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MC-Safe: Multi-Channel Real-time V2V Communication for Enhancing Driving Safety

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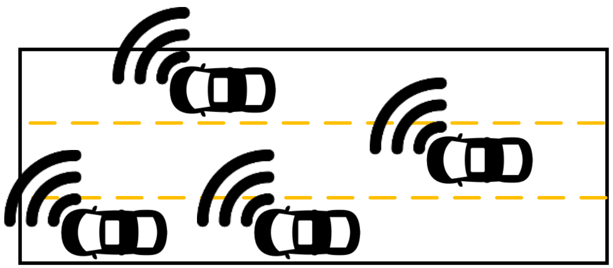
Introduction

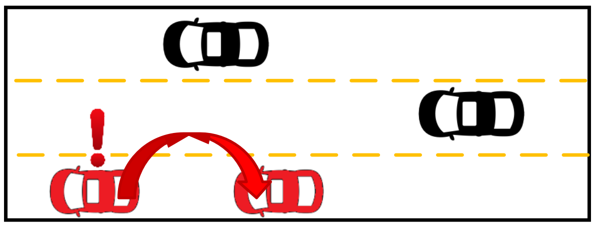
- Road safety has always been a major objective of Vehicle-to-Vehicle (V2V) network.
- In order to prevent road accident using V2V network, safety messages must be delivered in real time.
- Our goal: Develop a multi-channel communication framework for real-time safety V2V message delivery.

Background: V2V Safety Messages

- Periodic Safety Messages
  - Broadcast to indicate the vehicle's dynamics (e.g., position, speed, etc.) periodically.
- Event-based Safety Messages
  - These messages are generated when an emergency situation happens (e.g., road accident).
- Missing the deadline of event-based safety messages can result in serious accidents.
  - Main focus of our work.



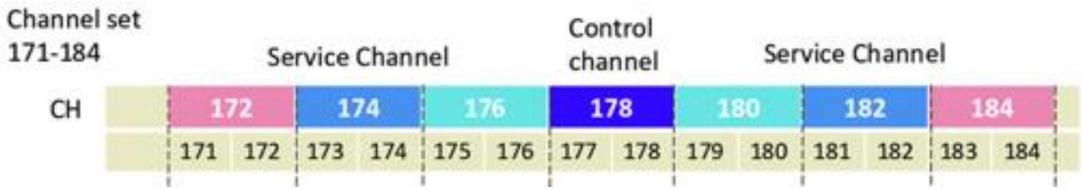
Periodic Safety Messages



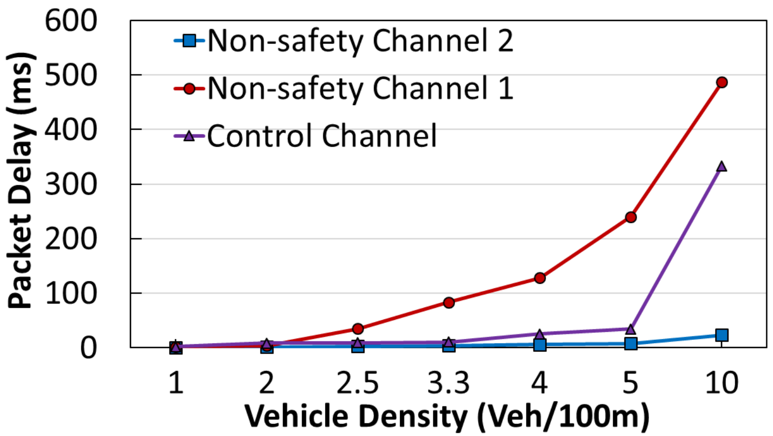
Event-based Safety Safety Messages

Motivation

- Real-time delivery for event based-messages is challenging.
  - Only one (control) channel is designed to deliver safety messages, despite six more channels are available in V2V network.
  - When the vehicle density increases, the delay on the control channel increases significantly.



- What if another available channel can be used temporarily?
  - The best channel must be dynamically selected at runtime.
  - A randomly selected channel can result in even longer delay.



Related Work on V2V Real-time Designs

- Single-Channel Solutions
  - Transmission power optimization *[TVT'17][INFOCOM'16][TITS'13]*.
  - Routing protocol improvements *[TWC'13][INFOCOM'13]*.
  - *Limitations:* Rely on only one channel for real-time transmission, unable to work under dense traffic scenarios.
- Multi-Channel Solutions:
  - Channel pre-allocation *[Communications Letters'17][Ad hoc networks'14]*
  - V2V Subnet formation *[Pervasive and Mobile Computing'14]*
  - *Limitations:* Focus on two pre-selected channels, no dynamic selection; Does not consider vehicle control requirements.

Major Contributions of Our Paper

- First work to explore all the available channels for better real-time communication in V2V network.
  - Seven non-overlapping channels available for V2V networks.
  - Best channel must be selected dynamically so that all the vehicle can communicate on that channel in real time.

- MC-Safe, a multi-channel V2V communication framework that can:
  - Allow vehicles to dynamically select the best channel with the least interference, in a distributed way.
  - Minimize the negotiation delay and channel selection overhead.

MC-Safe: Design Overview

1. Before detecting an accident, MC-Safe on each vehicle

   (1) Periodic channel monitoring: Estimate the quality of each channel based on the network model.

