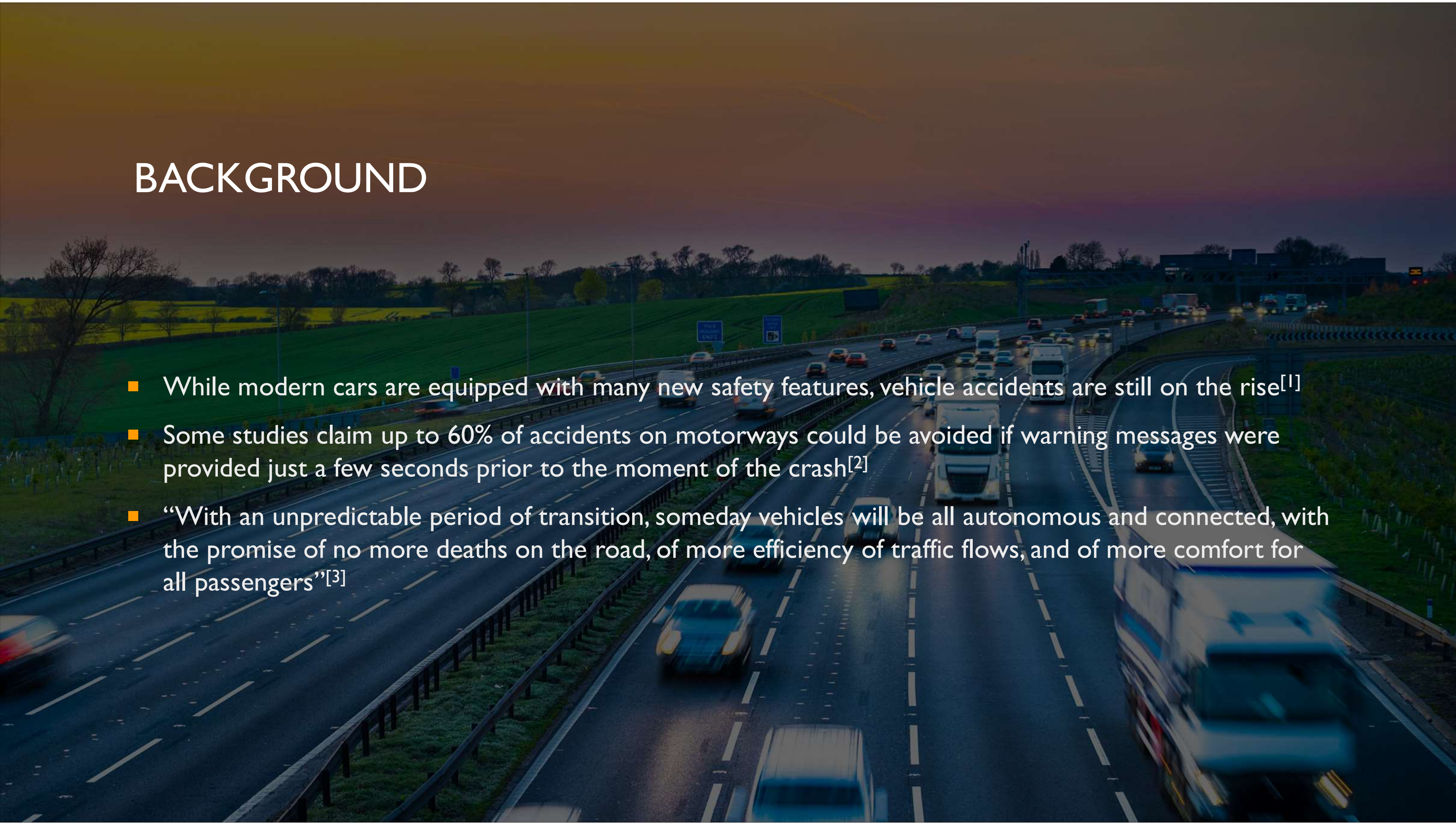
COMP ENG 5430: WIRELESS COMMUNICATIONS SEMESTER PROJECT

EXAMINATION OF VEHICULAR AD-HOC NETWORKS IN GNURADIO: 802.11P

IGOR POVARICH

12/06/2021



BACKGROUND

- While modern cars are equipped with many new safety features, vehicle accidents are still on the rise[1]
- Some studies claim up to 60% of accidents on motorways could be avoided if warning messages were provided just a few seconds prior to the moment of the crash[2]
- "With an unpredictable period of transition, someday vehicles will be all autonomous and connected, with the promise of no more deaths on the road, of more efficiency of traffic flows, and of more comfort for all passengers"[3]

