Final Report for Project #274:

Cost-Effective Designs of Smart City Technologies for Vehicular Communications

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FINAL RESEARCH REPORT

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1 Introduction

The long-term goal of this research is to provide results that inform decisions about technologies and public policies for smart cities and connected vehicles. In this year, under Project 274, we made particular progress on spectrum management issues, on policy processes, and in assessing the impact of wireless technologies on performance of wireless vehicular networks and the applications that they enable. This report summarizes that progress.

We consider wireless communications systems that support vehicle-to-vehicle communications (V2V), vehicle-to-infrastructure communications (V2I), vehicle to pedestrian communications (V2P), and all other vehicular communications, which we refer to collectively throughout this report as V2X. Difficult decisions are ahead related to V2X systems. Among the decisions specifically considered in this research are how much spectrum to allocate for Intelligent Transportation Systems (ITS) based on V2X, whether to share ITS spectrum with uses that are unrelated to V2X such as Wi-Fi, which of two competing technologies known respectively as Dedicated Short-Range Communications (DSRC) and cellular vehicle-to-everything (C-V2X) to adopt in ITS spectrum, and whether vehicular networks are sufficiently effective at supporting applications intended to prevent automotive crashes.

While these general questions apply for all V2X traffic, the specific needs for V2X communications depend greatly on what those V2X exchanges are used for. It is therefore a mistake, and a common one, to consider all V2X traffic as if it were homogeneous. In this report and in this research, we divide V2X traffic into two general categories, although diversity remains in each category. One category of V2X traffic is both latency-sensitive and safety-critical. This traffic is exchanged by life-saving applications, such as those that warn drivers when they are at risk of crashing into the car in front, or when it is not safe to turn left because there is oncoming traffic that might not yet be visible. This category may someday include messages that help autonomous vehicles adjust their speed and direction. For such V2X communications, sub-second delays can put lives at risk. Thus, the focus is on making technical and policy decisions that yield good latency and other similar measures of quality of service. The other broad category includes V2X traffic that is either not latency-sensitive or not safety-critical, so that while low latency is still desirable, it is less critical. For this traffic, we look at the effect of technical and policy decisions primarily on throughput. This includes communications for information or entertainment that does not involve safety. It also involves communications involving safety for which latencies in the seconds are not problematic.

The following three sections summarize contributions in three important areas, using the categorization above. Section 2 describes a simulation study of traffic that is not safety-critical or not latency sensitive. Section 3 describes a simulation study of traffic that is safety-critical and latency-sensitive. Section 4 describes contributions to the policy-making process, including a new proposal for the next administration. Our contributions to transportation workforce development are summarized briefly in Section 5. Section 6 shows that products of this work include four publications [1, 2, 3, 4] and eight presentations [5, 6, 7, 8, 9, 10, 11, 12]. These build on our previous products such as [13, 14, 15, 16, 17, 18, 19, 20, 21, 22].

2 Simulation Study of Non-Safety-Critical Communications

This portion of our research investigates the amount of spectrum that should be allocated for non-safety critical or non-latency-sensitive V2X traffic, and whether the spectrum allocated for this traffic should be shared with other types of wireless communications. Some results from this research were published this year [1], and some were presented publicly this year [7, 9].

Both of the above are open issues. The U.S. Federal Communications Commission (FCC) has been considering whether to share the ITS band since 2013. The FCC began testing two specific mechanisms to share spectrum between V2X and unlicensed devices such as Wi-Fi in 2018. In one mechanism, unlicensed devices only have secondary rights, while V2X communications is the primary use of the band. In the other, the two have co-equal primary rights. In December of 2019, the FCC voted to begin a proceeding in 2020 to consider reducing the amount of spectrum allocated to ITS.

In this portion of our research, we assume that some portion of the spectrum is available for safety-critical latency-sensitive V2X communications, and another portion for the rest. Only the latter might be shared with unlicensed devices, but sharing is done on a co-equal basis. We then investigate both the amount of spectrum that should be allocated, and whether sharing is more efficient. In this portion of the work, we consider only DSRC technology.

