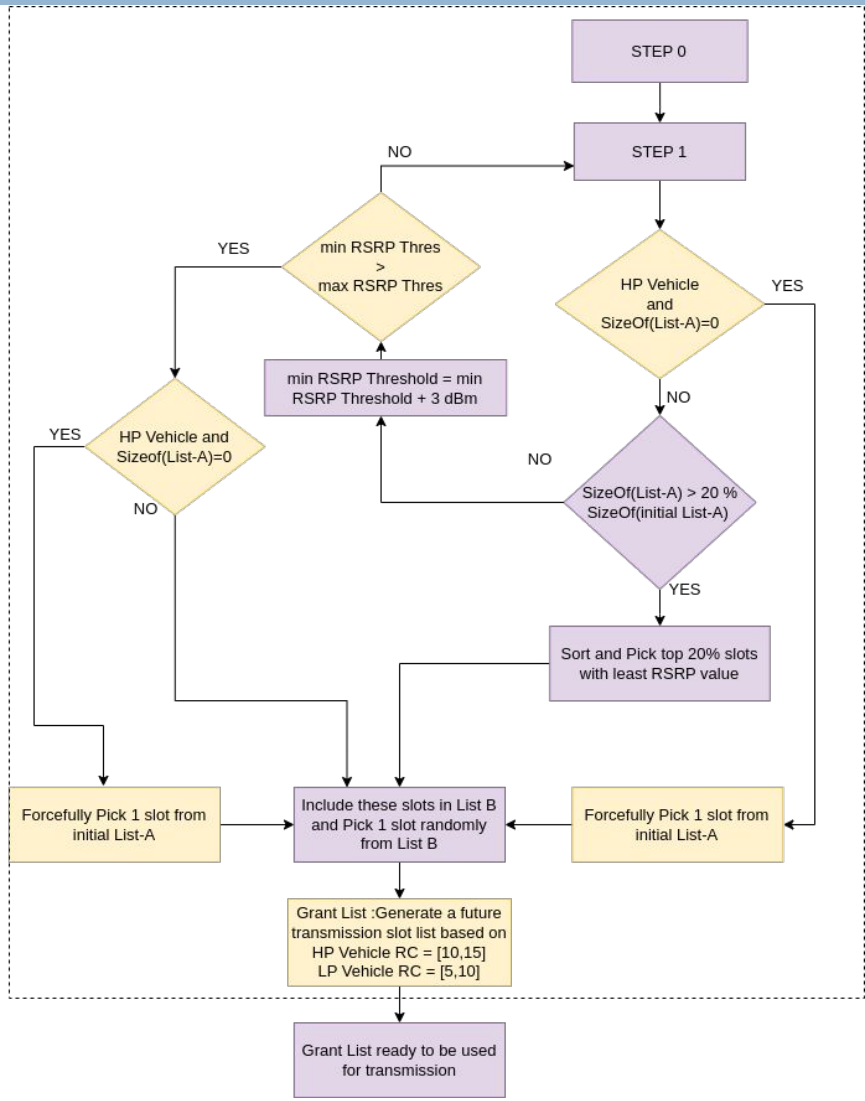


Fig : Representation of a HP Vehicle (red-white zig-zag boxes) can have atleast one collision-free transmission. The LP vehicles finishes its Tx faster. The HP vehicle continues transmission collision-free eventually.

P-SPS: A Priority Based Semi-Persistent Scheduling Algorithm (Proposed)

- P-SPS ensures the HP vehicle at least 1 resource to transmit CAM packets (even in severe traffic congestion scenarios)
- Worst Case Scenario : HP vehicle chooses a resource which is already in use by LP vehicles
- To reduce the time streak of collided packet transmissions, we segregate RC between HP and LP vehicles.
  - HP vehicle: RC in [10,15]
  - LP vehicle: RC in [5,10]
- Even though HP vehicles faces collision initially, LP vehicle finishes Tx faster and the HP vehicle gets a chance to Tx collision-free eventually.