VEHICULAR AD-HOC NETWORKS

- In recent years, significant interest has been directed toward the implementation of an ITS (Intelligent Transportation System) as a means of:
  - Increasing road safety
  - Enabling the implementation of autonomous vehicles
  - Increasing user convenience
- VANET (Vehicular Ad-Hoc network) topologies have received much attention as a potential solution
  - A subset of MANET (Mobile Ad-Hoc network) topology
  - Traditional networks such as TCP/IP are not suitable due to high overhead or slow initial connection
- A communication standard was approved in 2010 to facilitate this development
  - Initially allocated specifically for safety vehicles back in 1999
  - Often called WAVE or 802.11p – operates a 75MHz bandwidth at 5.85 to 5.925 GHz[5]
- Two main types of communication
  - V2V (Vehicle-to-Vehicle) – communication between any vehicles
  - V2I (Vehicle-to-Infrastructure) – communication between vehicles and RSU's (Road-side Units)

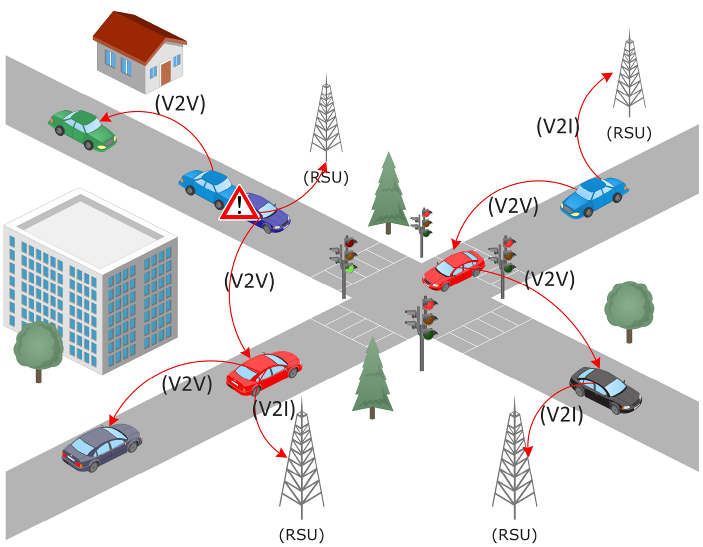


Figure 2 VANET Communication Architecture
Shah, Syed Sarmad, et al (2019) [11]

IEEE 802.11P / WAVE / DSRC

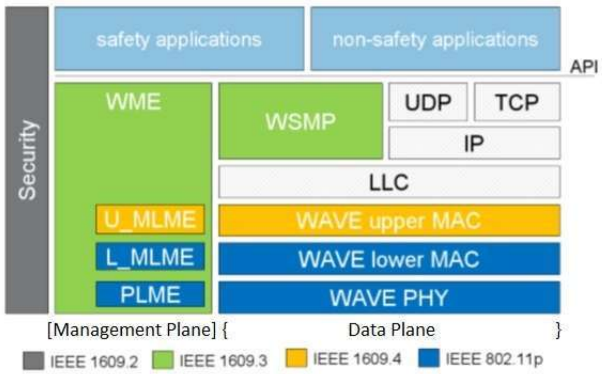
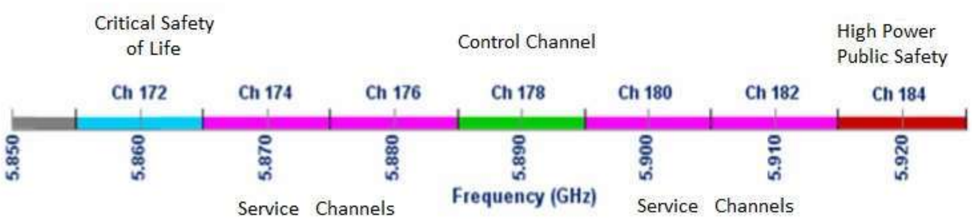


Figure 3 802.11p DSRC/WAVE Protocol Stack[4]