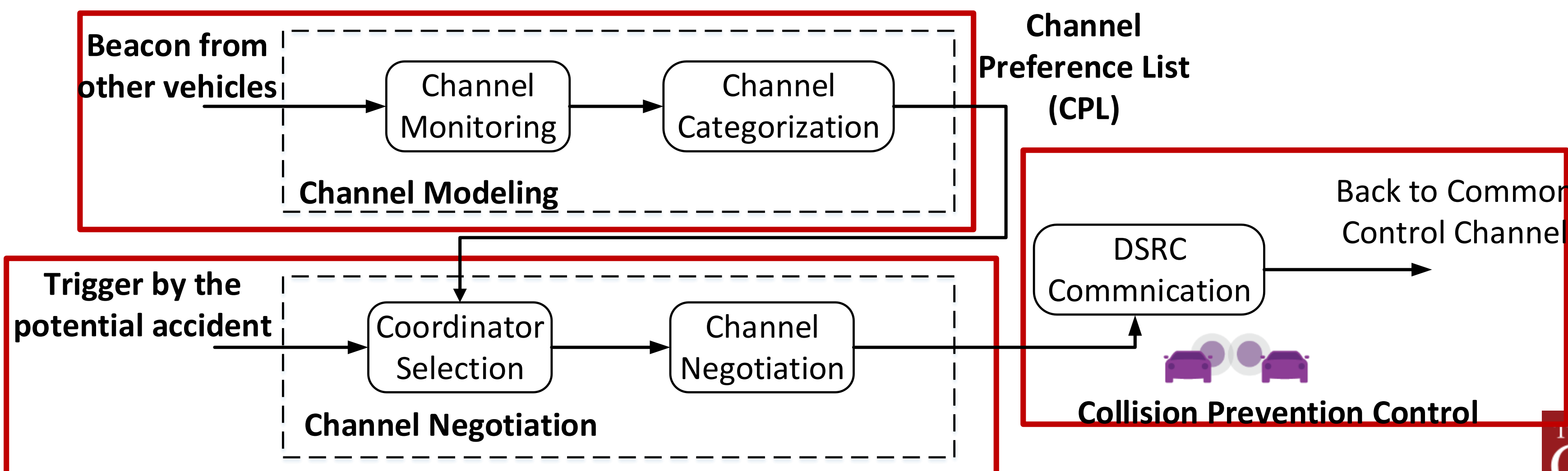
   (2) Periodic channel categorization: Rank channels based on their interference level.

2. After detecting an accident,

   Channel negotiation: Involved vehicles collaboratively find the best common channel.

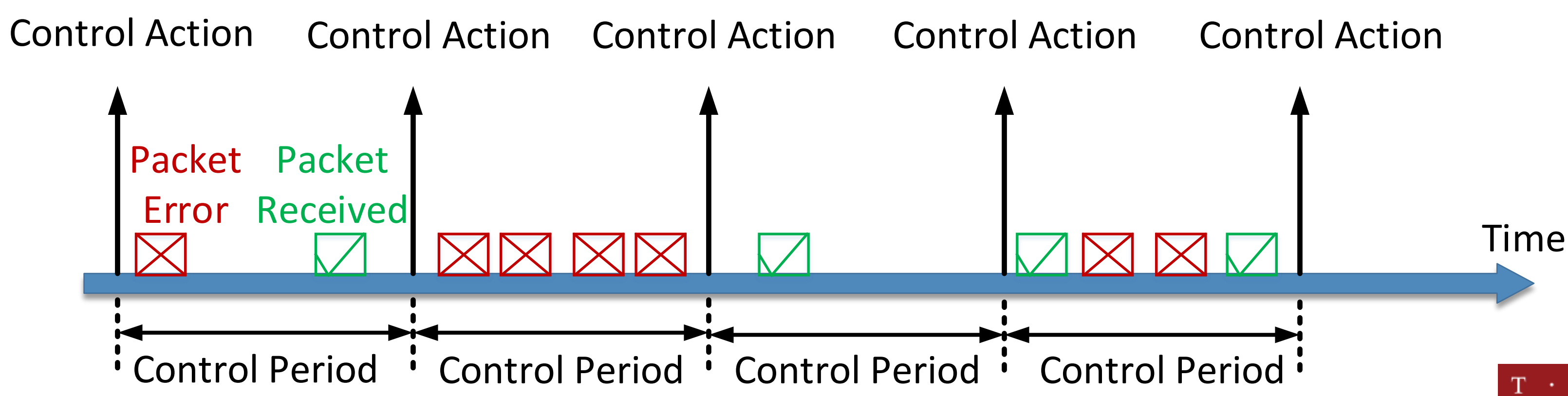
3. After selecting the best channel,

   All involved vehicles switch to the selected channel for real-time safety communication