P-SPS Procedure



SPS vs P-SPS

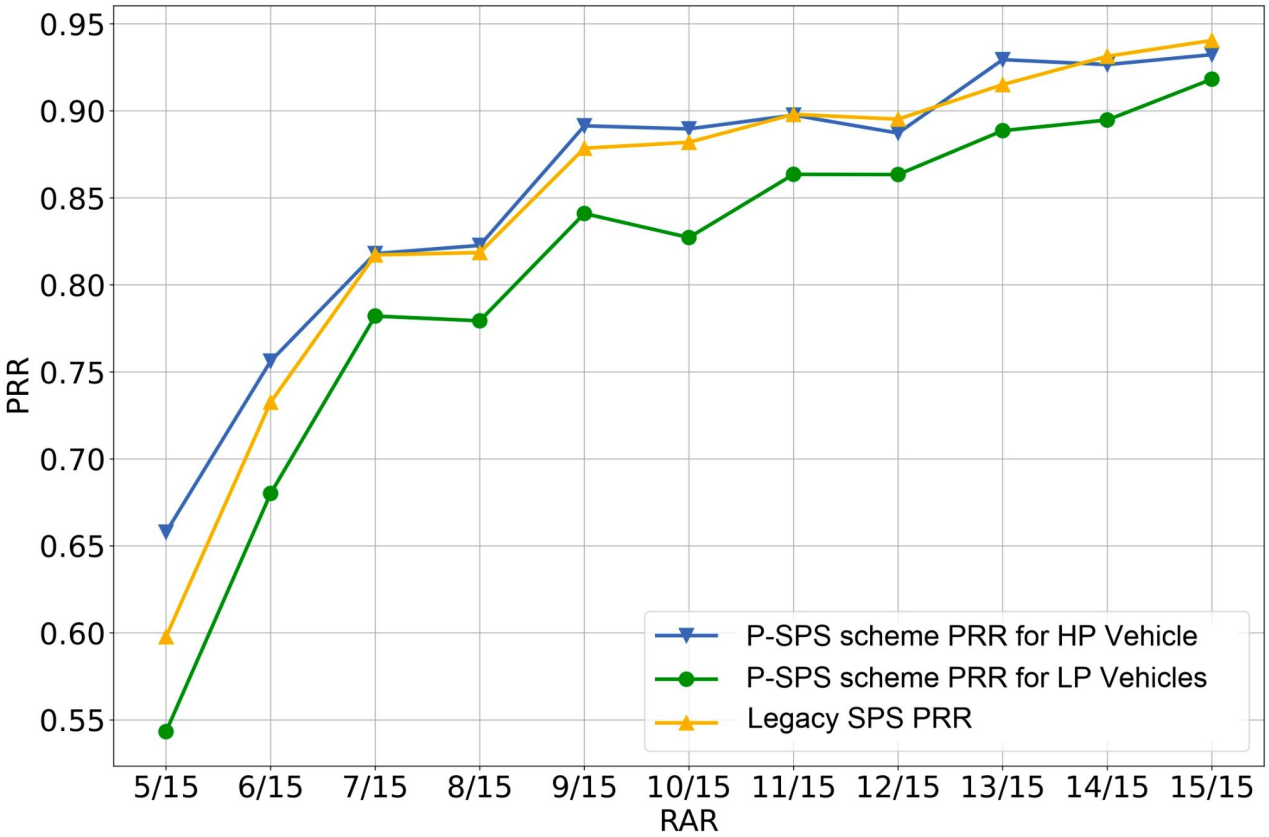


Fig: Variation of PRR vs RAR for P-SPS and Legacy SPS.

In extreme congestion of RAR< 40%, HP vehicles see an increase in PRR of 6% at the cost of LP vehicles (5.4% drop).

Probabilistic Collision Mitigation (PCM)