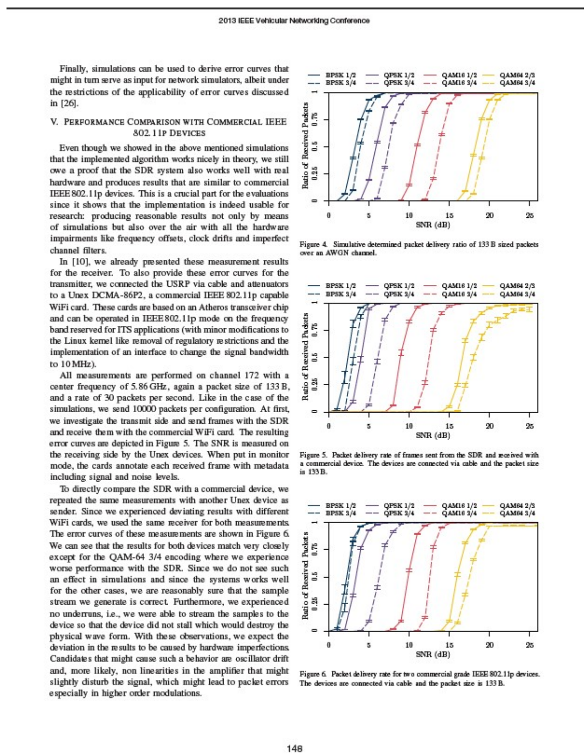


802.11p WAVE frequency spectrum[4]

- IEEE 802.11p is also known by the names Wireless Access for Vehicular Environments (WAVE) or Dedicated Short Range Communication (DSRC)
- FCC allocated spectrum of 75MHz bandwidth from 5850 to 5925 MHz for V2V and V2I communication
- IEEE 802.11p covers the MAC and PHY layers while IEEE 1609 covers the upper layers[12]
- Based on 802.11a standards to allow reuse of similar chips
  - Same modulation schemes such as BPSK, QPSK, 16QAM, 64QAM
  - Same number of data carriers (52/symbol)
- Differences from 802.11a highlighted[4]
  - Bandwidth of 10MHz instead of 20MHz
  - Supports half the number of bit rates
  - Double symbol duration ($8\mu s$ vs $4\mu s$) and guard time interval ($1.6\mu s$ vs $0.8\mu s$)
  - Can work without having to join a Basic Service Set (BSS)
  - CSMA but with no exponential backoff to reduce latencies

PREVIOUS RESEARCH AND GOALS

- Inspiration for the project was based on a series of papers by Bloessel, et al. [2] about 802.11p
- Demonstrated the ability of a simulated Transceiver in GNURadio to accurately simulate the performance of prototype hardware 802.11p transceiver
- The goal of this semester project was to re-use this structure to simulate and observe the performance of 802.11p in GNURadio



2013 IEEE Vehicular Networking Conference

Finally, simulations can be used to derive error curves that might in turn serve as input for network simulators, albeit under the restrictions of the applicability of error curves discussed in [26].

V. PERFORMANCE COMPARISON WITH COMMERCIAL IEEE 802.11P DEVICES

Even though we showed in the above mentioned simulations that the implemented algorithm works nicely in theory, we still owe a proof that the SDR system also works well with real hardware and produces results that are similar to commercial IEEE 802.11p devices. This is a crucial part for the evaluations since it shows that the implementation is indeed usable for research: producing reasonable results not only by means of simulations but also over the air with all the hardware impairments like frequency offsets, clock drifts and imperfect channel filters.

In [10], we already presented these measurement results for the receiver. To also provide these error curves for the transmitter, we connected the USRP via cable and attenuators to a Unex DCMA-86P2, a commercial IEEE 802.11p capable WiFi card. These cards are based on an Atheros transceiver chip and can be operated in IEEE 802.11p mode on the frequency band reserved for ITS applications (with minor modifications to the Linux kernel like removal of regulatory restrictions and the implementation of an interface to change the signal bandwidth to 10 MHz).

All measurements are performed on channel 172 with a center frequency of 5.86 GHz, again a packet size of 133 B, and a rate of 30 packets per second. Like in the case of the simulations, we send 10000 packets per configuration. At first, we investigate the transmit side and send frames with the SDR and receive them with the commercial WiFi card. The resulting error curves are depicted in Figure 5. The SNR is measured on the receiving side by the Unex devices. When put in monitor mode, the cards annotate each received frame with metadata including signal and noise levels.

