



# When Cryptography Needs a Hand: Practical Post-Quantum Authentication for V2V Communications

*Geoff Twardokus*

**RIT** | Rochester Institute of Technology

Nina Bindel

 **SANDBOX AQ**

Hanif Rahbari

**RIT** | Rochester Institute of Technology

Sarah McCarthy

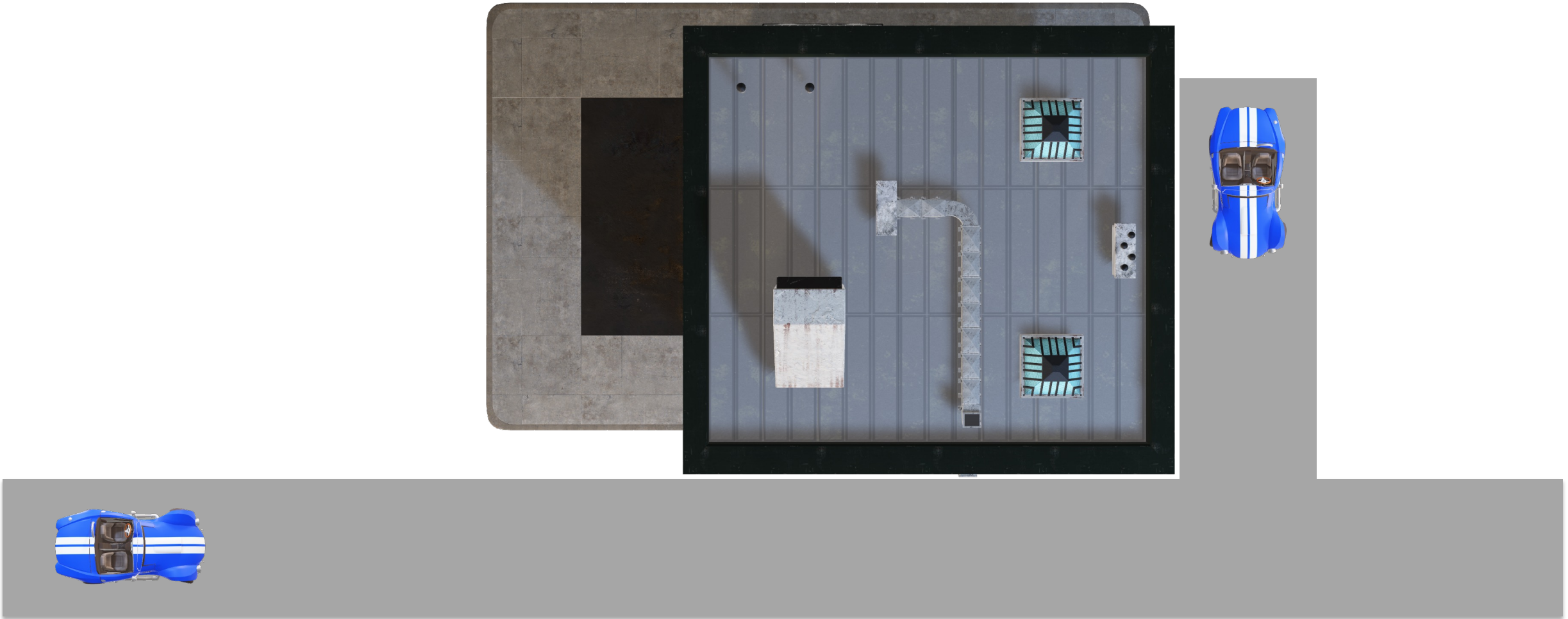
 **UNIVERSITY OF WATERLOO**

# Vehicle-to-Vehicle (V2V) Communication

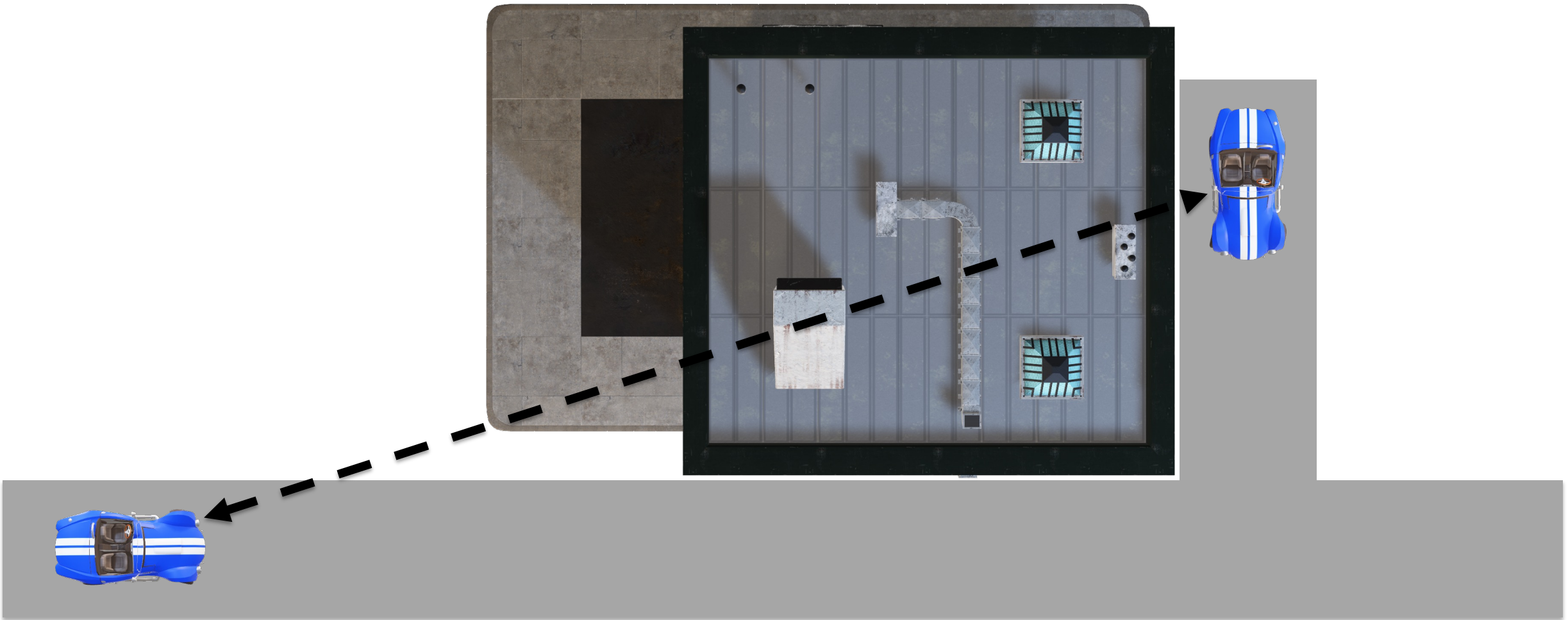
Direct wireless communication between vehicles for safety could **prevent 600,000 car crashes** every year<sup>1</sup>

<sup>1</sup>National Highway Transportation Safety Administration (NHTSA), "Federal Motor Vehicle Safety Standards; V2V Communications," Notice of Proposed Rulemaking (NPRM) for FMVSS No. 150, V2V Communications; 88 FR 80685, Nov. 2023.

# Vehicle-to-Vehicle (V2V) Communication



# Vehicle-to-Vehicle (V2V) Communication



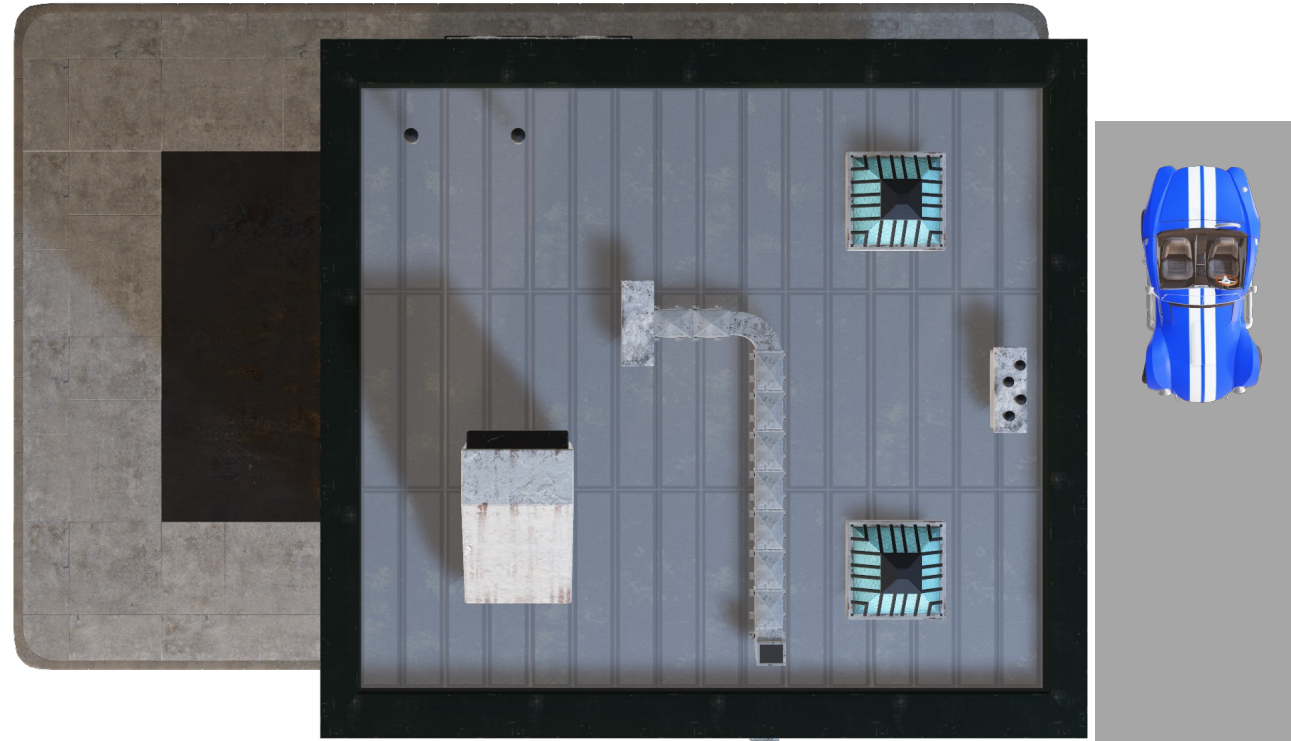
# Vehicle-to-Vehicle (V2V) Communication



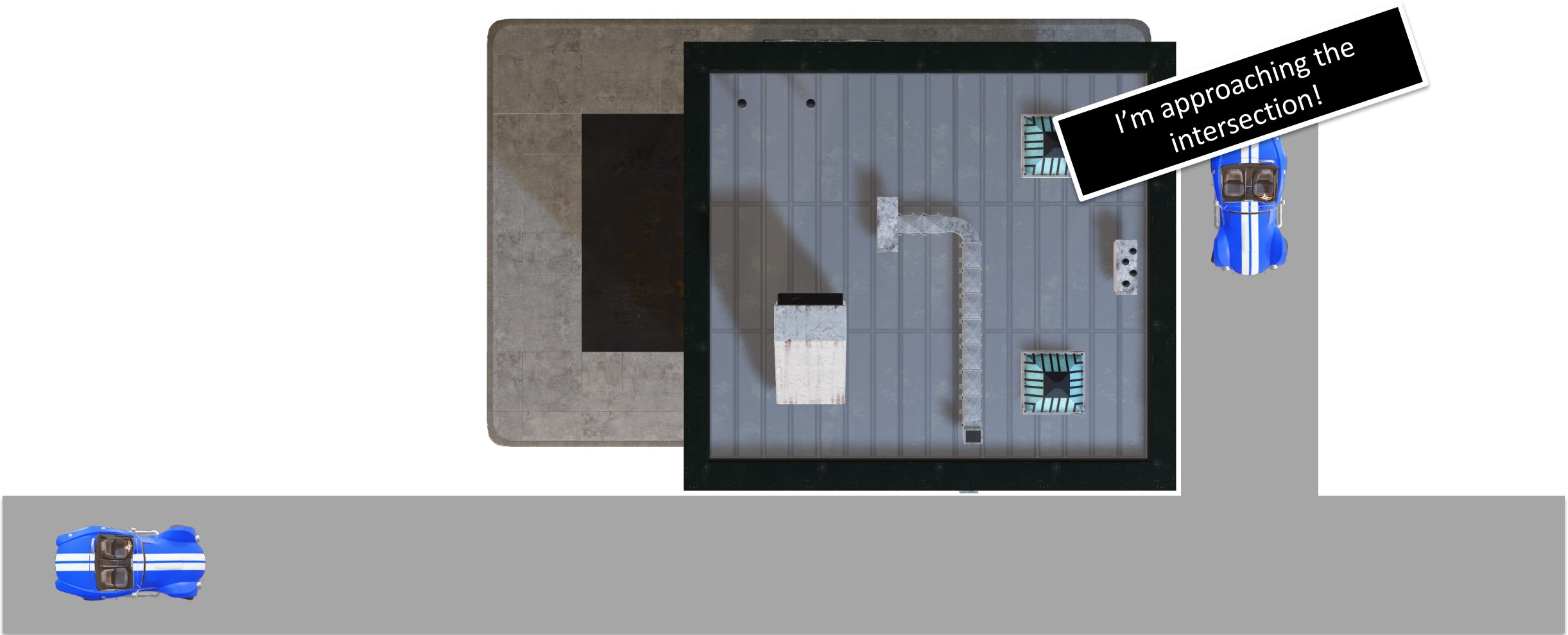
# Vehicle-to-Vehicle (V2V) Communication