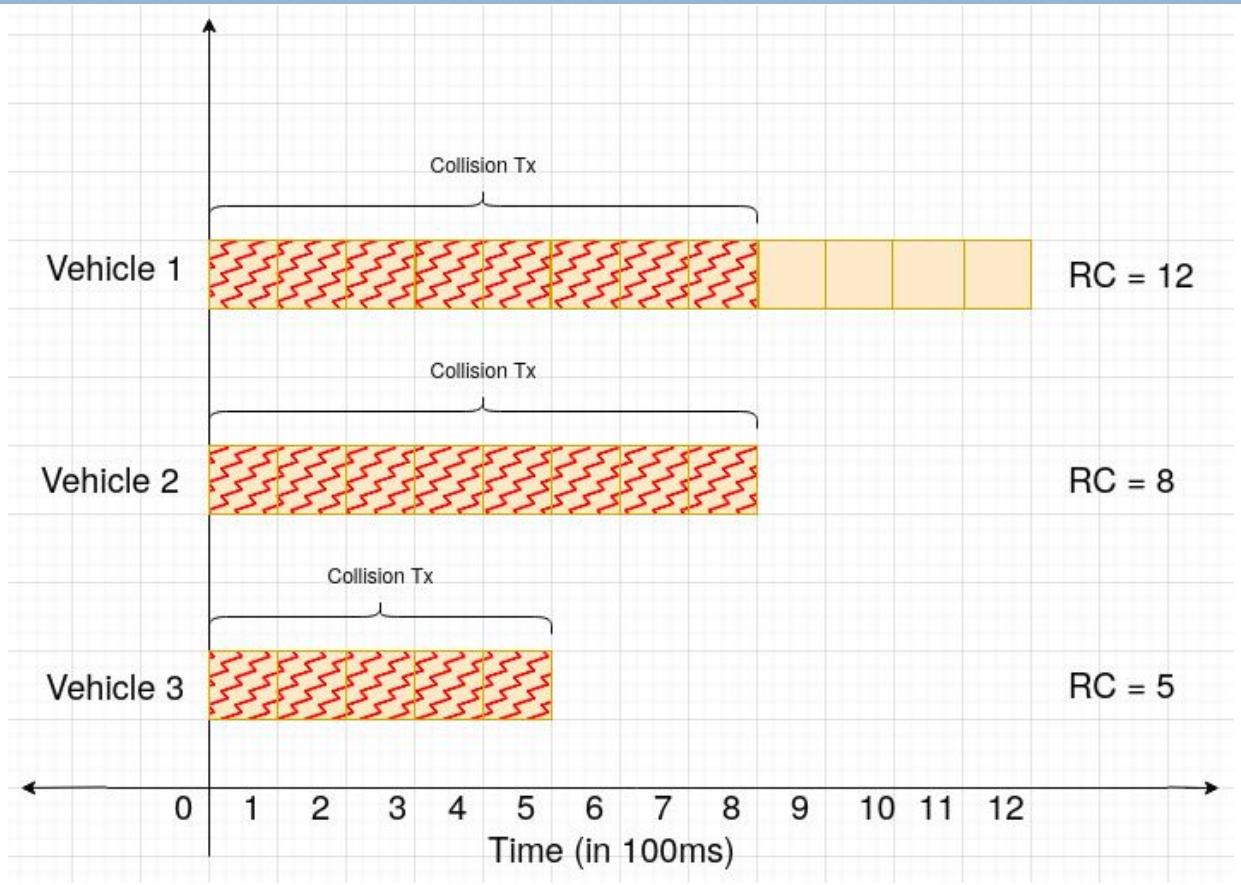
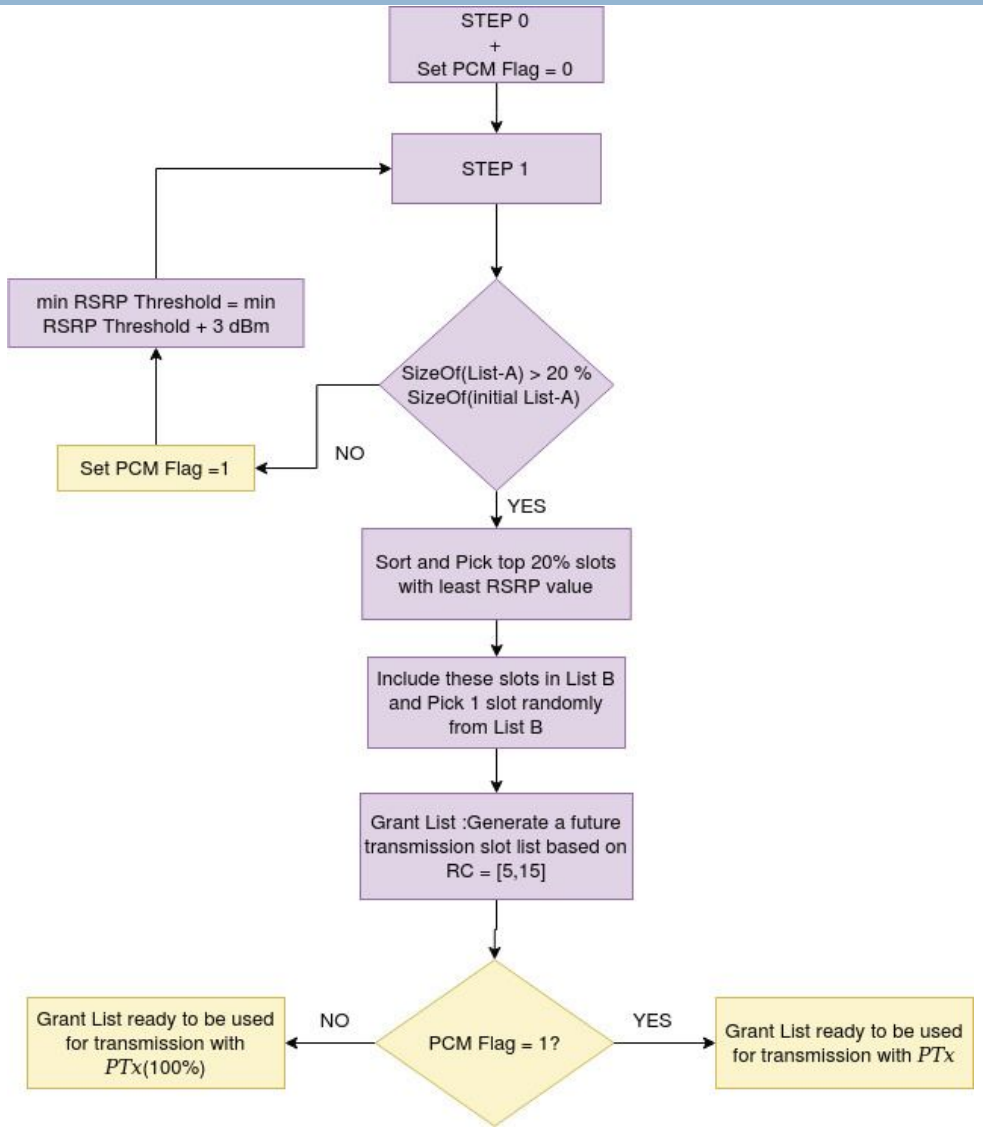