Periodic Channel Monitoring

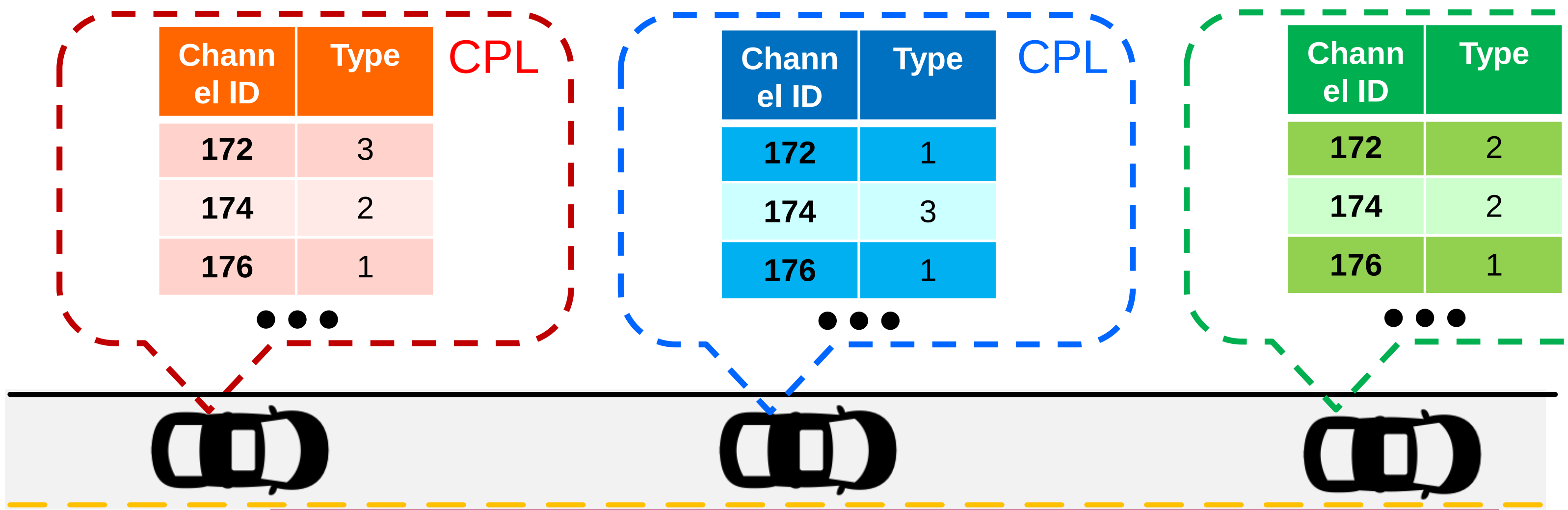
- 2D Markov model is used to estimate the quality of real-time performance on each channel.
  - This model describes the backoff procedure of V2V network, and calculates the delay and packet drop ratio given the number of interference nodes.
  - Periodic channel monitoring on each vehicle checks whether one channel can meet the two requirements based on the network model:
    - Maximum Allowable Delay (MAD): The data should be received within its deadline (50ms).
    - Maximum Allowable Transmission Interval (MATI): With in one control period (30ms), there must be one data update about the vehicle's dynamics.



Periodic Channel Categorization

- Each vehicle categorizes all channels into one of the three types:
  - Type-1: This channel fulfills MATI/MAD requirements.
  - Type-2: Cannot meet MATI/MAD requirements due to direct interference.
  - Type-3: Cannot meet MATI/MAD requirements due to hidden terminals.

- Each vehicle generates Channel Preference List (CPL), which ranks the channels preferred by this vehicle based on its local interference.

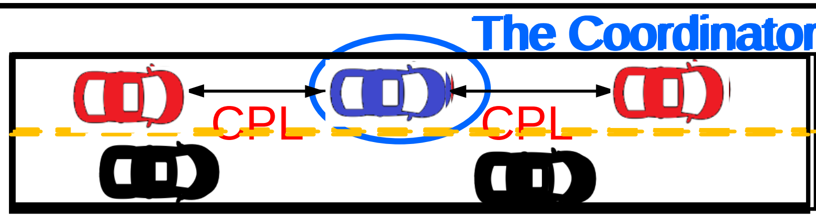


Channel ID	Type
172	3
174	2
176	1
•••	

Channel ID	Type
172	1
174	3
176	1
•••	

Channel ID	Type
172	2
174	2
176	1
•••	

Channel Negotiation: Four Steps



1. Coordinator selection

   The vehicle with the smallest MAC address is selected as the coordinator.

2. CPL transmission

   All the other vehicles (excluding the coordinator) send their CPLs to the coordinator.