To directly compare the SDR with a commercial device, we repeated the same measurements with another Unex device as sender. Since we experienced deviating results with different WiFi cards, we used the same receiver for both measurements. The error curves of these measurements are shown in Figure 6. We can see that the results for both devices match very closely except for the QAM-64 3/4 encoding where we experience worse performance with the SDR. Since we do not see such an effect in simulations and since the systems works well for the other cases, we are reasonably sure that the sample stream we generate is correct. Furthermore, we experienced no underruns, i.e., we were able to stream the samples to the device so that the device did not stall which would destroy the physical wave form. With these observations, we expect the deviation in the results to be caused by hardware imperfections. Candidates that might cause such a behavior are oscillator drift and, more likely, non linearities in the amplifier that might slightly disturb the signal, which might lead to packet errors especially in higher order modulations.

BPSK 1/2, BPSK 3/4, QPSK 1/2, QPSK 3/4, QAM16 1/2, QAM16 3/4, QAM64 2/3, QAM64 3/4

Ratio of Received Packets

SNR (dB)

Figure 4. Simulative determined packet delivery ratio of 133 B sized packets over an AWGN channel.

Figure 5. Packet delivery rate of frames sent from the SDR and received with a commercial device. The devices are connected via cable and the packet size is 133 B.

Figure 6. Packet delivery rate for two commercial grade IEEE 802.11p devices. The devices are connected via cable and the packet size is 133 B.

148

Figure 5: Hardware and simulated packet delivery ratio of 133B-sized packets
Bloessel, et al (2013) [2]

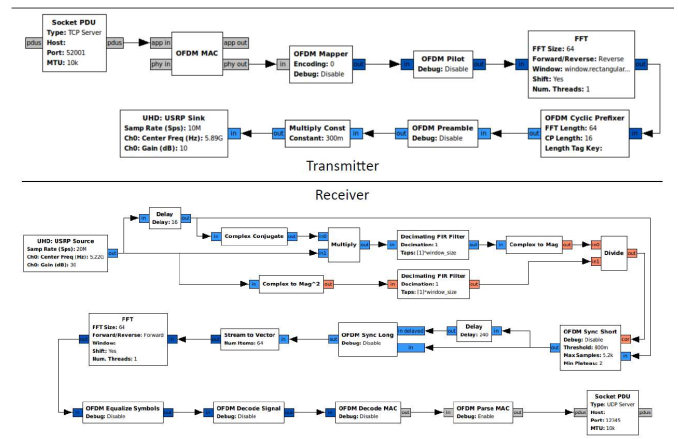


Figure 6: Overview of transceiver structure in GNURadio Companion
Bloessel, et al (2013) [2]

BUILDING THE WIFI BLOCKS IN GNURADIO

Several Github repos related to the papers were available at [7] and [8], partially supported by the open-source community and the authors of the previous studies

- Forked the main repo and built the OOT modules to simulate the PHY and MAC layers
- Heirarchical block was used for PHY layer, an OOT block for the MAC and some other supporting blocks
  - PHY block implemented the OFDM architecture (cyclic prefixers, stream management, etc.)
- Getting the blocks to build blocks was challenging – lots of issues with missing dependencies that had to be fixed plus issues with GNURadio 3.8 vs. 3.9