Our method is three-fold: (i) collect extensive data from large connected vehicle deployments in the U.S. and Europe, (ii) develop detailed packet-level network simulation using empirical data for an actual deployment to make the simulation realistic, and run that simulation to determine the achievable throughputs for any given design and deployment, (iii) develop extensive engineering-economic models to the cost of any given design and deployment. By using these three tools in combination, we can determine which set of spectrum, technology and infrastructure decisions can maximize benefits-costs in various scenarios and policy environments. For non-safety-critical traffic, the primary benefit is the ability to achieve high throughputs while offloading traffic from more traditional and typically more expensive infrastructures, and the primary costs are for the deployment and operations of V2X roadside units. (In some scenarios, it is also appropriate to consider the costs of spectrum and V2X on-board units.)

As shown in [1], we find that sharing spectrum between V2X devices and Wi-Fi devices was far more spectrally efficient in the scenarios we considered than allocating some spectrum exclusively for ITS and some spectrum exclusively for unlicensed devices. This was especially true when all wi-fi devices were indoors, since placement indoors reduces interference between wi-fi and the active V2X devices that are necessarily located on or near roads. However, the efficiencies are still great even when we add outdoor wi-fi, as would be appropriate for a municipal wi-fi system,

We also considered how much spectrum should be allocated for non-safety-critical uses of ITS spectrum, assuming that ITS spectrum is used exclusively for V2X, and the associated costs and benefits. We found that the uncertainty is high, because the optimal allocation depends on factors that are themselves uncertain, from the number of vehicles that will have the technology to the traffic volumes per vehicle.

For both of these reasons, we conclude that there are substantial benefits to the sharing of spectrum between non-safety-critical V2X devices and unlicensed devices, under an appropriate set of rules. The first result above shows that sharing is spectrally efficient. The second shows that there is risk of inefficiency with an exclusive allocation for V2X, and that this risk can be mitigated by sharing.

We therefore recommend that the FCC allow some degree of sharing. That may include allowing unlicensed devices to access ITS spectrum, as the FCC had been considering, but it could also mean allowing V2X devices to access unlicensed spectrum, which has not been part of the debate at the FCC and should be. Of course, this applies only for V2X traffic that is not safety-critical or not latency-sensitive.

3 Simulation Study of Safety-Critical Communications

In another portion of this research, we have been studying safety-critical V2X communications, i.e. communications in support of applications that can prevent crashes if network quality of service is sufficiently good. We simulate both DSRC and C-V2X technology. Similar to the research described in Section 2, we ultimately hope to inform decisions described in Section 1, including how much spectrum to allocate for ITS, whether it should be shared, what the rules for usage should be, and which technology or technologies should be supported. However, this time we consider those issues for spectrum that carries safety-critical traffic.

Our approach is to see how application-layer performance varies with different technical and policy choices, such as the choice of technology (e.g. DSRC vs. C-V2X mode 3 vs. C-V2X mode 4), and the choice of bandwidth for ITS. While other researchers have focused on network-level performance, we believe that the best way to assess performance for safety-critical traffic is to consider performance of the safety applications themselves. So far, we are focusing on the Forward Collision Warning application (FCW). We will consider other applications in the future. This application warns a driver when she is at risk of hitting the car immediately in front. An application can provide this warning without any sensors as long as vehicles exchange information about position, velocity and acceleration. When network-level quality-of-service is poor, this causes warning lights to turn on at suboptimal times, which in turn affects driver behavior and ultimately crash probability.