Fig : Depicts a scenarios where there are no HP vehicles. Transmission from one vehicle can collide with the other vehicle's transmission if both of them sense the channel at the same time and chose the same resources.

Probabilistic Collision Mitigation (PCM)

- PCM minimizes potential risk of collision when two vehicles senses channel simultaneously.
- Each vehicle decides with a probability whether to Tx in the selected resource or not.
- Slight delay in Tx better than multiple collided Tx in acute shortage of resources.



PCM: Illustration

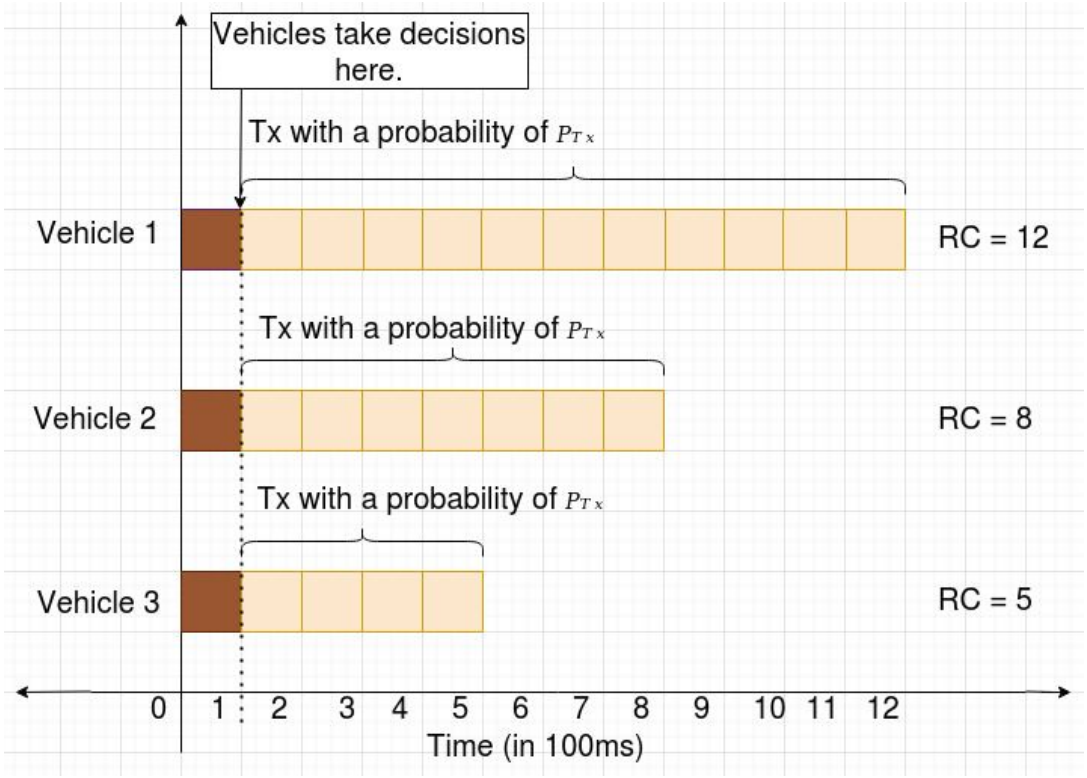


Fig: Three vehicles sense the channel simultaneously. Using PCM scheme, a vehicle decides whether to Tx in chosen slot with a probability $P\,T\,x$.