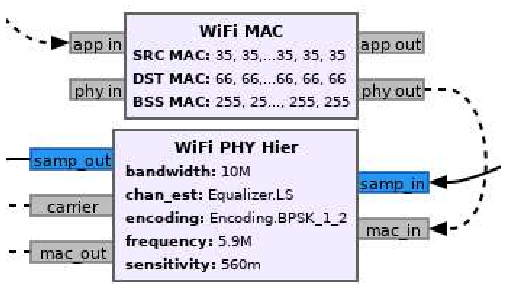


Figure 7: WiFi PHY and MAC blocks

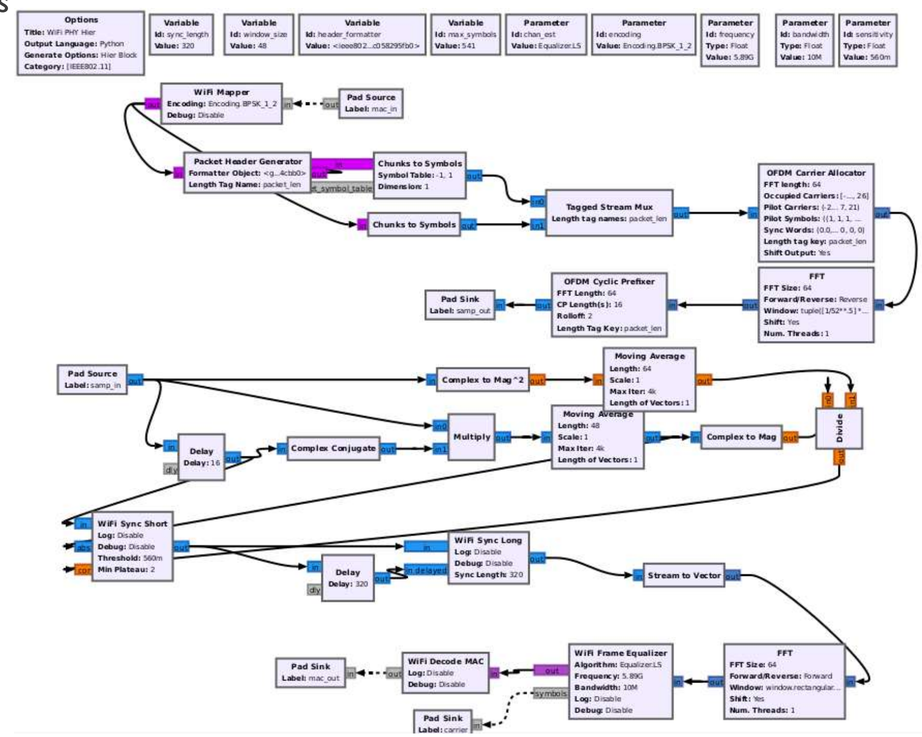


Figure 8: WiFi PHY Hier Block Architecture

SIMULATE CHANNEL WITH AWGN

- To ensure the system was behaving correctly, the first step was to re-create the simulated results of [2], and some templates were available
  - The simulations were performed using a headless (no GUI) GRC file outputting to a .pcap through a Wireshark connecter and executed using GRCC
  - It was orchestrated by an iterative Makefile compile script, afterwards parsed by a shell script into a .csv file, then plotted using python
  - The simulation used the Signal-to-Noise ratio and modulation as dependent variables
  - Each set of simulations was re-run 10 times and aggregated to smooth out stochastic effects
- In the GRC file, the SNR plus the channel model were fed back into the Wifi PHY block
  - The channel model consisted of Additive White Gaussian Noise with a noise voltage of 1.0