A Basic Safety Message (BSM)

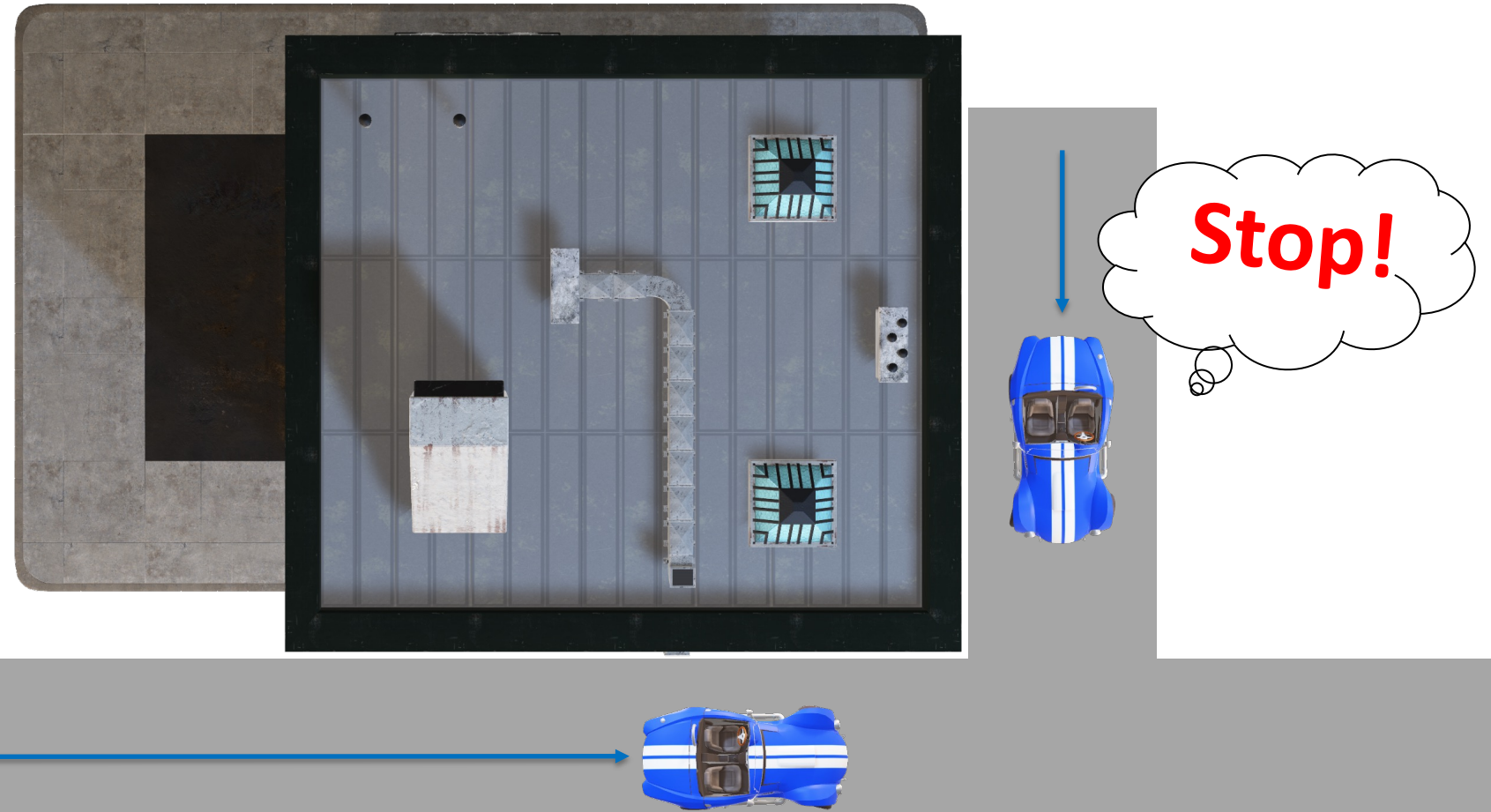
I'm approaching the intersection!



# Vehicle-to-Vehicle (V2V) Communication

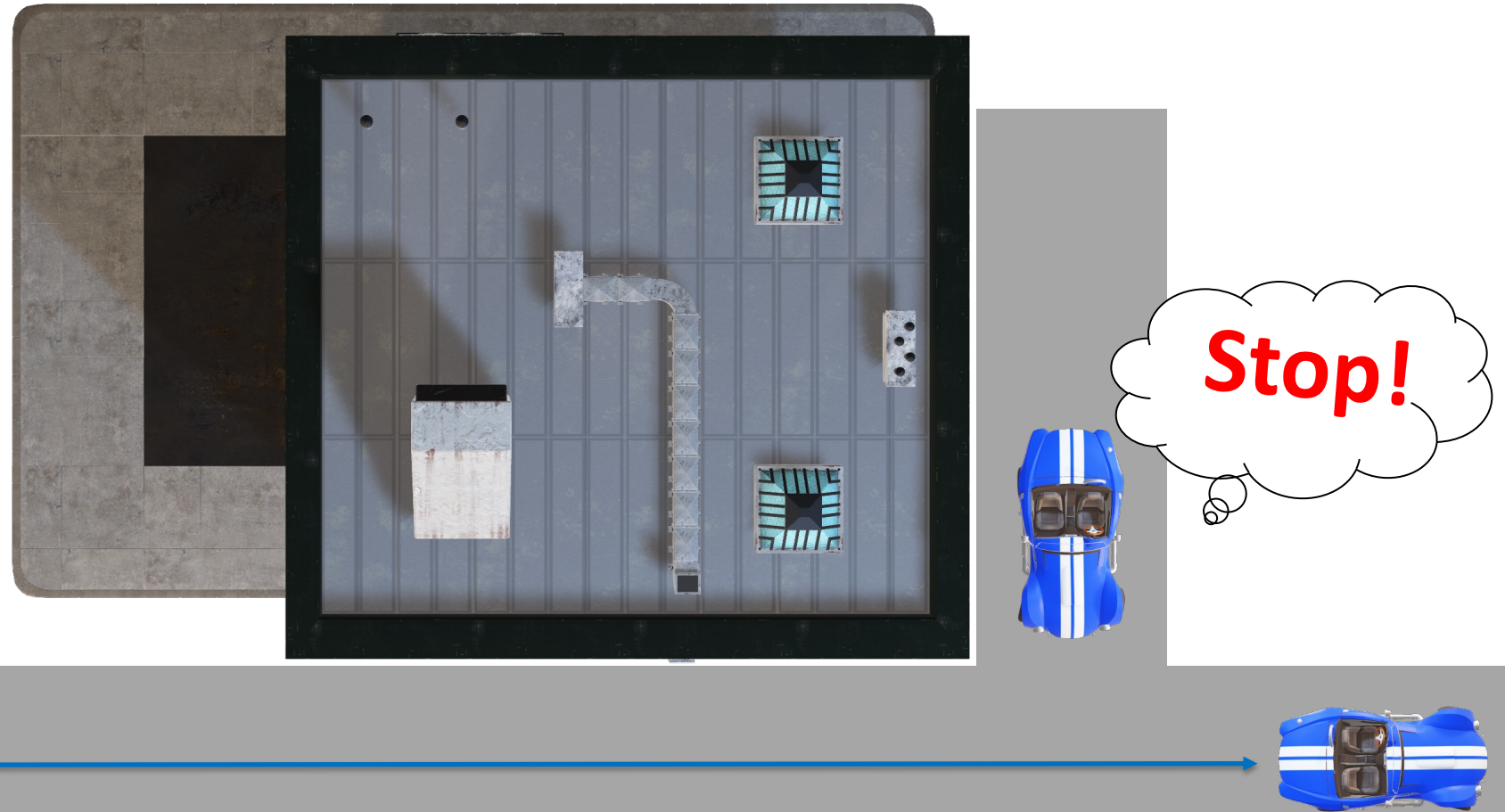


# Vehicle-to-Vehicle (V2V) Communication





# Vehicle-to-Vehicle (V2V) Communication

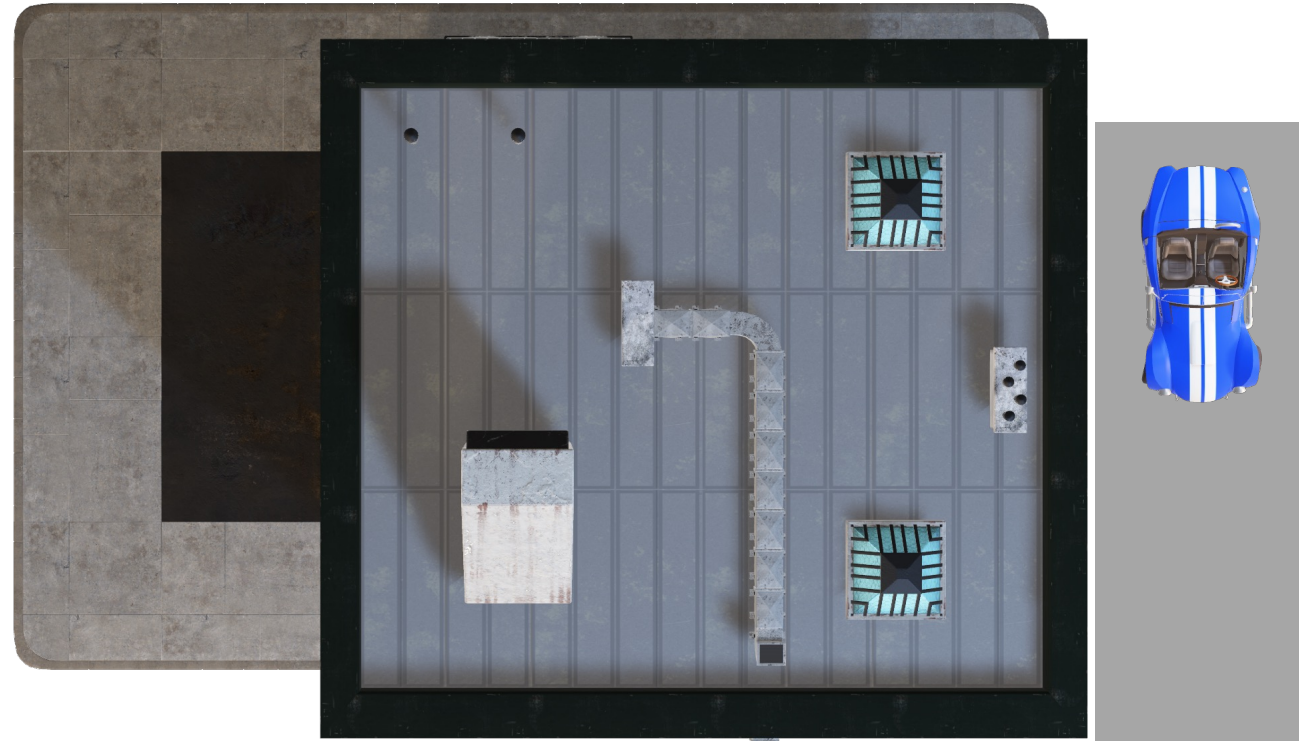


# V2V Authentication

A Basic Safety Message (BSM)



I'm approaching the intersection!