3. Channel selection

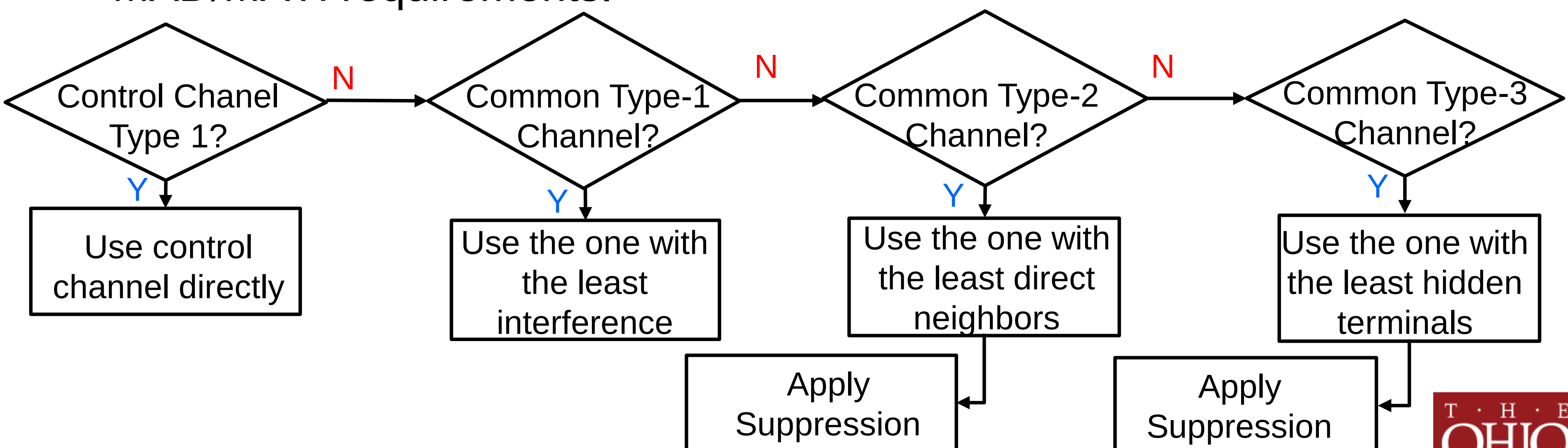
   The coordinator selects the channel to use for all vehicles (details on the next slide).

4. Decision sending

   The final channel decision is sent back to all the others using reliable multicast.

More on Channel Selection

- The coordinator uses list matching to determine the best common channel:
  - If the control channel is Type-1 for all involved vehicles, the control channel is selected.
  - If there are common Type-1 channels, then the one with the least interference is selected.
  - A common Type-2 channel with the least number of direct neighbors is selected.
  - A Type-3 channel with the least number of hidden terminals is selected.
- Suppression is applied if a non Type-1 channel is selected to enforce the MAD/MATI requirements.

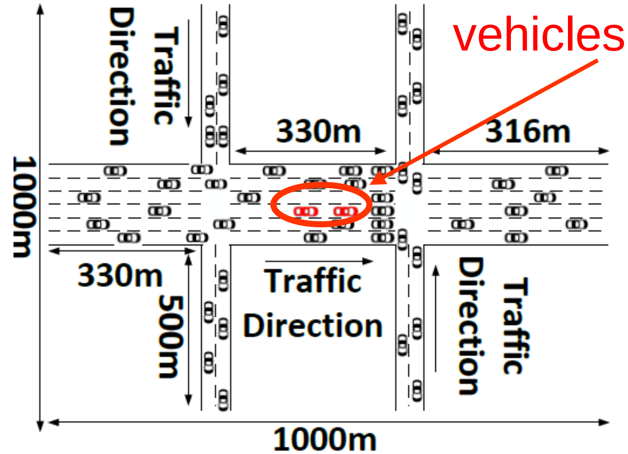


Baselines for Comparison

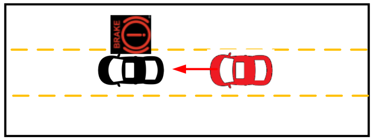
- **CCC**
  - Like state-of-the-art solution, vehicles use the control channel to communicate with each other.
- **Random (RAN)**:
  - A random channel (exclude the control channel) is select to do the communication for the involved vehicles.
- **Least Congested Channel First (LCCF)**
  - A variant of MC-Safe, LCCF only considers the direct interference vehicles
  - Selects the channel with the least interference.
- **Ideal**
  - One channel is preserved for this specific channel.
  - Not practical and serves as the upper bound.

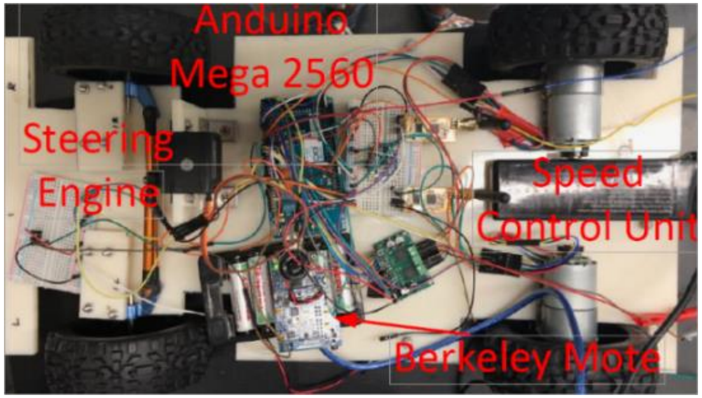
Experiment Setup

- Simulation
  - Network simulator: NS2
  - Road scenarios:
    - 8-lane highway
    - 6-lane intersection

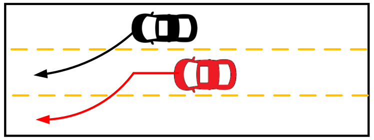


- Hardware Testbed
  - The 1:8 size scaled car
  - Arduino Mega 2560 control broad
  - Road scenarios:
    - Hard braking