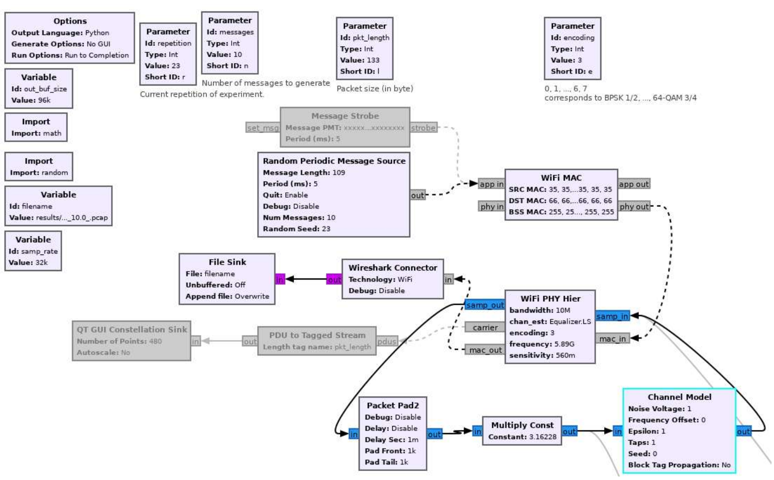


Figure 9: Headless GRC file for simulation

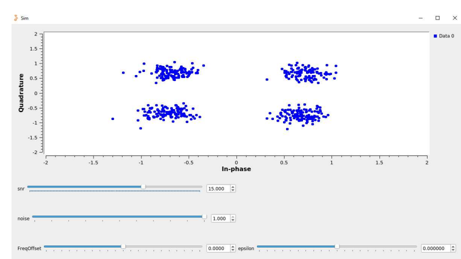


Figure 10: Constellation plot with QPSK

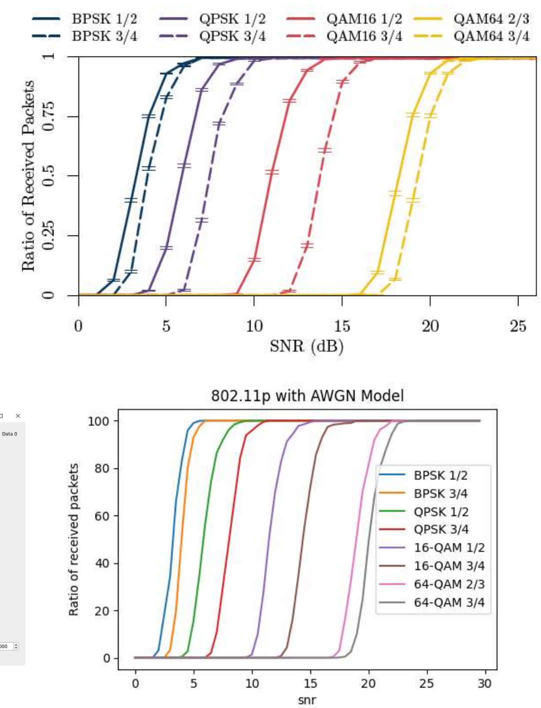


Figure 11,12: Comparison of wifi simulations

SIMULATE CHANNEL WITH VARIOUS CHANNEL MODELS

- Experimented with different channel models and varied loss parameters
  - Simulation A
    - Noise Voltage: 0.2
    - Frequency Offset: 0.01
    - Multipath Delay Profile: 0.5+0.5j
    - Sample Timing Offset: 0.00005
  - Added other sources of noise but reduced the noise voltage

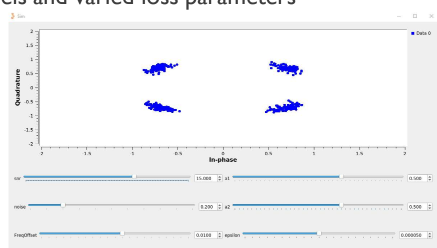


Figure 13: Simulation A constellation plot with QPSK

- Simulation B
  - Noise Voltage: 0.2
  - Frequency Offset: 0.02
  - Multipath Delay Profile: -0.5-0.5j
  - Sample Timing Offset: 0.0002
- Other sources high enough that signal was barley unreadable

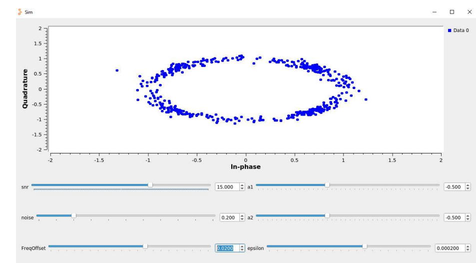


Figure 14: Simulation B constellation plot with QPSK

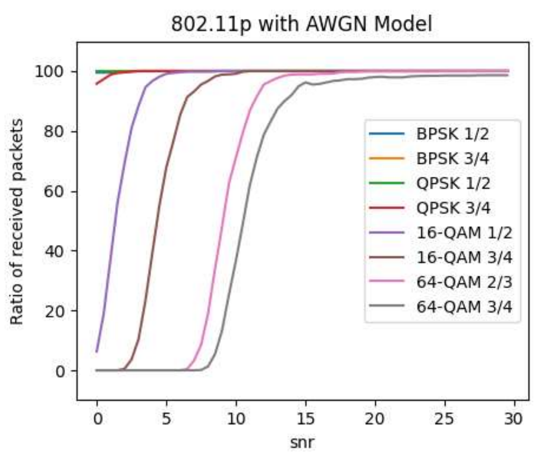


Figure 15: Simulation A results

Channel noise appears to be biggest driver of missed packets, up until the point where freq/timing offsets make the signal unreadable