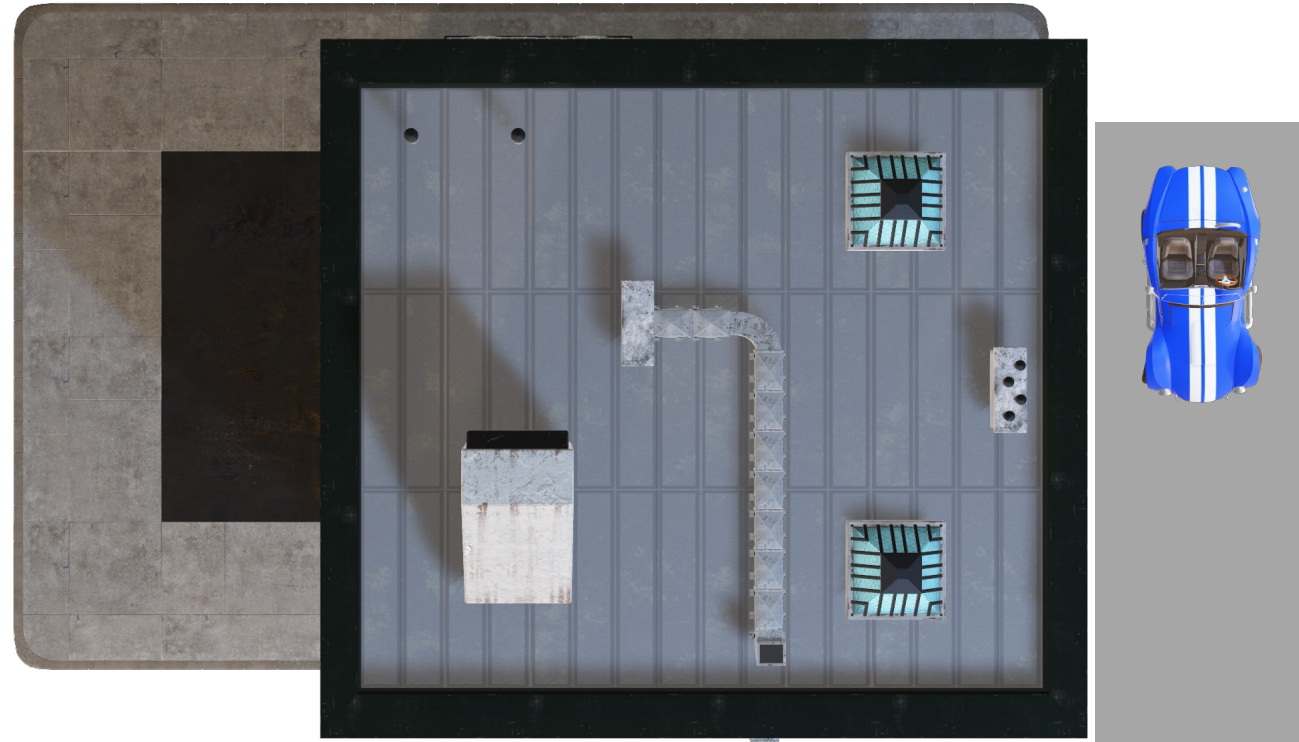


# V2V Authentication

Secure Protocol Data Unit (SPDU)



SPDU



# V2V Authentication

Secure Protocol Data Unit (SPDU)



SPDU



# V2V Authentication

Secure Protocol Data Unit (SPDU)

BSM ("I'm approaching...")



SPDU



# V2V Authentication

Secure Protocol Data Unit (SPDU)

Digital Certificate

BSM ("I'm approaching...")



SPDU



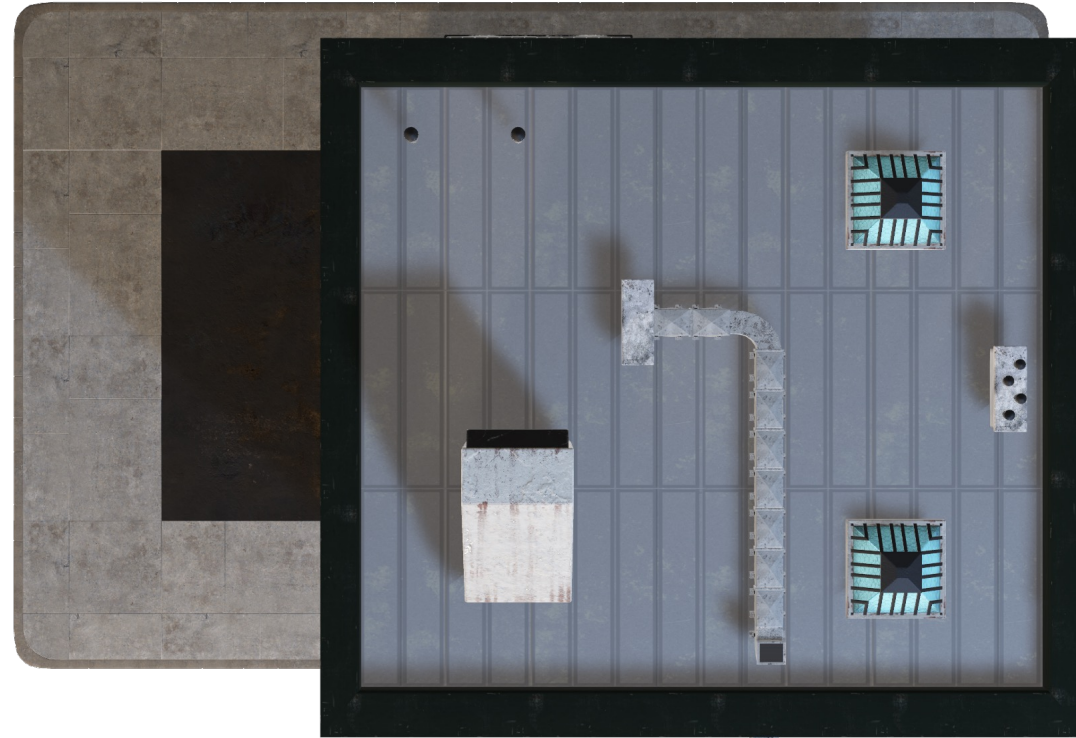
# V2V Authentication

Secure Protocol Data Unit (SPDU)

Digital Certificate

BSM ("I'm approaching...")

Digital Signature (by vehicle)



SPDU



# V2V Authentication

Secure Protocol Data Unit (SPDU)

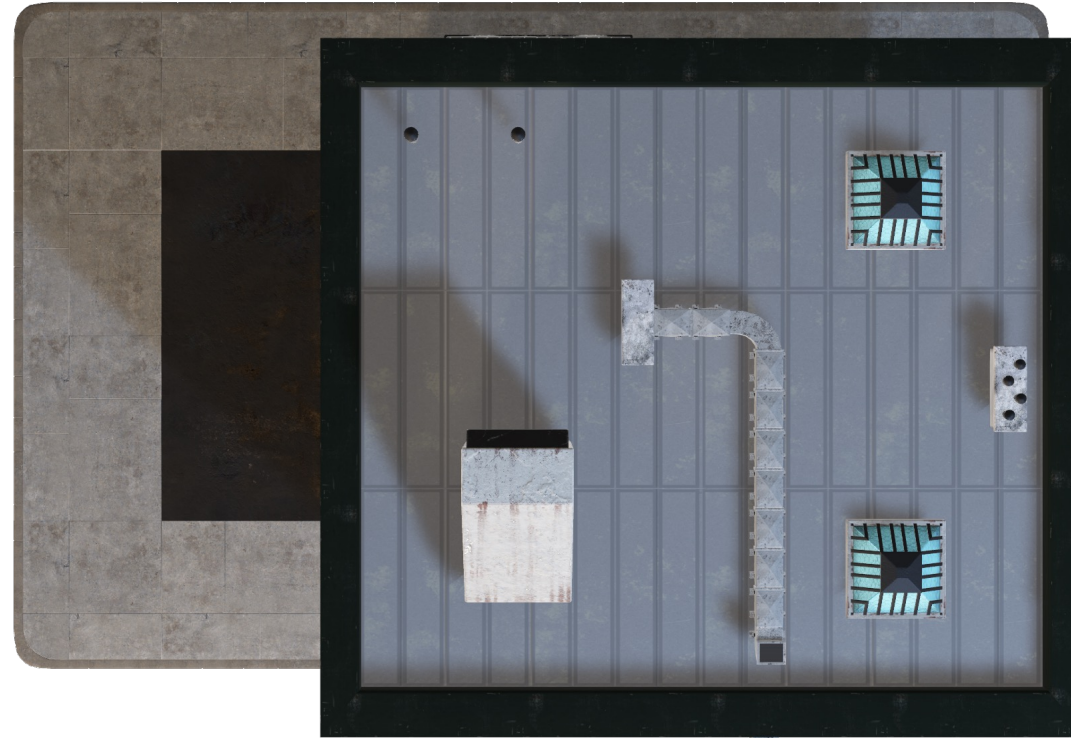
Digital Certificate

Public Key (of vehicle)

Digital Signature (by CA)

BSM ("I'm approaching...")

Digital Signature (by vehicle)



SPDU





# V2V Authentication

Secure Protocol Data Unit (SPDU)

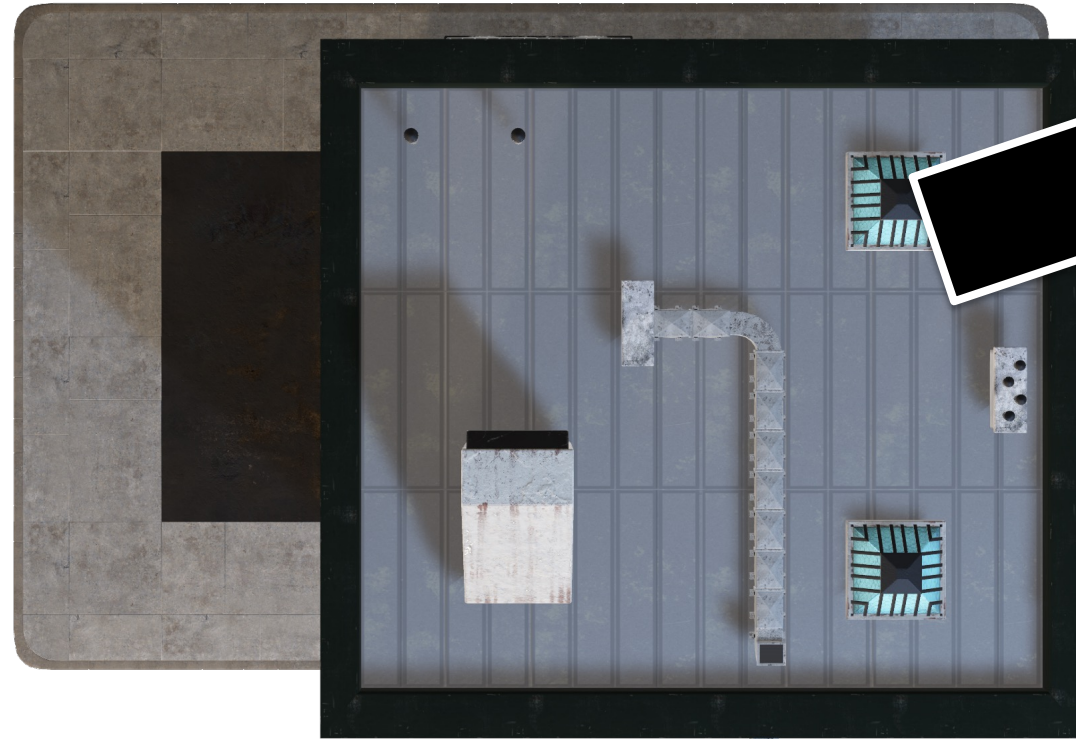
Digital Certificate

Public Key (of vehicle)

Digital Signature (by CA)

BSM ("I'm approaching...")