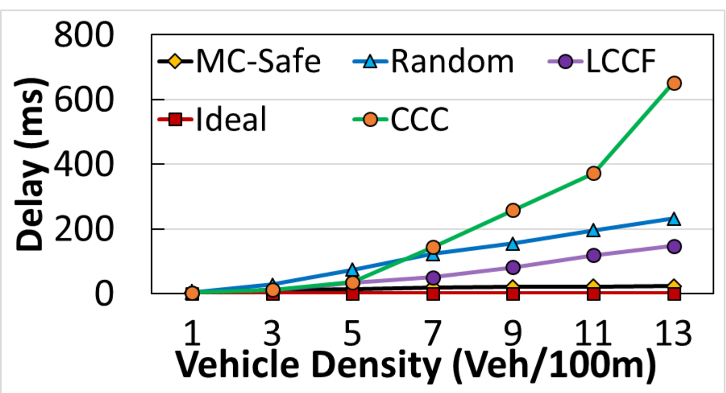


    - Abrupt lane change



Simulation Results

- In term of packet delay, MC-Safe:
  - Achieves 64ms less delay compared with LCCF.
  - Outperforms CCC by 150ms less packet delay.
- In term of Collision Probability:
  - MC-Safe achieves the lowest collision probability.
- Reasons for the improvements over LCCF:
  - The channel is selected with strict models.
  - Suppression is applied to enforce MATI/MAD requirements.



Distance between the vehicles of interests.

Inter-vehicle Distance	MC-Safe	RAN	LCCF	CCC
25m	18%	42%	60%	78%
30m	11%	25%	38%	50%
40m	0%	0%	6%	15%

Hardware Testbed Result

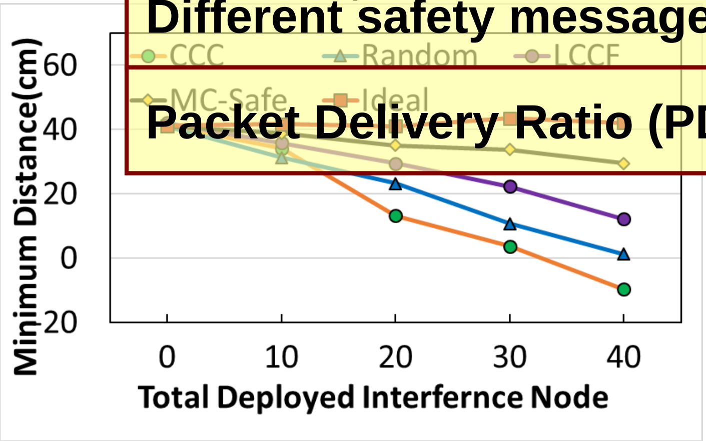
- MC-Safe outperforms The-State-of-Art solution:
  - 3.43m (73.5%) shorter braking distance
  - 46.01cm (54.2%) less minimum distance between the two vehicles.
- MC-Safe outperforms LCCF:
  - 1.32m (35.4%) shorter braking distance
  - 13.24cm (22.7%) less minimum distance between the two vehicles.
- Reasons for the improvements:
  - Smaller delay lead to earlier reception of V2V packets.
  - Earlier reception lead to earlier vehicle control actions.

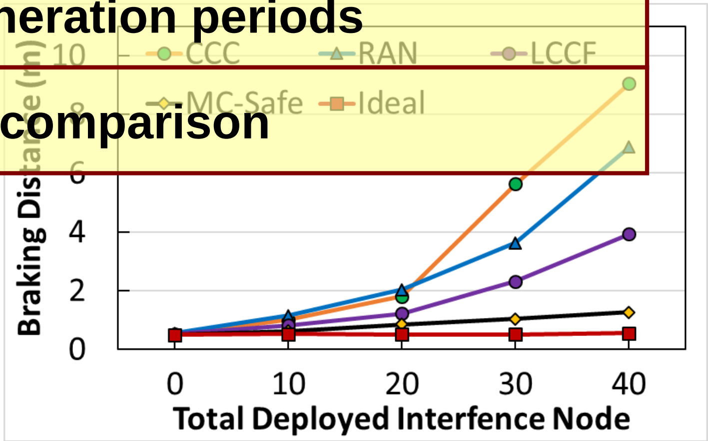
More results are in the paper…

Different deadline requirements

Different safety message generation periods

Packet Delivery Ratio (PDR) comparison





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Conclusion

- MC-Safe
  - A dynamic multi-channel real-time V2V communication framework.
  - Features a novel negotiation scheme that can explore seven available channel and selects the best one at run time.
- Experiment results show that MC-Safe outperforms the baselines by:
  - 23.4% in terms of packet delay in the simulation.
  - 48.1% in the terms of braking distance in the testbed experiment.

Q&A

- Thanks a lot for the attention!

- Questions?

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The Control Requirements (Cont'd)

- Mathematically, the two requirements can be summarized as :
  - MAD: $\boxed{d} \leq \boxed{D}$