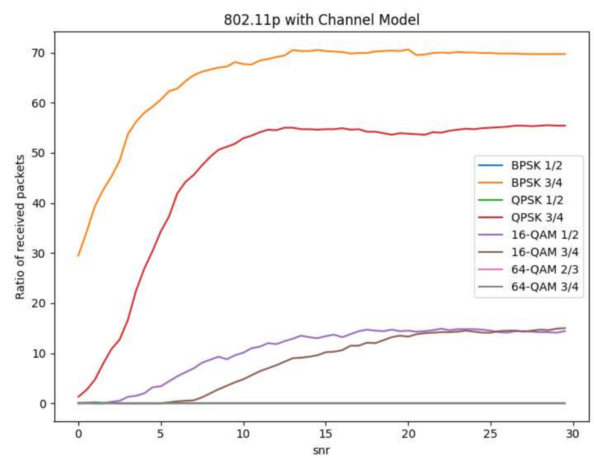


Figure 16: Simulation B results

CHALLENGES IN IMPLEMENTATION

- The 802.11p standard has been around for a long time – why hasn't it or some similar standard been implemented in modern vehicles?
  - DSRC [802.11p] has been extensively studied and it has been shown to be satisfactory for most vehicular safety applications that require end-to-end latency to be around 100msec and the density of vehicles is moderate
  - Performance rapidly deteriorates when vehicle density exceeds a certain limit, due to packet collisions due to simultaneous transmissions and due to hidden nodes[7]
- Another standard that was developed around 2016-2018 by 3GPP for cellular networks, aimed at the same purpose, also called Sidelink Cellular-V2X (C-V2X)
  - Sidelink Mode 4 is for communication to nodes that may not have access to a satellite uplink/downlink (i.e. sidelink)
    - Can reserve resources anonymously by means of a resource reservation algorithm
  - Performance has been shown to be better than 802.11p in terms of a higher link budget and more efficient utilization of the spectrum
  - But performance of C-V2X also falls off rapidly when traffic density increases, especially in Sidelink Mode 4[7]

GOING FORWARD

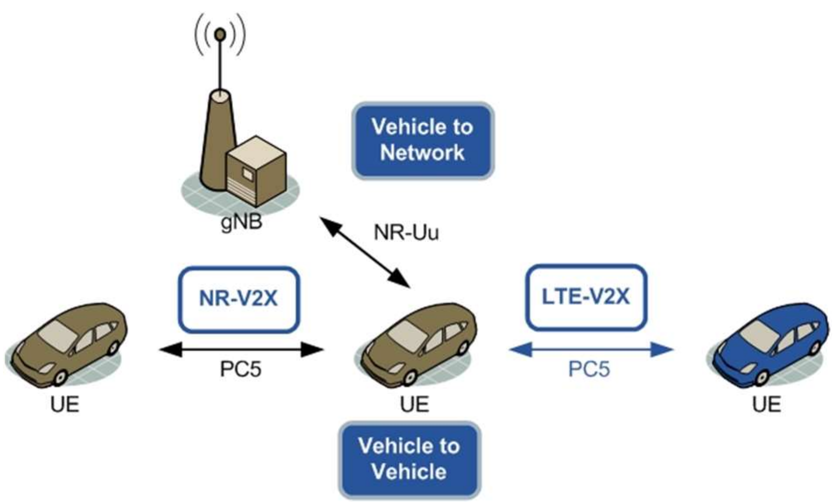


Figure 17: Simulation B results

- Both standards are capable of supporting a basic set of vehicular safety applications based on issuing driver-alerts to indicate potentially dangerous situations (i.e. day-1 applications), however neither standard is capable of scaling to applications such as autonomous vehicles in its current state which have much more stringent QoS requirements[8][9]
- Both standards are currently being revised or improved upon and it remains to be seen which one will proliferate
  - For 802.11p, that is the amendment 802.11bd (also called NR-V2X), which currently has a working group, with the goal of investigating more advanced PHY technologies to amend the downfalls of the current standard – this will be backwards compatible with older 802.11P
  - 3GPP decided to leave C-2VX as the only core of basic safety communications and will build the NR-C2X on top of 5G-NR
    - Not backwards compatible but adds an optional second interface with improved performance on other channels