Our method is to develop and use more simulation software, which in this case can mimic the behavior of DSRC, C-V2X mode 3, and C-V2X mode 4. This software is also fed by data collected from previous connected-vehicle deployments and from emulators used by real human subjects, so that we can incorporate into the simulation reasonable models of driver behavior under normal steady-state conditions and when confronted with the risk of collision

Our results are only preliminary, but show promise. In scenarios simulated to date, we have seen better application-layer performance with C-V2X than with DSRC in some scenarios, and little difference in others. However, the differences we observe do not necessarily translate to significantly better safety outcomes. When distances between cars is small, network-layer quality of service is similar. When distances are great, we see greater differences in network-layer performance, but this matters less at the application layer because larger distances generally mean lower risk of crash anyway. We are working on characterizing the circumstances in which performance differences matter at the application layer, which is where they affect actual crash probabilities. The first public presentation of our preliminary results will occur at the next Transportation Research Board (TRB) Transit Safety and Security Conference [6], which has accepted our submission. We hope to continue this avenue of research next year.

4 A New Approach for Policy Advancement

The impediments to progress in connected vehicles are not all technical. Public policy governs spectrum management, and the deployment of infrastructure for purposes such as safety on our roads. In the U.S., the Department of Transportation and the Federal Communications Commission are currently in vehement public disagreement over how to manage spectrum for V2X, while state and local governments that are critical to the ultimate success of any policy for connected vehicles mostly sit on the sidelines, and industry players remain divided. This puts the future of connected vehicles in jeopardy.

We have proposed a new process by which effective policies can be produced. Rather than allowing different players such as the FCC and the Department of Transportation to develop policies related to connected vehicles piecemeal, we believe the federal government should establish an interagency task force, which would then convene players who are not part of the federal government, including state and local governments, the automobile industry, the telecommunications industry, consumer protection and privacy groups, and outside experts. This task force would establish a vision of applications that will be supported for both connected and autonomous vehicles, select a standard, develop an infrastructure strategy including the roles for both government agencies and commercial operators, create appropriate spectrum rules, and seed deployment. A paper describing this approach [2] was recently published as part of the *Day One Project,* which showcases promising technology policies for the coming years. It has also been presented publicly [9].

We also actively participated in the ongoing work at the U.S. Federal Communications Commission (FCC) on making spectrum available for V2X. This includes submission of formal comments to the FCC on Intelligent Transportation Systems spectrum [3, 4], as reported in *Communications Daily* [23].

Of course, this same challenge of advancing connected vehicles with appropriate policies is not unique to the United States. The PI will later be presenting our results internationally [5], as an invited speaker at a workshop of the International Telecommunications Union (ITU), which is the telecom arm of the United Nations.

5 Expanding the Transportation Workforce

This project has sought to expand the transportation workforce by contributing to the education of engineers regarding connected vehicles. We have presented some material from this work in a seminar for undergraduate engineers at Carnegie Mellon University [12], and a seminar for students and faculty at multiple universities along with other researchers [9]. This research has also involved one current Ph.D. student at Carnegie Mellon University, and one former Ph.D. student at Carnegie Mellon University.

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6 Bibliography

Publications during this project

[1] Alexandre Ligo and Jon M. Peha, "Spectrum for V2X: Allocation and Sharing," *IEEE Transactions on Cognitive Communications and Networking*, Volume 5, Number 3, pp. 768-779, September 2019. https://ieeexplore.ieee.org/abstract/document/8712390

[2] Jon M. Peha, *Leading the Way: A National Task Force on Connected Vehicles,* Day One Project, Federation of American Scientists, August 2020. https://www.dayoneproject.org/post/leading-the-way-a-national-task-force-on-connected-vehicles

[3] Jon M. Peha, "The Need for Analysis and a Shared Vision for Intelligent Transportation Systems," Comments in the Matter of Use of the 5.850-5.925 GHz Band, Federal Communications Commission ET Docket No. 19-138, April 27, 2020. https://ecfsapi.fcc.gov/file/10427026777534/Peha_Need_for_Shared_V2X_Vision.pdf

[4] Jon M. Peha, "Technical Standards and Spectrum Sharing for Intelligent Transportation Systems," Comments in the Matter of Use of the 5.850-5.925 GHz Band, Federal Communications Commission ET Docket No. 19-138, March 7, 2020. https://ecfsapi.fcc.gov/file/1030702006624/Peha_Standards_and_Spectrum_for_ITS.pdf

Presentations during this project

[5] Jon M. Peha, **"**KEYNOTE: Spectrum for Intelligent Transportation Systems (ITS)**,"** invited to appear at a United Nations workshop, International Telecommunications Union Workshop on Radio Spectrum for IMT-2020 and beyond, December 2020.