    Packet Delay

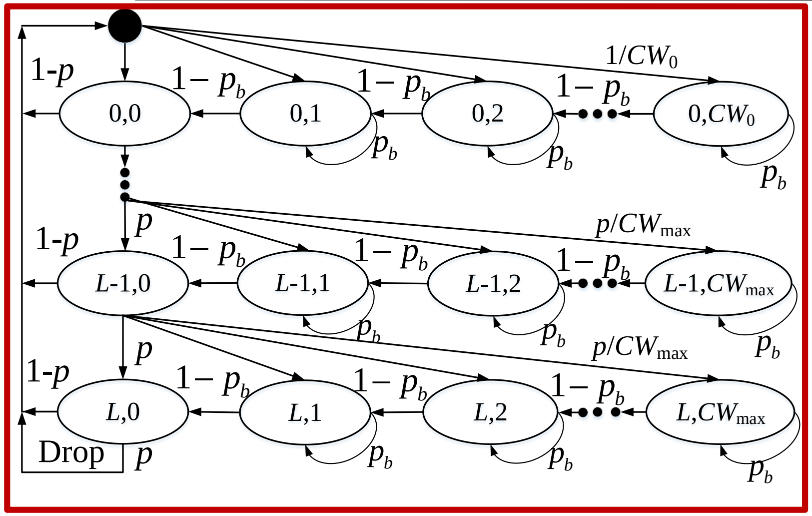
    Deadline Requirement
  - MATI: $1 - \boxed{p}^{\boxed{n}} \geq \boxed{\delta}$

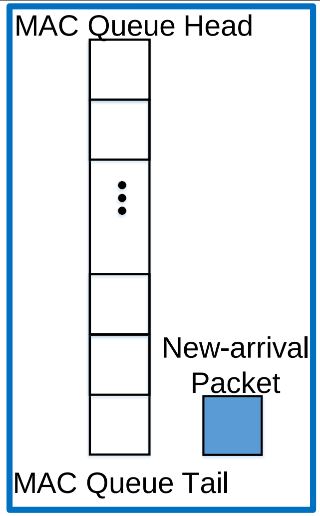
    Packet Drop Ratio

    Packets sent within one control period

    Probability Threshold
- The threshold value (D and δ) can be determined by the specific vehicle control algorithm.
- We use the 2D Markov backoff model with queuing theory to calculate d, p and n for each non-safety channel.

The Network Model: 2D Markov Chain





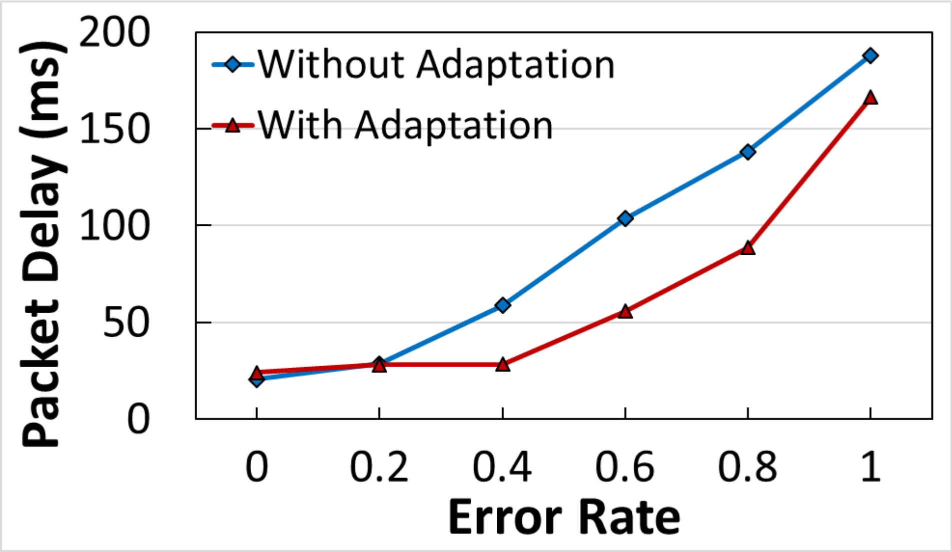
- p: Transmission failure probability
- P_b: Backoff probability
- CW_0: Initial contention window
- CW_{max}: Maximum contention window
- L : maximum retransmission limit

Backoff Delay Queuing Delay

- Total Delay = Backoff Delay + Queuing Delay
  - The Expectation of backoff delay can be calculated using the Markov model.
  - The Expectation of queuing delay can be calculated using the queuing theory.
- The theoretical model is not always accurate. Thus, we use the sensing information to adjust our theoretical input parameter.
  - Adaptively update the model parameter with observed delay with weighted averaging.
  - Also increase the robustness of existing theoretical model.

Adaptation

- We use the slot occupation (busy media ratio) as the observed data from the wireless sensing component.
- Also, from Markov model, we could calculate the busy media ratio.
- Then we use a weighed averaging to combine the observed data and theoretical value.
- To test the performance, we deliberately add errors and compare the packet delay with/without adaptation:



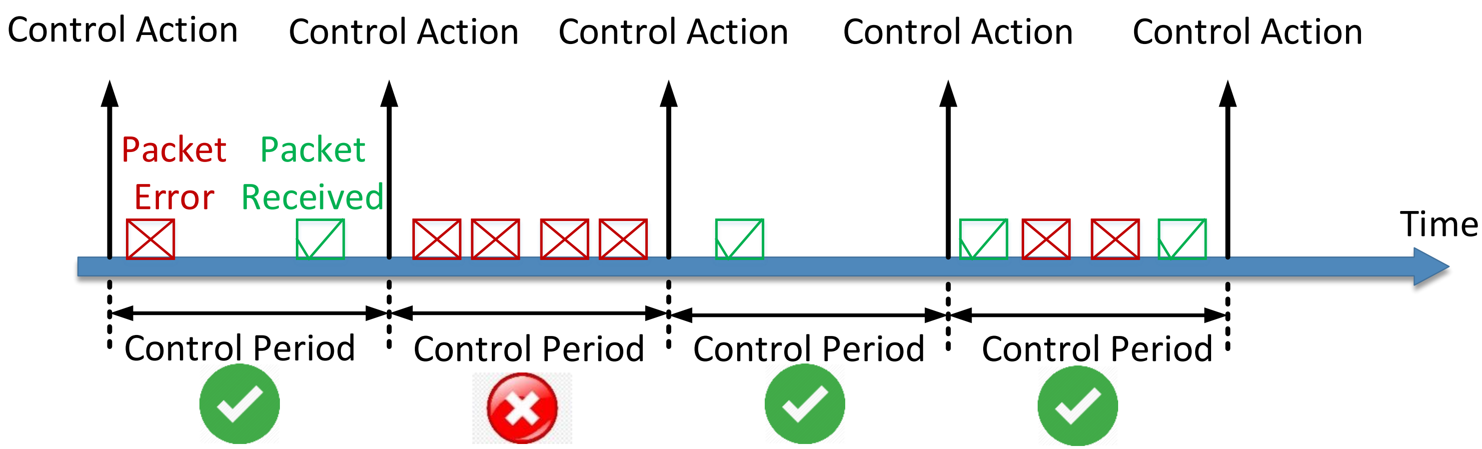
Negotiation Overhead

- The negotiation delay have three parts:
  - Delay of communication: The transmissions of CPL and the final channel result.
  - Commutation and Channel switching overhead.
- To reduce the delay of communication, we
  - Fix the backoff window of CPL transmission packet.
  - Put it in the head of the MAC queue.
  - Make the final channel result sent in ACK frame.
- Total delay of negotiation can be estimated as:

$$\underbrace{\frac{s_0}{p}}_{\text{Single backoff delay / Packet Delivery ratio}} + \underbrace{\text{SIFS}}_{\text{Protocol delay}} + \underbrace{T_{ack}}_{\text{ACK delay}} + \underbrace{T_s}_{\text{Channel Switching Overhead}}$$

Periodic Channel Monitoring

- Periodic channel monitoring on each vehicle checks whether one channel can meet the two requirements:
  - Maximum Allowable Delay (MAD): The data should be received within its deadline (50ms).
  - Maximum Allowable Transmission Interval (MATI): With in one control period (30ms), there must be one data update about the vehicle's dynamics.
- 2D Markov backoff model is used to calculate corresponding delay and packet delivery ratio for each channel.



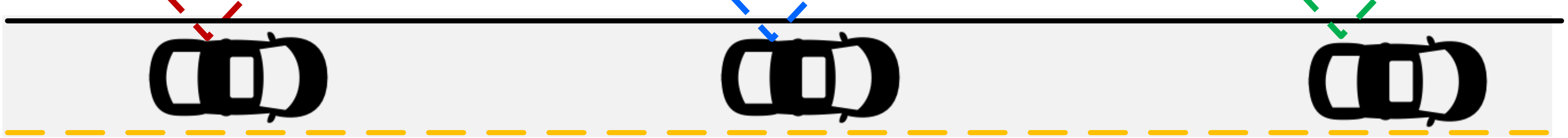
Channel Preference List (CPL)

- Each vehicle generates Channel Preference List (CPL), that contains:
  - Channel ID: Indicate the ID for the channel.
  - Type: Indicates the type of the channel by checking MAD/MATI requirements.
  - Interference: The secondary reference for selecting a channel to break the tie (depends on the channel type).

Channel ID	Type	Interference
172	3	10
174	2	17
176	1	4

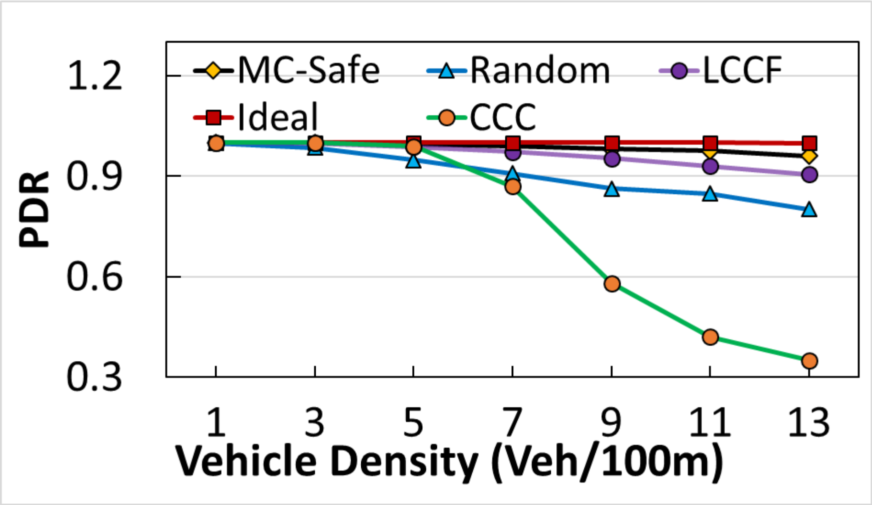
Channel ID	Type	Interference
172	1	7
174	3	18
176	1	5