REFERENCES

1. C. D. Wang and J. P. Thompson, "Apparatus and method for motion detection and tracking of objects in a region for collision avoidance utilizing a real-time adaptive probabilistic neural network," US5613039A, Mar. 18, 1997 Accessed: Oct. 04, 2021. [Online]. Available: https://patents.google.com/patent/US5613039A/en
2. B. Bloessl, M. Segata, C. Sommer, and F. Dressler, "Towards an Open Source IEEE 802.11p stack: A full SDR-based transceiver in GNU Radio," in *2013 IEEE Vehicular Networking Conference*, Boston, MA, USA, Dec. 2013, pp. 143–149. doi: 10.1109/VNC.2013.6737601.
3. A. Bazzi *et al.*, "Survey and Perspectives of Vehicular Wi-Fi versus Sidelink Cellular-V2X in the 5G Era," *Future Internet*, vol. 11, no. 6, p. 122, 2019, doi: http://dx.doi.org/10.3390/fi11060122.
4. "IEEE 802.11p tutorial-802.11p, WAVE, DSRC protocol stack." https://www.rfwireless-world.com/Tutorials/802-11p-WAVE-tutorial.html (accessed Dec. 05, 2021).
5. E. C. Eze, S. Zhang, and E. Liu, "Vehicular ad hoc networks (VANETs): Current state, challenges, potentials and way forward," in *2014 20th International Conference on Automation and Computing*, Cranfield, Bedfordshire, United Kingdom, Sep. 2014, pp. 176–181. doi: 10.1109/IConAC.2014.6935482.
6. Shah, Syed Sarmad, Asad Malik, Anis Ur Rahman, Sohail Iqbal, and Samee Khan. "Time Barrier-Based Emergency Message Dissemination in Vehicular Ad-Hoc Networks." *IEEE Access* PP (January 31, 2019): 1–1. https://doi.org/10.1109/ACCESS.2019.2895114.
7. https://www.wime-project.net/
8. https://github.com/bastibl/gr-ieee802-11
9. G. Naik, B. Choudhury, Jung-Min, and Park, "IEEE 802.11bd & 5G NR V2X: Evolution of Radio Access Technologies for V2X Communications," *arXiv:1903.08391 [cs, math]*, Mar. 2019, Accessed: Dec. 04, 2021. [Online]. Available: http://arxiv.org/abs/1903.08391
10. K. Hafeez, L. Zhao, B. Ma, and J. Mark, "Performance Analysis and Enhancement of the DSRC for VANET's Safety Applications," *Vehicular Technology, IEEE Transactions on*, vol. 62, pp. 3069–3083, Sep. 2013, doi: 10.1109/TVT.2013.2251374.
11. R. Molina-Masegosa and J. Gozálvez, "LTE-V for Sidelink 5G V2X Vehicular Communications: A New 5G Technology for Short-Range Vehicle-to-Everything Communications," *IEEE Vehicular Technology Magazine*, 2017, doi: 10.1109/MVT.2017.2752798.
12. IEEE Standard for Wireless Access in Vehicular Environments (WAVE) – Multi-Channel Operation, IEEE Standard 1609, Mar. 2016, pp. 1-94.
13. "Highlighting the delivery and operation modes of 5G V2X," *Mpirical*, Sep. 13, 2019. https://website.localhost.com/blog/5g-v2x-and-autonomous-vehicles (accessed Dec. 05, 2021).

APPENDIX

IMPROVEMENTS OF 802.11P AND C-V2X

- 802.11bd proposed improvements over 802.11p
  - OFDM numerology re-design: definition of new optimized tone spacing and guard interval
  - duration to better cope with 5.9 GHz frequencies and high-speed mobility;
  - LDPC codes to improve coding effectiveness;
  - MIMO diversity through STBC codes or cyclic shift diversity (CSD);
  - Addition of midambles (control sequences in the middle of the packet) to improve Doppler recovery;
  - Dual carrier modulation (DCM) and 20 MHz channels.
- 5G-V2X modifications designed to enhance PC5 interface
  - Carrier aggregation with support of up to eight bands;
  - Use of frequencies above 6 GHz;
  - Flexible numerology, with the possibility of subcarrier spacing of 30 kHz and 60 kHz at 5.9 GHz;
  - Higher order of MCSs, also including 64-QAM;
  - Possibility to transmit over single slots and even portions of slots;
  - Addition of a sidelink feedback channel to allow higher reliability and lower latency;
  - LDPC and polar codes designed to offer higher robustness without increasing encoding and decoding complexity;
  - Use of MIMO receiving antennas to enable spatial diversity especially useful to mitigate multipath
  - in urban scenarios;

802.11P AND C-V2X TIMELINE

Table 1. Chronology of the main facts in the US and Europe.

1999	Frequencies are allocated in the US	General
2004	IEEE 802.11p Task Group is formed	IEEE 802.11p
2008	Frequencies are allocated in Europe	General
2010	IEEE 802.11p is approved	IEEE 802.11p
2012	The Ann Arbor experiment starts with thousands of devices	IEEE 802.11p
2016, October	The first part of 3GPP Release 14 is published	C-V2X
2016, November	The Livorno Plug test: ITS-G5 is declared ready	IEEE 802.11p
2016, November	The European Commission publishes the "Strategy"	General
2017, January	The proposed rule is issued in the US to mandate short-range	General
2017, March	3GPP Release 14 is frozen	C-V2X
2018, May	IEEE 802.11 Next Generation V2X is announced (IEEE 802.11bd)	IEEE 802.11p
2019, March	3GPP Release 15 is frozen	C-V2X