Digital Signature (by vehicle)



# V2V Authentication

Secure Protocol Data Unit (SPDU)

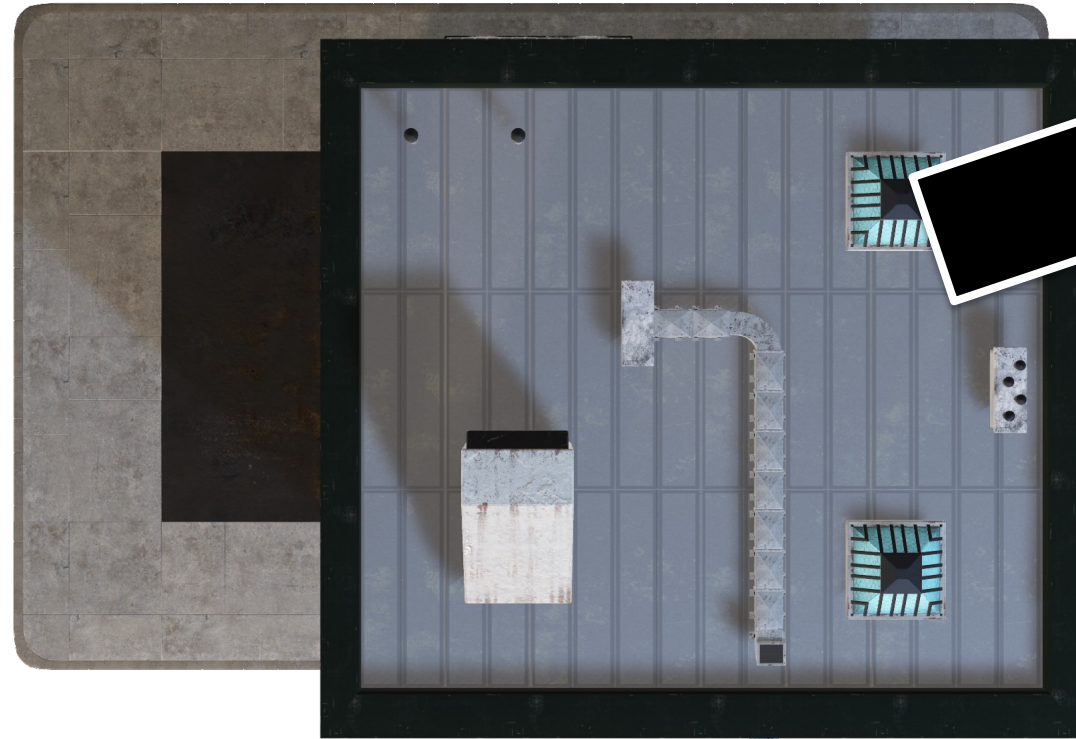
Digital Certificate

Public Key (of vehicle)

Digital Signature (by CA)

BSM ("I'm approaching...")

Digital Signature (by vehicle)



SPDU



# V2V Authentication

Secure Protocol Data Unit (SPDU)

Digital Certificate

Public Key (of vehicle)

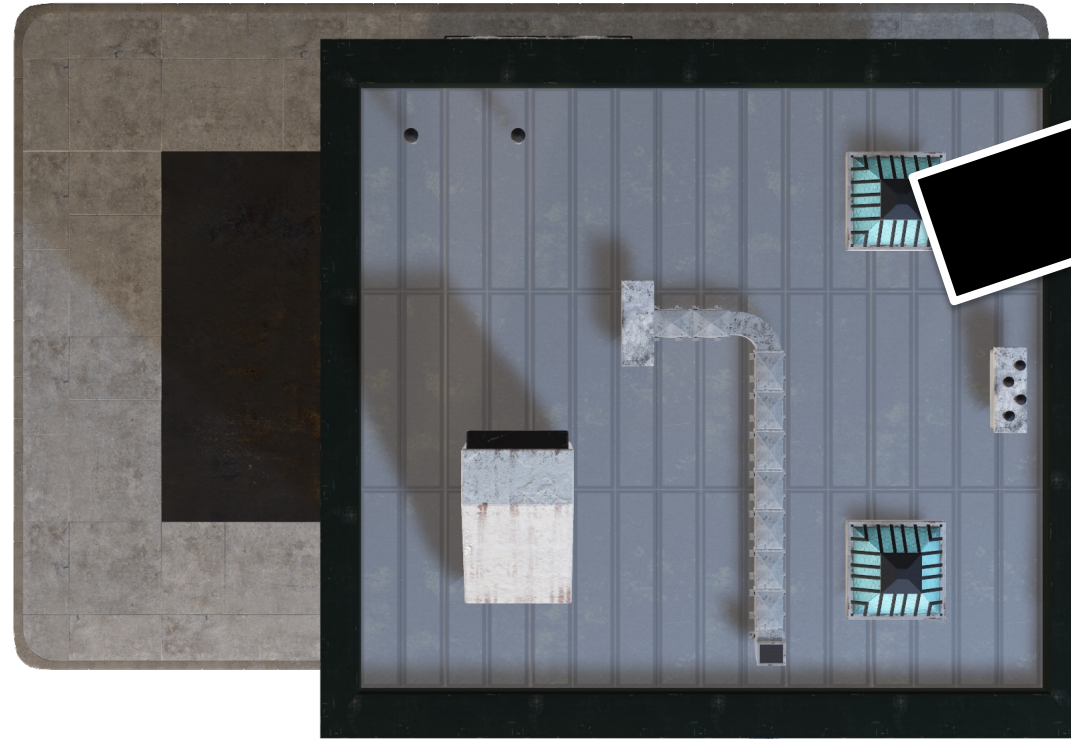
Digital Signature (by CA)

BSM ("I'm approaching...")

Digital Signature (by vehicle)

Certificate Valid?

SPDU



# V2V Authentication

Secure Protocol Data Unit (SPDU)

Digital Certificate

Public Key (of vehicle)

Digital Signature (by CA)

BSM ("I'm approaching...")

Digital Signature (by vehicle)

Certificate Valid?

Signature Valid?

SPDU



# V2V Authentication

Secure Protocol Data Unit (SPDU)

Digital Certificate

Public Key (of vehicle)

Digital Signature (by CA)

BSM ("I'm approaching...")

Digital Signature (by vehicle)

Certificate Valid?

Signature Valid?

Accept BSM ✓



# V2V Authentication

Secure Protocol Data Unit (SPDU)

Digital Certificate

Public Key (of vehicle)

Digital Signature (by CA)

BSM ("I'm approaching...")

Digital Signature (by vehicle)

Certificate Valid?

Signature Valid?

Accept BSM ✓



**Stop!**



# Quantum Computers (QCs) Threaten V2V

Digital signatures in V2V use [elliptic curves \(ECDSA\)](#)

# Quantum Computers (QCs) Threaten V2V

Digital signatures in V2V use **elliptic curves (ECDSA)**

QCs will break ECDSA → forge signatures, issue bogus certificates



# Quantum Computers (QCs) Threaten V2V

Digital signatures in V2V use **elliptic curves (ECDSA)**

QCs will break ECDSA → forge signatures, issue bogus certificates

**Good news:** NIST is standardizing post-quantum (PQ) algorithms

# Quantum Computers (QCs) Threaten V2V

Digital signatures in V2V use **elliptic curves (ECDSA)**

QCs will break ECDSA → forge signatures, issue bogus certificates

**Good news:** NIST is standardizing post-quantum (PQ) algorithms

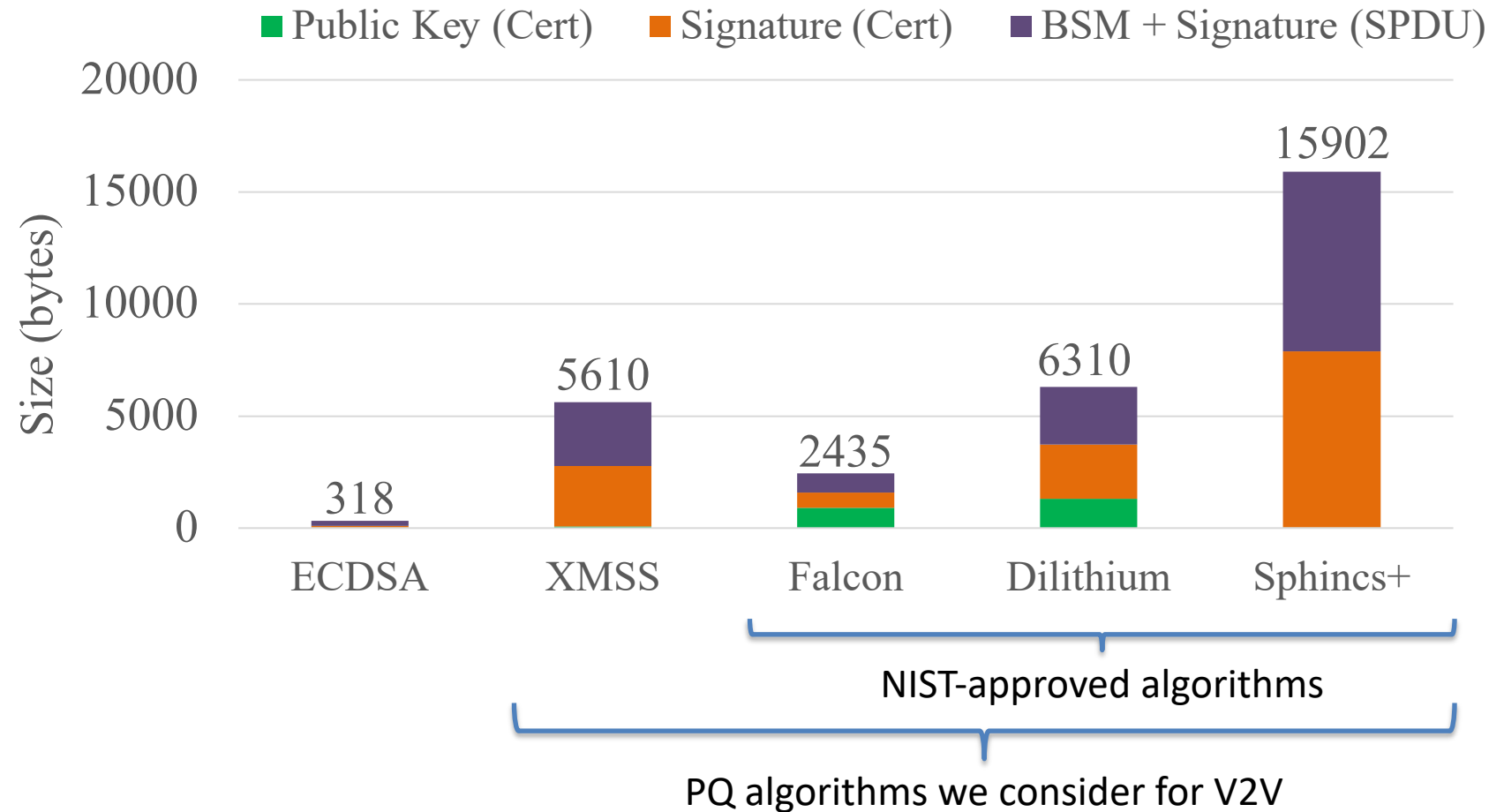
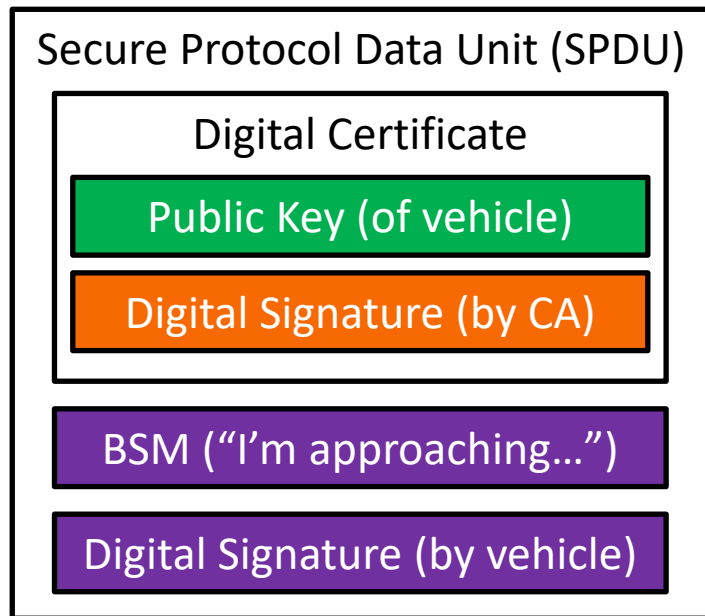
Problem: V2V protocols cannot easily adopt these PQ signatures