Performance of PCM

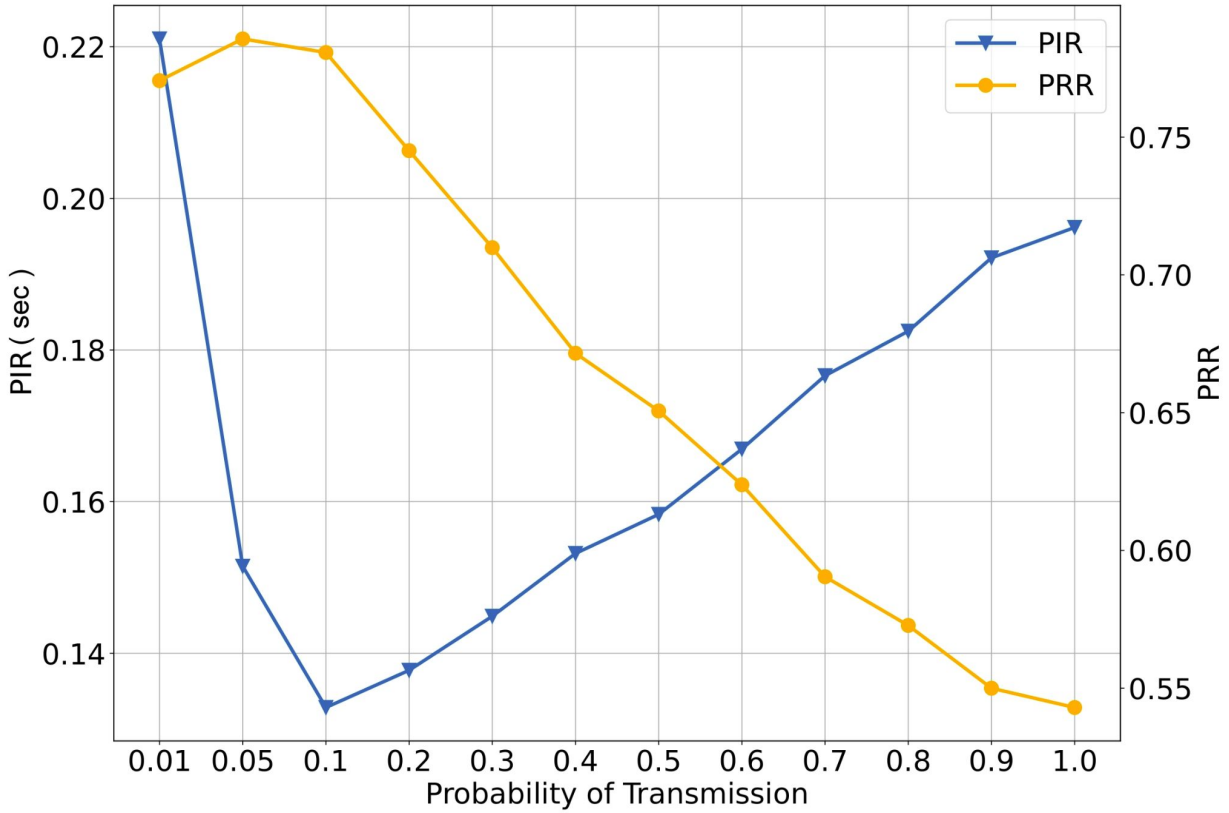
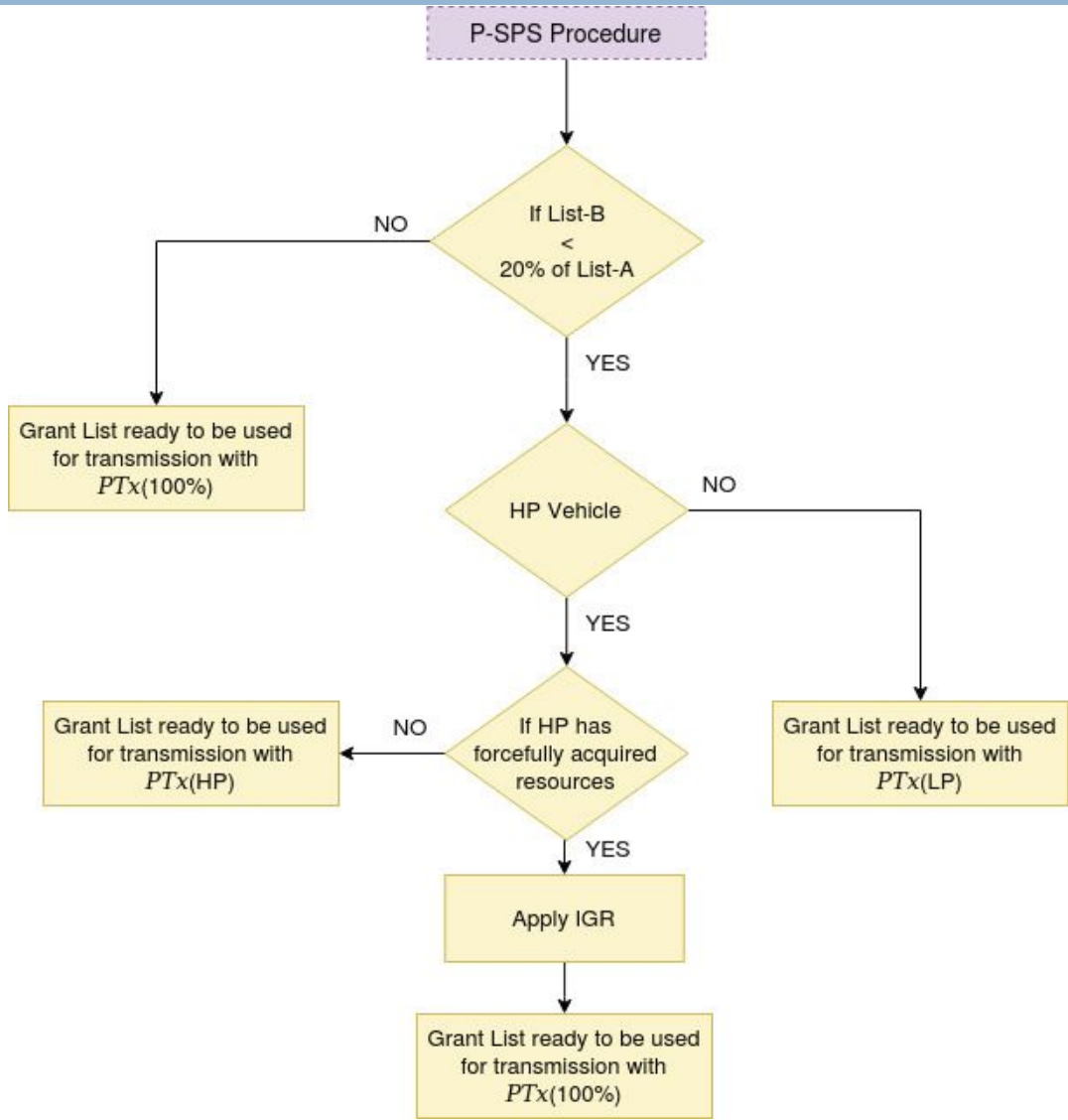