Channel ID	Type	Interference
172	2	12
174	2	12
176	1	4

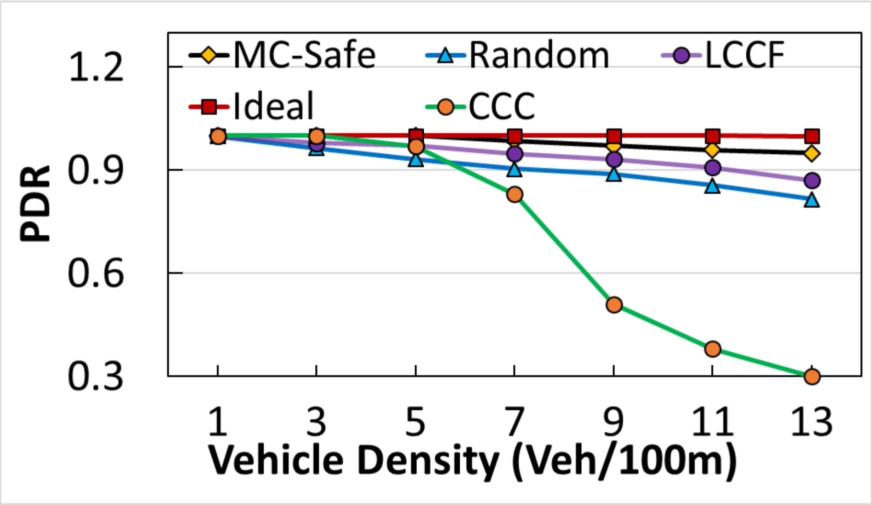


PDR results

- The PDR of MC-Safe is only 4.56% lower than that of Ideal.
- The PDR of MC-Safe is 8.21% higher than that of LCCF.
- The PDR of MC-Safe is 16.75% higher than that of CCC.



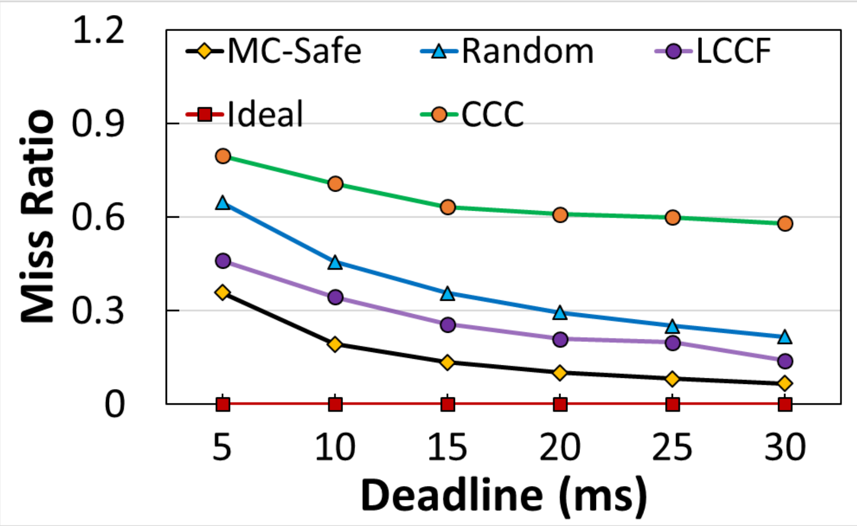
6-lane Intersection

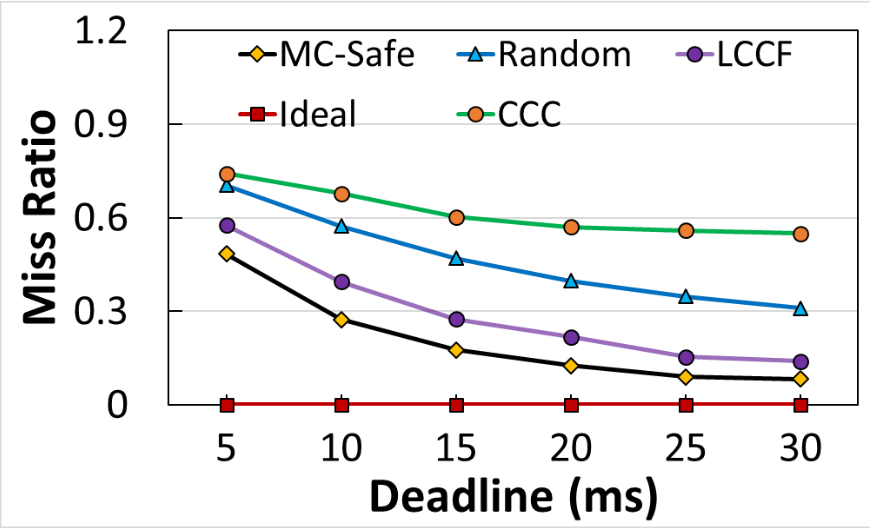


8-lane Highway

Different Deadline Requirements

- The deadline miss ratio of MC-Safe is the lowest among all the practical schemes.
- For a deadline of 20ms (usually for lateral shift control applications), the missing ratio for MC-Safe is 11.2%.





Different Safety Message Periods

- We change the sending frequency of safety messages and test the packet delivery ratio (PDR).
- MC-Safe can achieve a PDR of 99.2% when the period of safety message is 15ms.
- MC-Safe outperforms LCCF by 25.3% on average.
- The state-of-the-art solution does not achieve a PDR higher than 65% as a result of packet drop.