# Why Isn't PQ “Plug-and-Play” in V2V?

- ❑ PQ signatures and keys are **much larger** than ECDSA

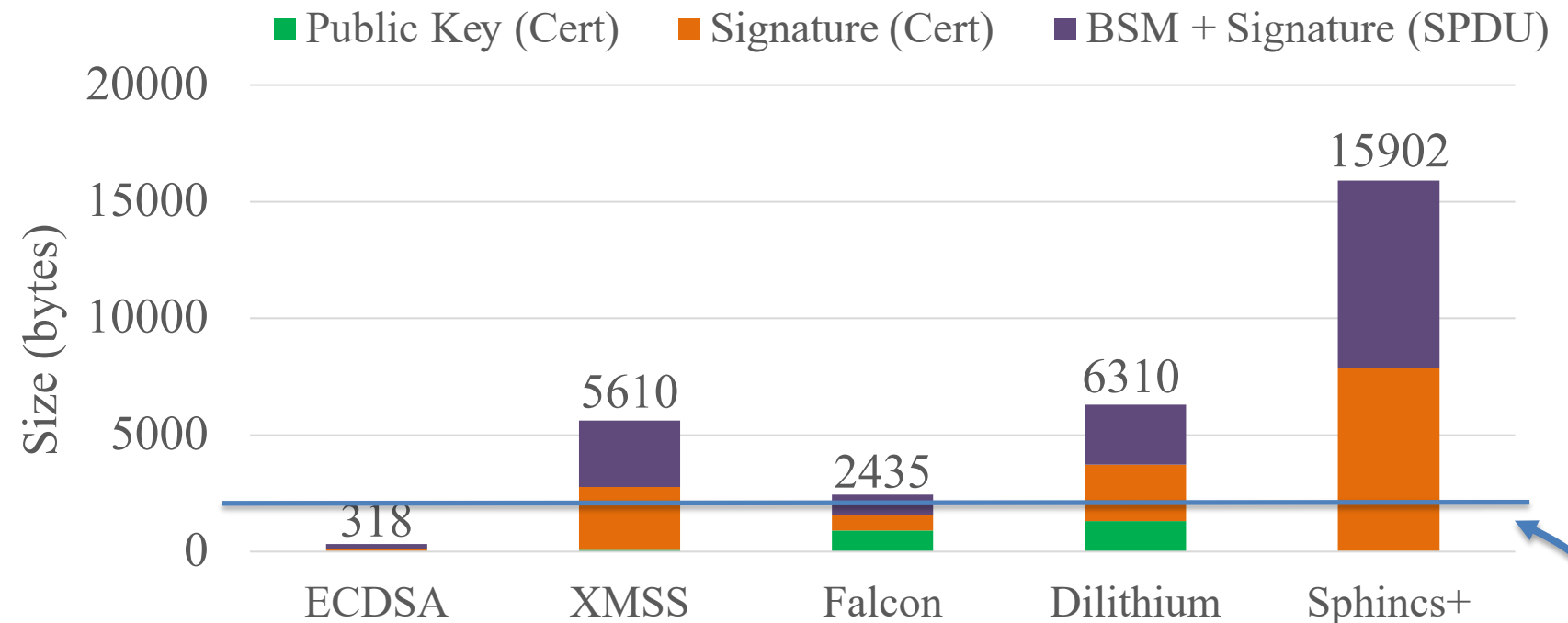
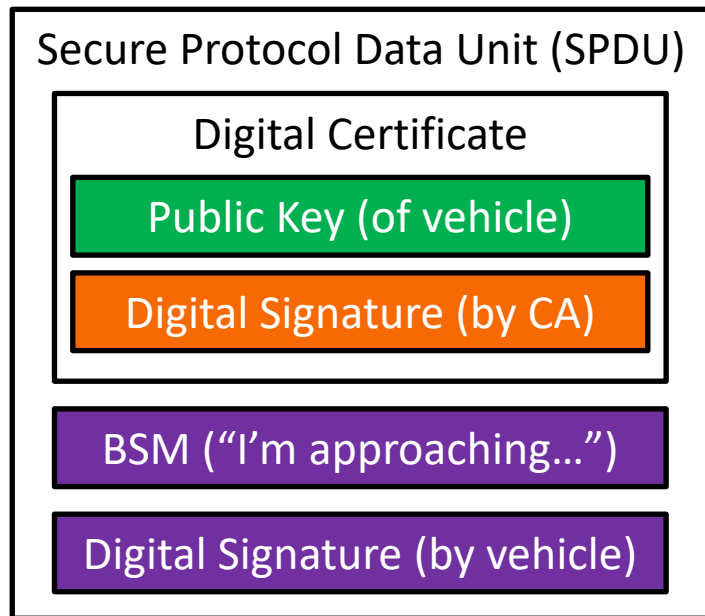
# Why Isn't PQ "Plug-and-Play" in V2V?

- ❑ PQ signatures and keys are **much larger** than ECDSA



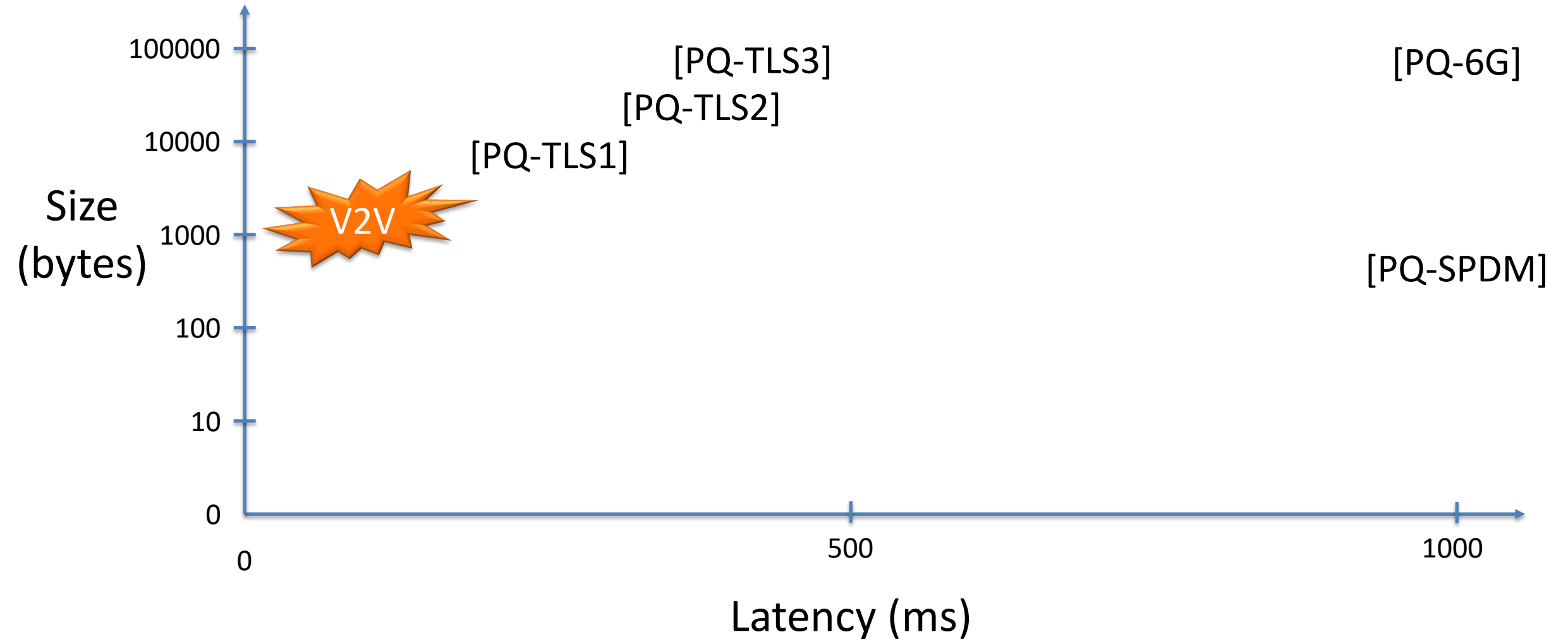
# Why Isn't PQ "Plug-and-Play" in V2V?