Fig: Report on PRR and PIR values with varying a $P\,T\,x$ when RAR = 5/15

The sweet spot for transmission in PCM scheme is with $P\,T\,x$ (0.1) which balances the two metrics with significant gain of 23.7% increase in PRR and 64ms decrease in PIR as compared to Legacy SPS [$P\,T\,x$ (1)].

Intelligent Grant Removal (IGR) Scheme

- IGR scheme intelligently creates the grant list containing future transmissible resources by skipping some probable collision prone resources.
- To this add the PCM scheme to minimize collision risk.
- HP vehicle uses lower $P\ T\ x$ to allow frequent sensing for improved awareness of resource usage.



IGR: Illustration

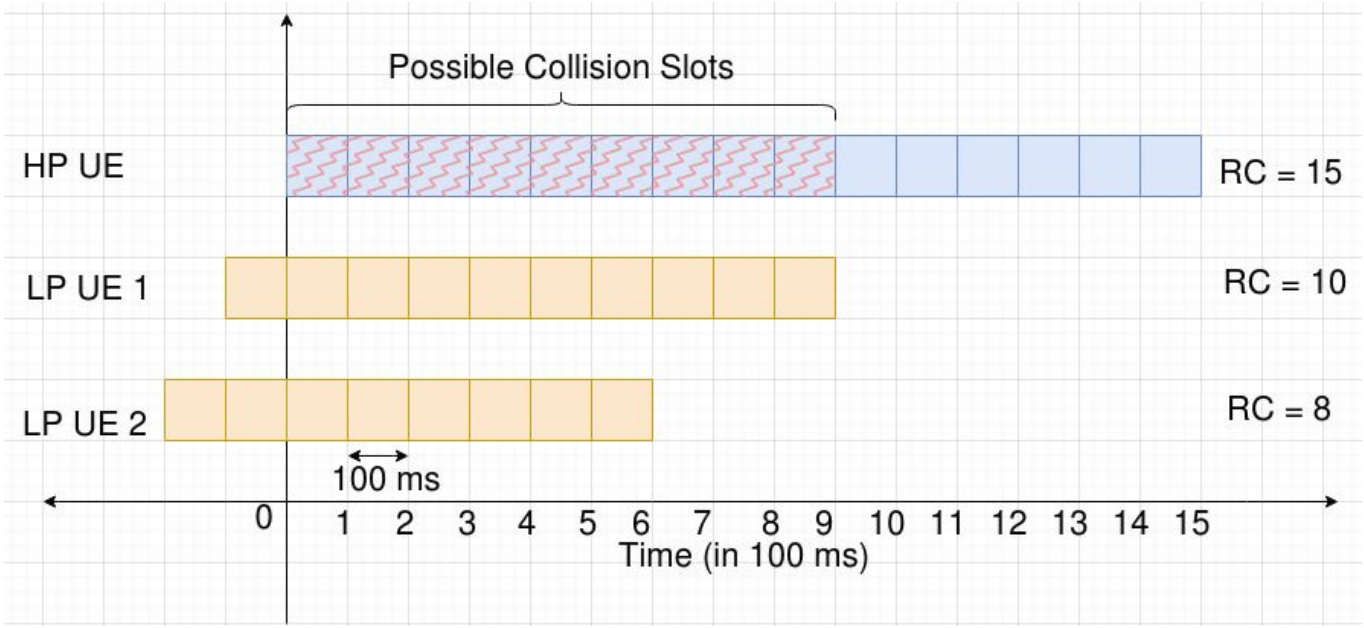


Fig: Through IGR scheme, the HP vehicle skips nine single-subframe resources and then transmits its CAM packets from the tenth slot onwards till its RC expires, avoiding unnecessary initial collisions with nearby LP vehicles.

Performance of IGR

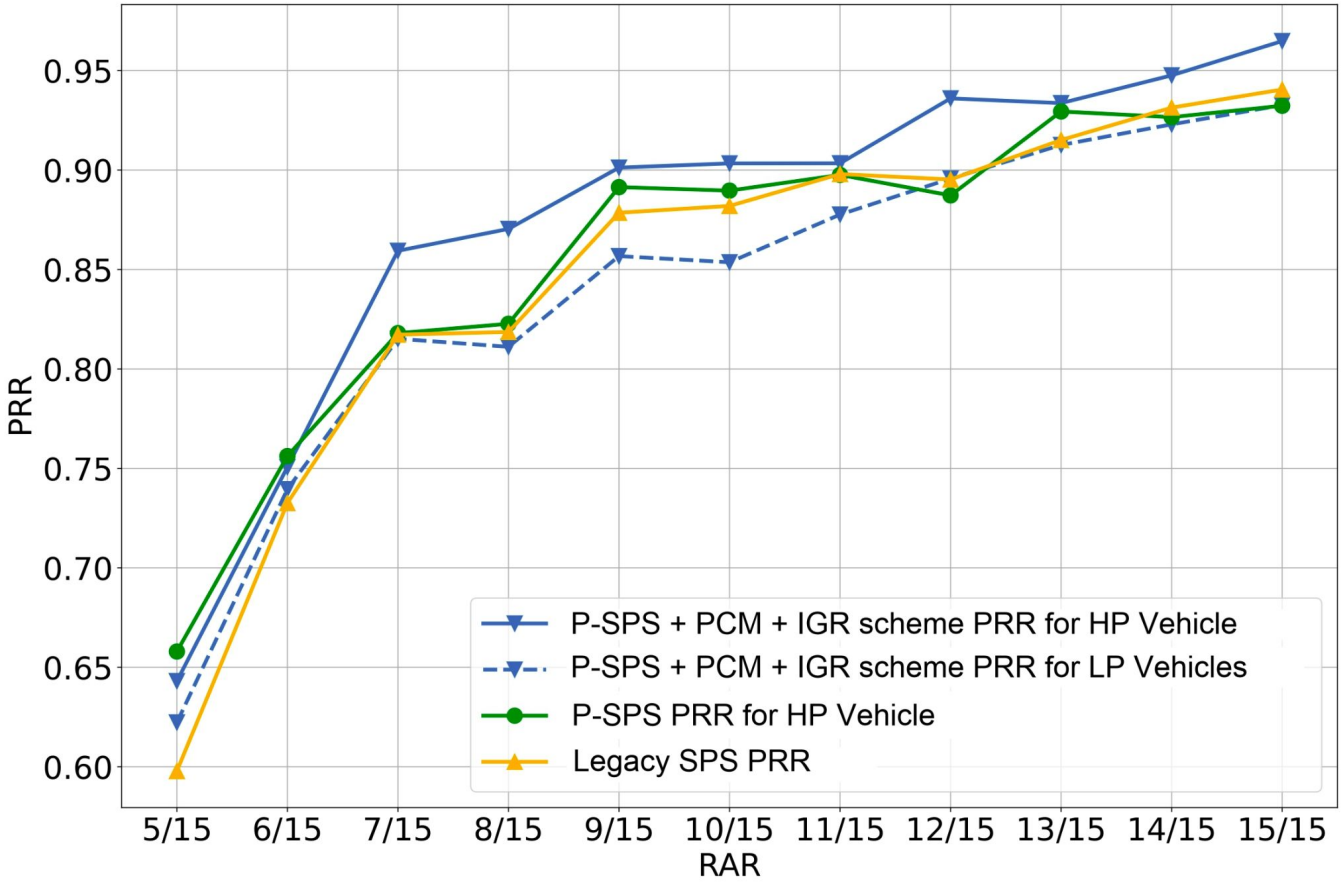


Fig: Variation in PRR for different RAR values for P-SPS+PCM+IGR schemes and the legacy SPS. The plot depicts the performance boost achieved for both HP and LP vehicles has improved against the legacy SPS.