[6] Jon M. Peha, **"**Comparison of Vehicle-to-Everything (V2X) Technologies for Road Safety**,"** accepted to appear in Transportation Research Board (TRB) Transit Safety and Security Conference, November 2020.

[7] Jon M. Peha, KEYNOTE: "Spectrum Policy for Intelligent Transportation Systems," *19th IEEE Wireless Telecommunications Symposium*, April 2020.

[8] Jon M. Peha, "What 5G Cannot Solve and the Need for 6G," *IEEE DySPAN*, November 11, 2019

[9] Jon M. Peha, “Spectrum Policies for Connected Vehicles,” Smart Mobility Connection Seminar, October 9, 2020

[10] Jon M. Peha, “Emerging Wireless Technology and Competition,” *NSF Workshop on Wireless, Spectrum & Innovation*, August 28, 2020

[11] Jon M. Peha, “Improving Spectrum Efficiency for 5G through Multi-Network Access,” *IEEE/IET International Symposium on Communication Systems, Networks and Digital Signal Processing*. July 2020.

[12] Jon M. Peha, “Connected Vehicles: Technology and Policy,” Undergraduate Seminar, Carnegie Mellon University, February 11, 2020

Some of previous work

[13] Alexandre Ligo, Jon M. Peha, Pedro Ferreira and Joao Barros, "Comparison between Benefits and Costs of Offload of Mobile Internet Traffic Via Vehicular Networks," *Proceedings of 43rd Telecommunications Policy Research Conference (TPRC)*, Arlington, VA, September 2015.

[14] A. Ligo, J. M. Peha and Joao Barros, "Throughput and Cost-Effectiveness of Vehicular Mesh Networks for Internet Access," *IEEE 84th Vehicular Technology Conference (VTC),* Sept. 2016.

[15] A. Ligo and J. M. Peha, “Cost-Effectiveness of Using Connected Vehicles Infrastructure for Internet Access,” MASITE/ITSPA Annual Conference, 2016.

[16] A. Ligo and J. M. Peha, "Is It Cost-Effective to Share Roadside Infrastructure for Non-Safety Use?," *IEEE 85th Vehicular Technology Conference (VTC),* June 2017.

[17] A. Ligo and J. M. Peha, "Spectrum Policies for Intelligent Transportation Systems," *45th Telecommunications Policy Research Conference (TPRC)*, Sept. 2017.

[18] J. M. Peha, KEYNOTE: “Wireless Communication and Municipal Governments – Looking Forward,” *Association of Boroughs*, August 2017.

[19] A. Ligo, J. M. Peha, Pedro Ferreira and Joao Barros, "Throughput and Economics of DSRC-Based Internet of Vehicles," *IEEE Access*, vol. 6, pp. 7276–90, 2018.

[20] A. Ligo and J. M. Peha, "Cost-Effectiveness of Sharing Roadside Infrastructure for Internet of Vehicles," *IEEE Transactions on Intelligent Transportation Systems*, Volume 19, Issue 7, July 2018, pp. 2362-2372.

[21] A. Ligo and J. M. Peha, "Spectrum for Intelligent Transportation Systems: Allocation and Sharing," *IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN),* Oct. 2018.

[22] J. M. Peha, “Smart City Technologies for Local Governments,” *Fall Conference of Townships, Boroughs & Authorities*, August 2017.

Press

[23] Howard Buskirk, “Auto Industry's New 5.9 GHz Offer Doesn't Impress O'Rielly,” *Communications Daily*, April 29, 2020.