- ❑ PQ signatures and keys are **much larger** than ECDSA



- ❑ Dedicated Short-Range Communication (DSRC) → 2,304-byte limit

# V2V is (Uniquely) More Constrained



# Our Contributions

Analyze quantum threat  
&  
Identify V2V constraints for PQC

# Our Contributions

Hybrid (PQ/EC) Authentication Protocol  
&  
AI-based Transmission Optimization

Analyze quantum threat  
&  
Identify V2V constraints for PQC



# Our Contributions

Hybrid (PQ/EC) Authentication Protocol  
&  
AI-based Transmission Optimization

Security Reduction (Proofs)  
&  
Extensive Experiments

Analyze quantum threat  
&  
Identify V2V constraints for PQC

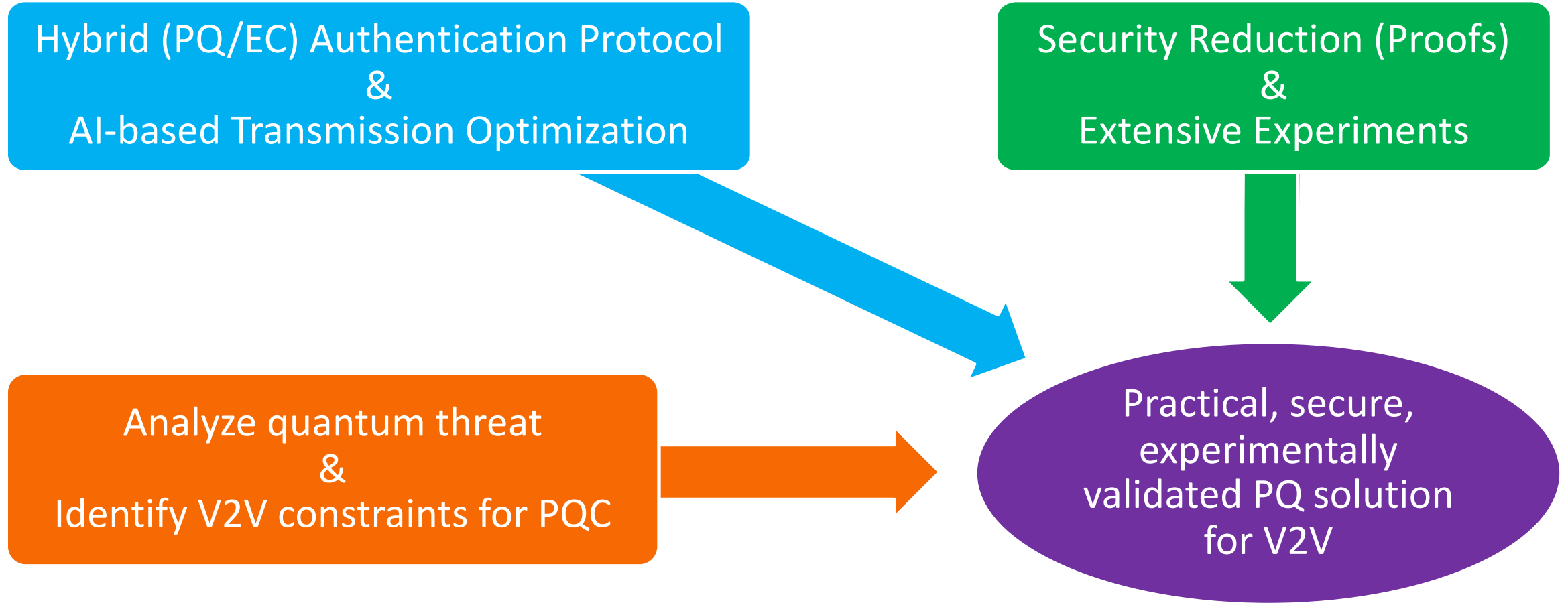
# Our Contributions

Hybrid (PQ/EC) Authentication Protocol  
&  
AI-based Transmission Optimization

Security Reduction (Proofs)  
&  
Extensive Experiments

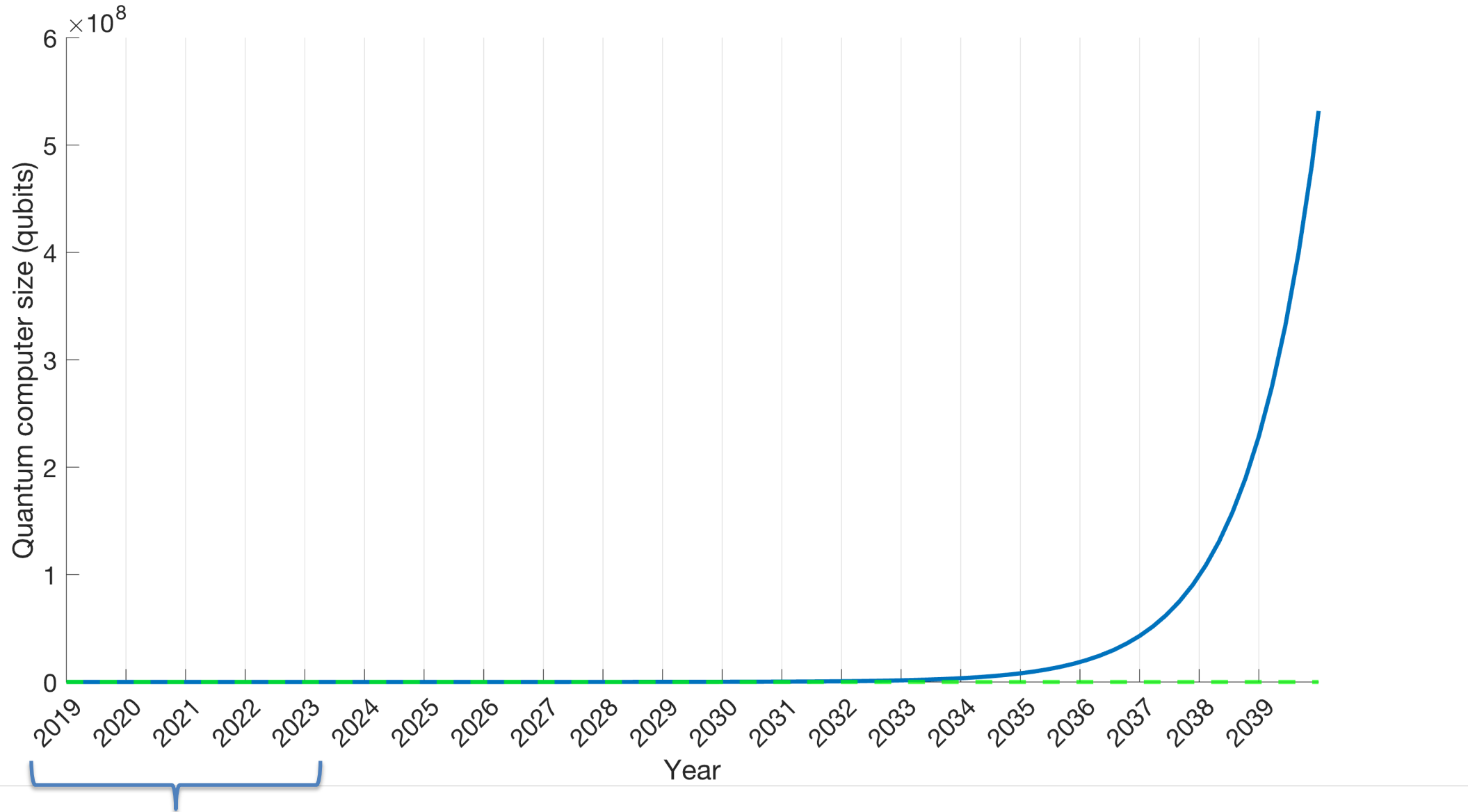
Analyze quantum threat  
&  
Identify V2V constraints for PQC

Practical, secure,  
experimentally  
validated PQ solution  
for V2V

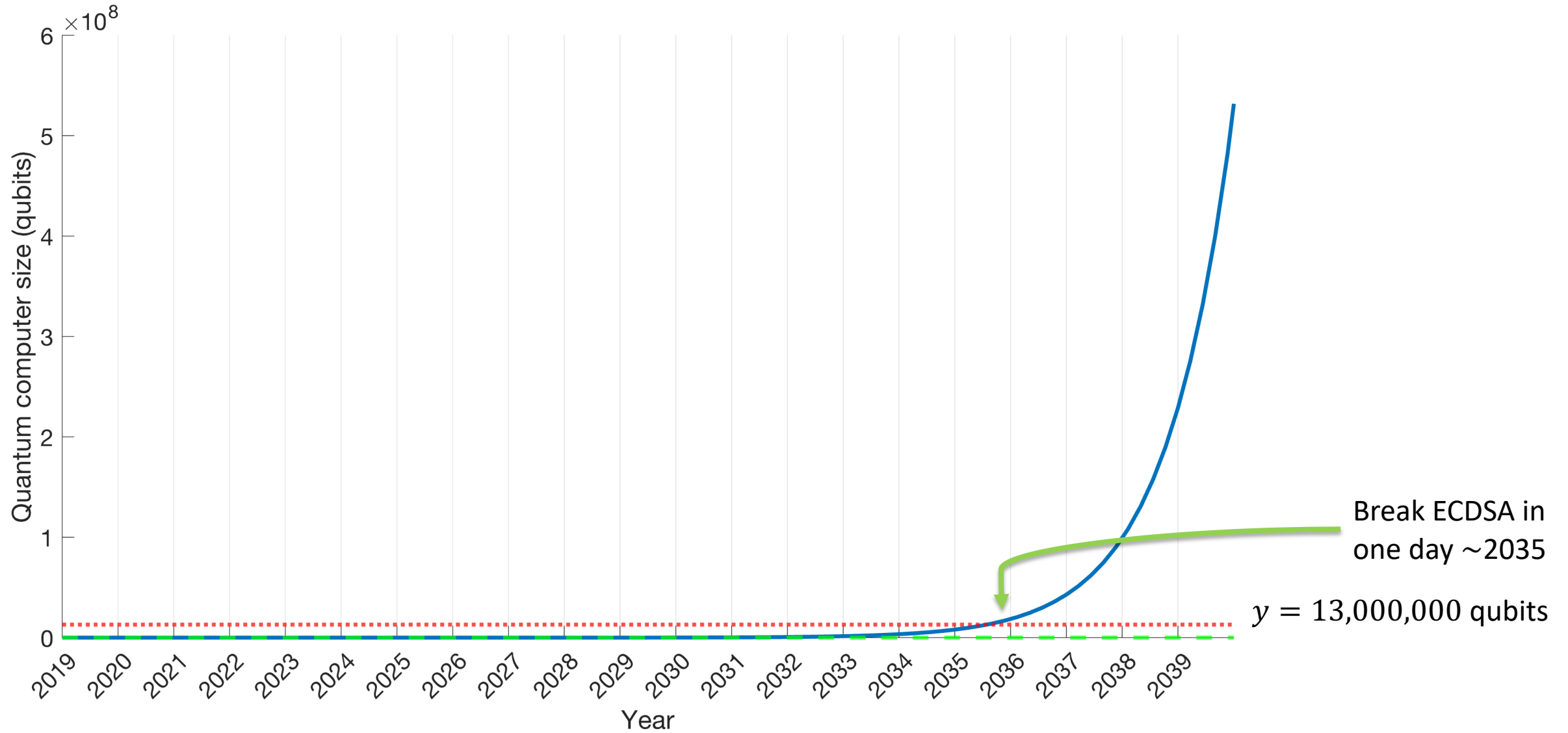


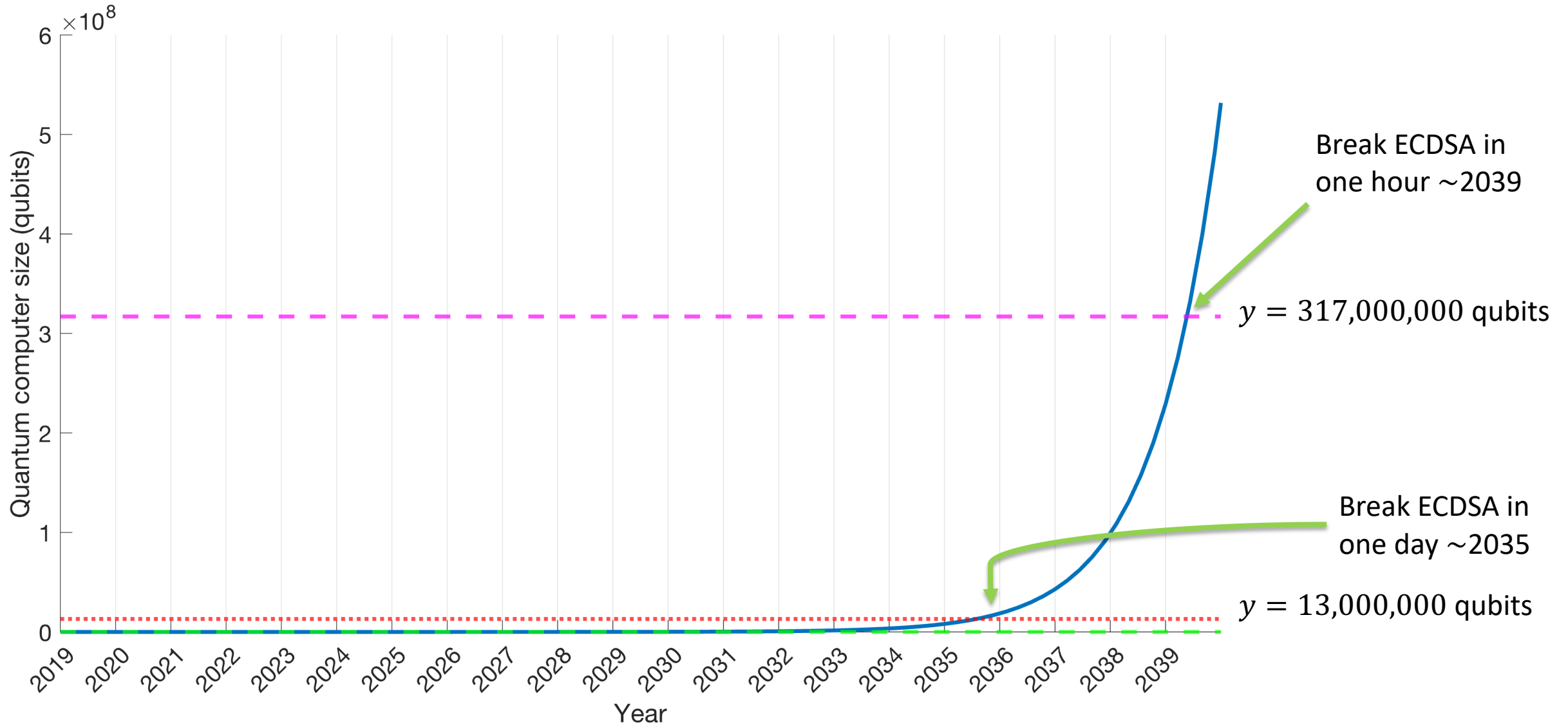
# How Much PQ Security Do We Need *Now*?

- ❑ Quantum computers (QCs) can't break much (yet)



Extrapolation from 2019-2023 IBM data and forecast





# So, why worry about this now?

Unlikely to have quantum threat before ~2035

# So, why worry about this now?

Unlikely to have quantum threat before ~2035

Average vehicle lifetime is 12-15 years



# So, why worry about this now?

Unlikely to have quantum threat before ~2035

Average vehicle lifetime is 12-15 years

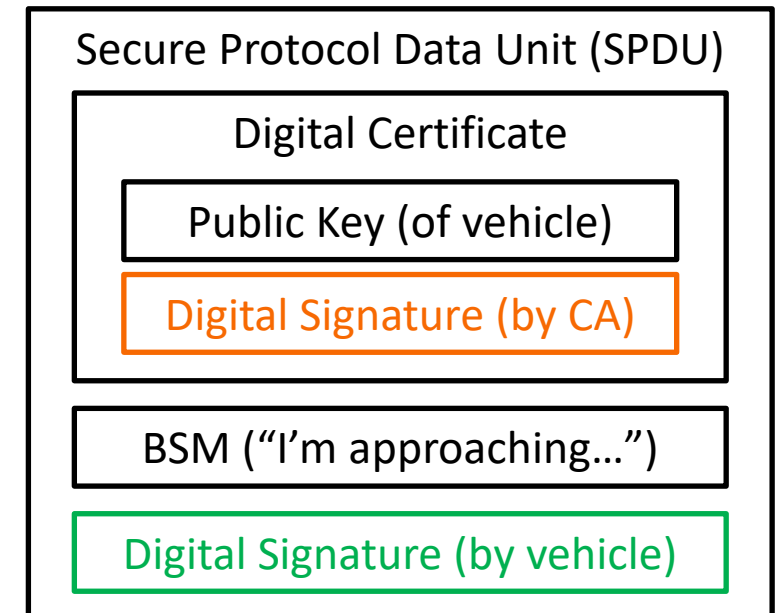
**Today's V2V wireless protocols and vehicle hardware need quantum resistance**

# How Much PQ Security Do We Need *Now*?

- ❑ Quantum computers (QCs) can't break much (yet)
- ❑ Two critical message elements have digital signatures:

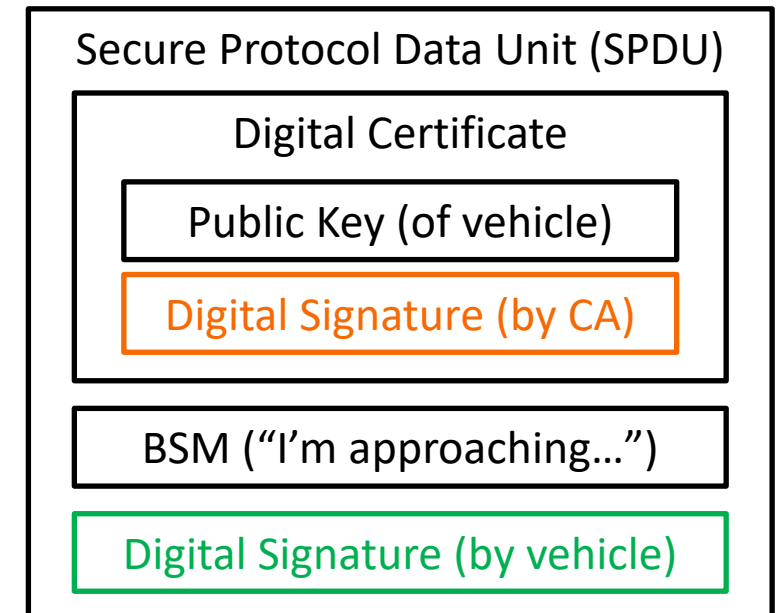
# How Much PQ Security Do We Need *Now*?