Comparative Study of Different Schemes

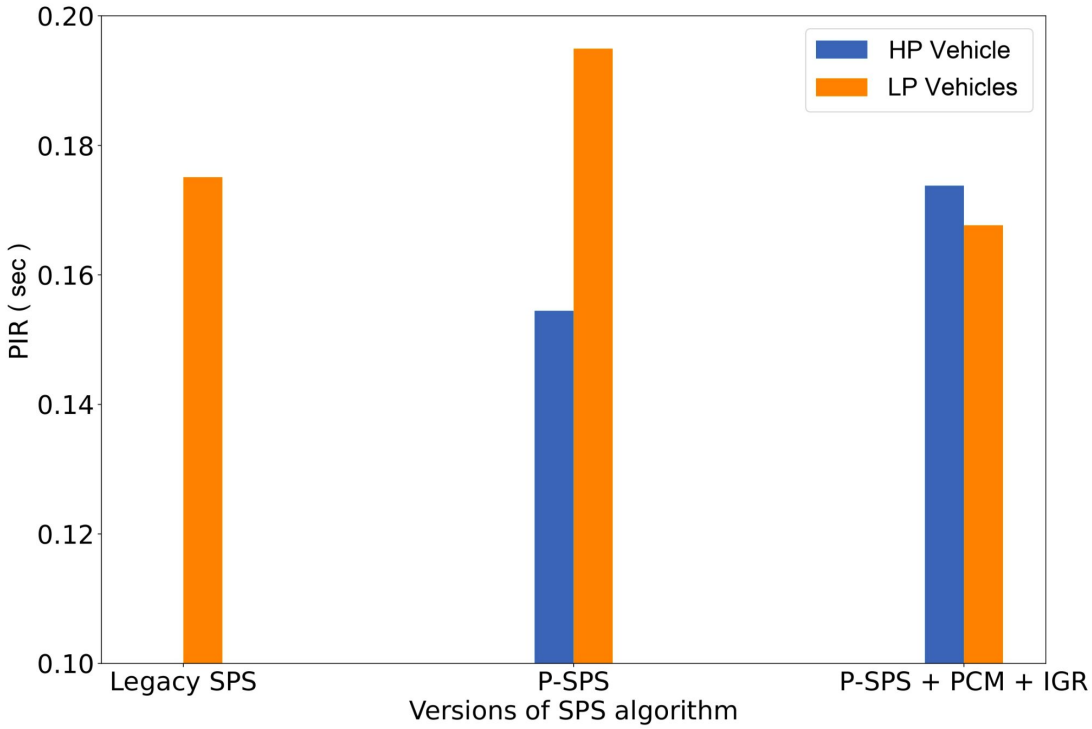


Fig: PIR of HP and LP vehicles for different schemes when RAR is 5/15.

- The HP vehicle has the least PIR in P-SPS. However LP vehicles suffer.
- This issue is mitigated by employing P-SPS in conjunction with PCM and IGR schemes where LP vehicles are treated fairly.

Comparative Study of Different Schemes

RAR %	SPS scheme	HP Vehicle		LP Vehicle	
		Avg. PRR	Avg. PIR	Avg. PRR	Avg. PIR
≤ 40%	P-SPS	70.7% (+4.2%)	143 ms (-14 ms)	61.17% (-5.33%)	173ms (+16 ms)
	P-SPS + PCM + IGR	69.68% (+3.2%)	156 (-1 ms)	68.09% (+1.5%)	152 ms (-4 ms)
>40%	P-SPS	88.83% (+0.22%)	113 (-0.5 ms)	85.09% (-3.5%)	118 ms (+5 ms)
	P-SPS + PCM + IGR	91.33 % (+2.7%)	109 ms (-4 ms)	87.53 % (-1%)	115 ms (+1 ms)

- When RAR is less than 40%, the differences in the PRR are significant between the proposed schemes and the legacy SPS.
- As RAR increases, the differences almost vanish.
- P-SPS with PCM and IGR schemes achieves an overall improvement over the legacy SPS by treating all the vehicles fairly.

Conclusions

- Through consecutive enhancements over the legacy SPS, we reported PRR rise of 3.2% for the HP vehicle and rise of 1.5% for the LP vehicles in extreme congestion scenario and of 2.7% rise in PRR for the HP vehicles as the congestion wanes out.
- The LP vehicles are treated fairly and are negligibly affected.

Future Directions

- Accurately incorporate the optimal probability of transmission by developing an analytical model for the proposed collision reduction schemes – PCM and IGR
- Working on supporting the emergency vehicles CAM messages as aperiodic DENM traffic and designing an algorithm to support scheduling of CAM and DENM jointly.

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THANK YOU!

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