- ❑ Quantum computers (QCs) can't break much (yet)
- ❑ Two critical message elements have digital signatures:
  - **Payload (BSM) signature** valid for ~30 seconds
  - **Digital certificate signature** valid for 1 week



# How Much PQ Security Do We Need *Now*?

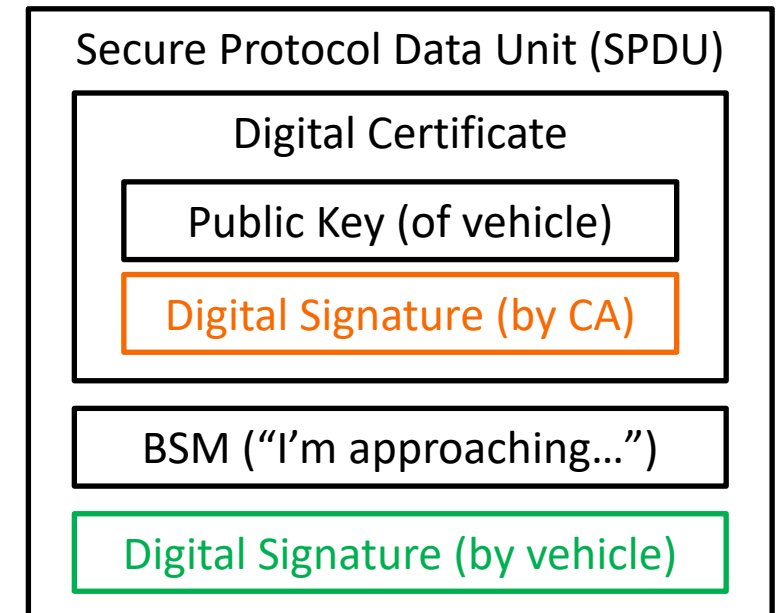
- ❑ Quantum computers (QCs) can't break much (yet)
- ❑ Two critical message elements have digital signatures:
  - Payload (BSM) signature valid for ~30 seconds
  - Digital certificate signature valid for 1 week
- ❑ Certificate forgery possible by 2035!



# How Much PQ Security Do We Need *Now*?

- ❑ Quantum computers (QCs) can't break much (yet)
- ❑ Two critical message elements have digital signatures:
  - **Payload (BSM) signature** valid for ~30 seconds
  - **Digital certificate signature** valid for 1 week
- ❑ Certificate forgery possible by 2035!

For the near future, focus on protecting **certificates** from quantum attacks in a **hybrid solution** for PQ V2V



# *Partially Hybrid* Authentication Protocol

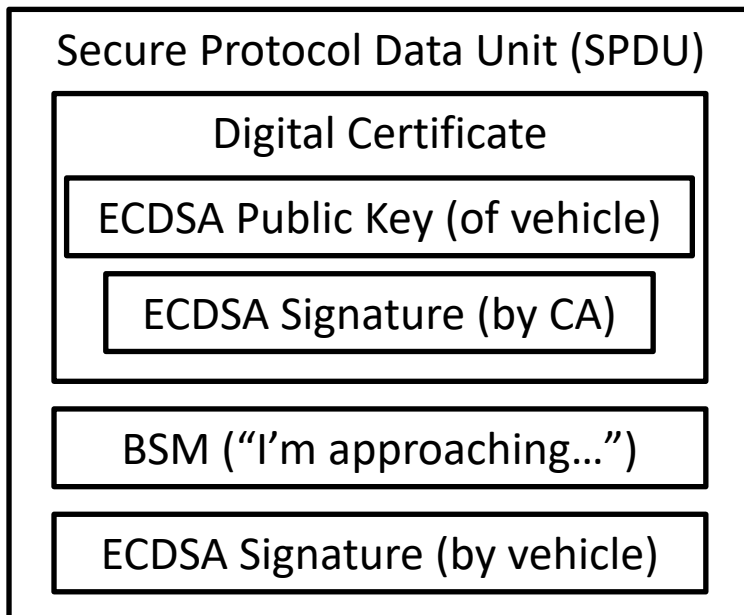
- ❑ PQC protects what is most imminently at risk: [certificates](#)

# *Partially Hybrid* Authentication Protocol

- ❑ PQC protects what is most imminently at risk: [certificates](#)
- ❑ Kickstart transition to PQ hardware and protocols

# *Partially Hybrid Authentication Protocol*

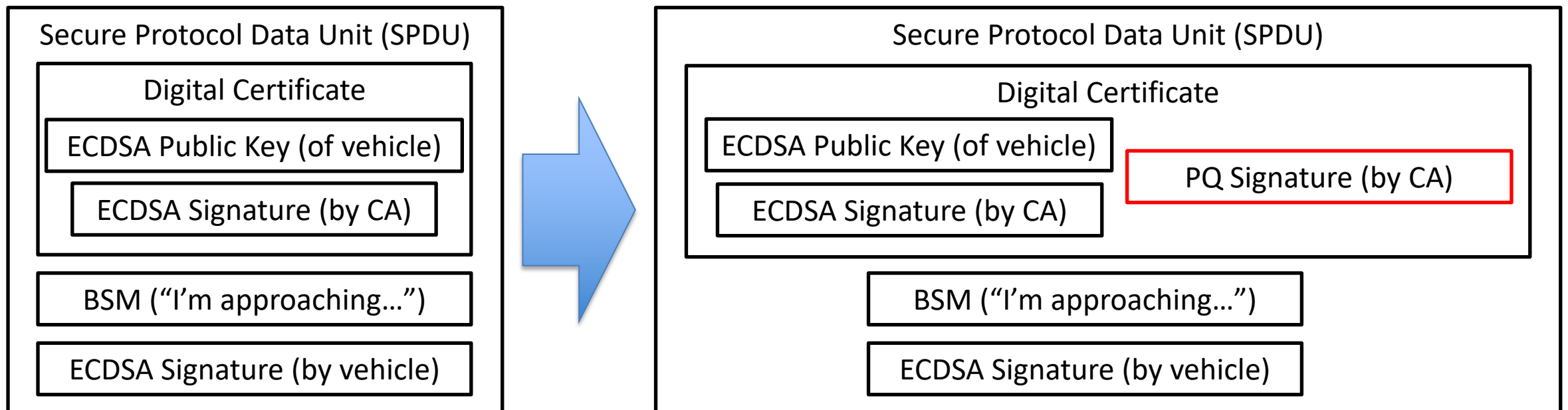
- ❑ PQC protects what is most imminently at risk: [certificates](#)
- ❑ Kickstart transition to PQ hardware and protocols





# *Partially Hybrid Authentication Protocol*

- ❑ PQC protects what is most imminently at risk: **certificates**
- ❑ Kickstart transition to PQ hardware and protocols
- ❑ Use PQ signature for certificate, keep EC signature for message



# For Every Message, (Not) a Certificate

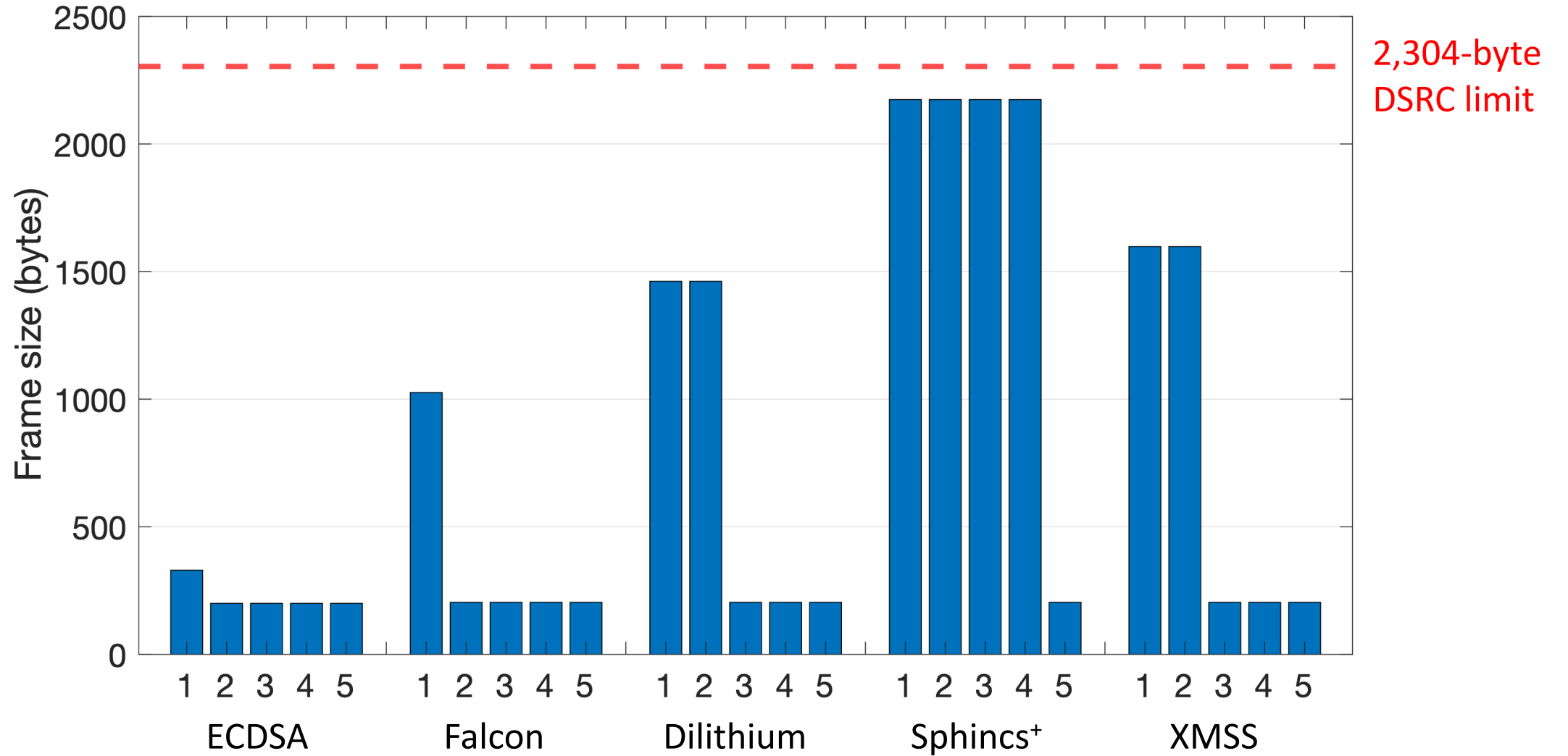
- ❑ Certificates are transmitted in every **fifth** SPDU
  - Certificate must be shared every 500ms

# For Every Message, (Not) a Certificate

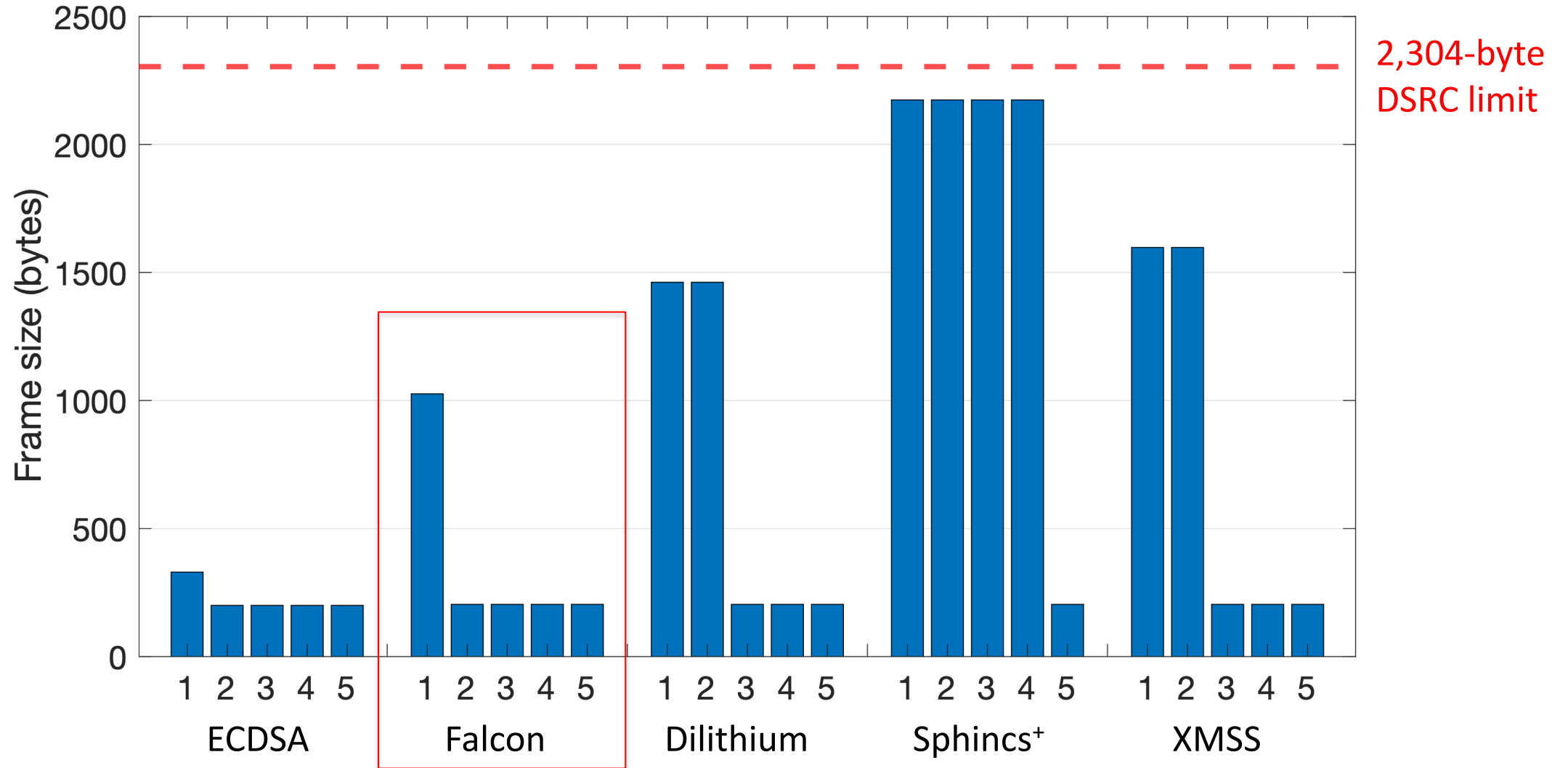
- ❑ Certificates are transmitted in every **fifth** SPDU
  - Certificate must be shared every 500ms
  
- ❑ Insight: **fragment** hybrid certificates across up to 5 SPDUs

# For Every Message, (Not) a Certificate

- ❑ Certificates are transmitted in every **fifth** SPDU
  - Certificate must be shared every 500ms
  
- ❑ Insight: **fragment** hybrid certificates across up to 5 SPDUs
  
- ❑ Goal: Minimize message size



5-SPDU certificate cycle for ECDSA and selected PQ algorithms



5-SPDU certificate cycle for ECDSA and selected PQ algorithms

# Larger Frames → Less Reliable

- ❑ Medium contention, hidden terminals in mobile network

# Larger Frames → Less Reliable

- ❑ Medium contention, hidden terminals in mobile network
- ❑ Frame Loss Rate (FLR):  $\frac{\# \text{ lost frames}}{\# \text{ total frames}}$  for entire system



# Larger Frames → Less Reliable

- ❑ Medium contention, hidden terminals in mobile network
- ❑ Frame Loss Rate (FLR):  $\frac{\# \text{ lost frames}}{\# \text{ total frames}}$  for entire system

Problem: In high-density scenarios (100 vehicles/km), **FLR is +63%** when ECDSA replaced with *Partially Hybrid* design (using Falcon)



Source: <https://bit.ly/3UPmBCG>

# Solution: Optimize Transmissions

- Insight:  $> 95\%$  of certificate transmissions are unnecessary!
  - Vehicles do not move very far in  $\sim 500$  ms

# Solution: Optimize Transmissions

- ❑ Insight:  $> 95\%$  of certificate transmissions are unnecessary!
  - Vehicles do not move very far in  $\sim 500$  ms
  
- ❑ Idea: send certificates **less frequently**, decrease spectrum waste

# Use AI to Optimize Transmissions

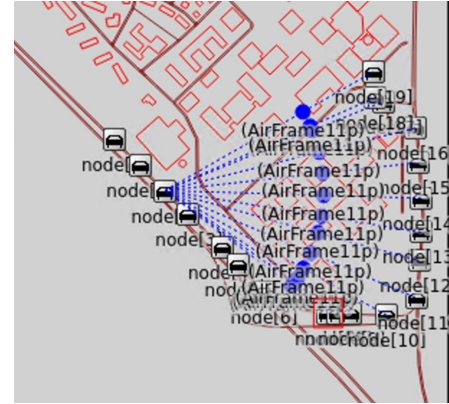
- ❑ Insight:  $> 95\%$  of certificate transmissions are unnecessary!
  - Vehicles do not move very far in  $\sim 500$  ms
  
- ❑ Idea: send certificates **less frequently**, decrease spectrum waste
  
- ❑ Use **distributed** AI to dynamically adjust certificate interval

# Use AI to Optimize Transmissions

- ❑ Insight:  $> 95\%$  of certificate transmissions are unnecessary!
  - Vehicles do not move very far in  $\sim 500$  ms
  
- ❑ Idea: send certificates **less frequently**, decrease spectrum waste
  
- ❑ Use **distributed** AI to dynamically adjust certificate interval
  
- ❑ Also optimize peer-to-peer certificate sharing protocol (P2PCD)

# Experiments

- Extensive simulations in VEINS
  - Custom PQ-V2V module

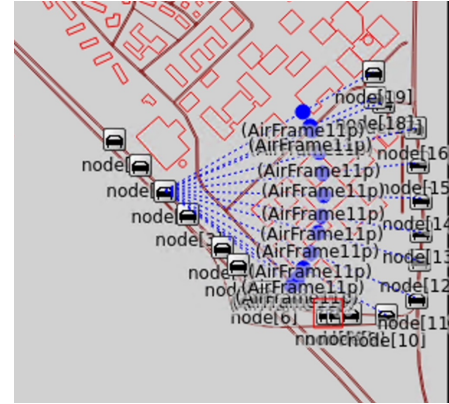


# Experiments

## ❑ Extensive simulations in VEINS

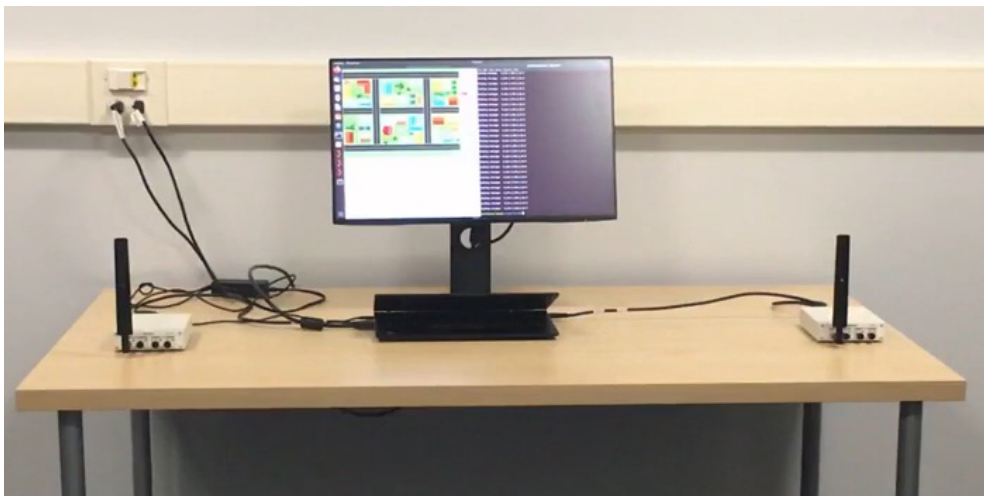
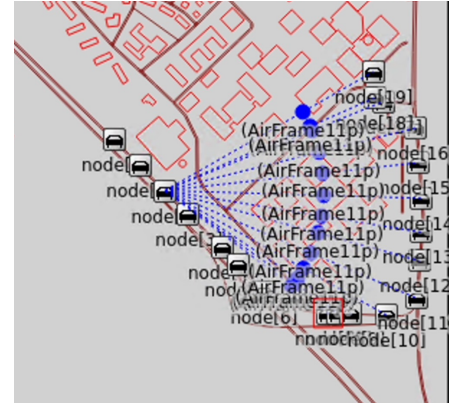
- Custom PQ-V2V module

## ❑ Benchmarking PQ algorithms on ARM-based V2V chipset



# Experiments

- ❑ Extensive simulations in VEINS
  - Custom PQ-V2V module
- ❑ Benchmarking PQ algorithms on ARM-based V2V chipset
- ❑ USRP experiments in the lab and **on real roadways**
  - New testbed: *PQ-V2Verifier*





# Experimental Results

- Combining hardware benchmarks, over-the-air measurements, and infusing data into VEINS simulations:

	Metric (vs. ECDSA)	Low-density (60 vehicles/km)	High-density (100 vehicles/km)
<i>Partially Hybrid</i>	Per-BSM delay	+0.66 ms	+0.67 ms
	$\Delta$ FLR	+29%	+61%

# Experimental Results

- Combining hardware benchmarks, over-the-air measurements, and infusing data into VEINS simulations:

	Metric (vs. ECDSA)	Low-density (60 vehicles/km)	High-density (100 vehicles/km)
<i>Partially Hybrid</i>	Per-BSM delay	+0.66 ms	+0.67 ms
	$\Delta$ FLR	+29%	+61%
<i>Partially Hybrid w/ Spectrum Optimization</i>	$\Delta$ FLR	+7.9%	+7.1%

# Conclusions

- ❑ Forecasted and assessed quantum risk to V2V

# Conclusions

- ❑ Forecasted and assessed quantum risk to V2V
- ❑ Developed **practical, hybrid** authentication protocol

# Conclusions

- ❑ Forecasted and assessed quantum risk to V2V
- ❑ Developed **practical, hybrid** authentication protocol
- ❑ Identified **Falcon** as best PQ algorithm for V2V

# Conclusions

- ❑ Forecasted and assessed quantum risk to V2V
- ❑ Developed **practical, hybrid** authentication protocol
- ❑ Identified **Falcon** as best PQ algorithm for V2V
- ❑ Applied AI to optimize spectrum, improve reliability

# Conclusions

- ❑ Forecasted and assessed quantum risk to V2V
- ❑ Developed **practical, hybrid** authentication protocol
- ❑ Identified **Falcon** as best PQ algorithm for V2V
- ❑ Applied AI to optimize spectrum, improve reliability
- ❑ Validated through simulations and **hardware experiments**

## Key Contributions

Forecast/assessment of quantum risk

**Hybrid authentication protocol**

Falcon is best PQ algorithm for V2V

AI to optimize spectrum, reliability

Simulations + hardware experiments

# Thank You! Questions?



← Our paper



← Artifacts



Geoff Twardokus  
[geoff.twardokus@mail.rit.edu](mailto:geoff.twardokus@mail.rit.edu)



Nina Bindel



Hanif Rahbari



Sarah McCarthy

