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ITS Band Roadside to Vehicle Communications in a Highway Setting

**Susan Dickey, Jared Dulmage,
Ching-Ling Huang, Raja Sengupta**

California PATH Research Report
UCB-ITS-PRR-2010-17

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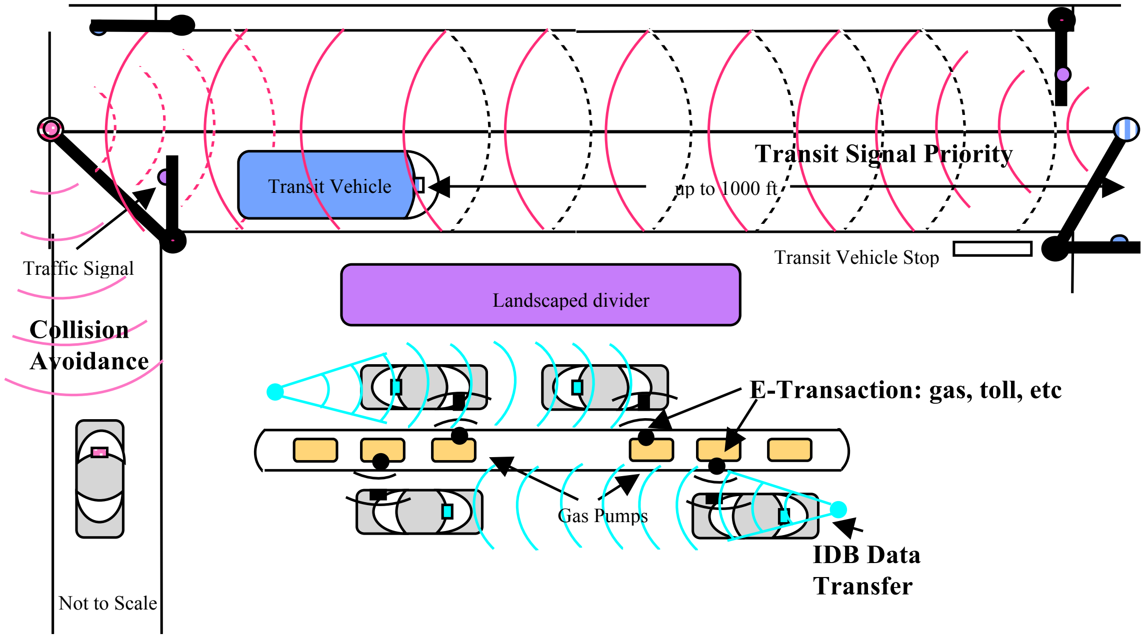
Final Report



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16. ABSTRACT

Researchers investigated the testing and evaluation of radio and communication protocol standards for the 5.9 GHz spectrum that has been approved by the Federal Communications Commission for exclusive transportation use. This spectrum allocation is intended for use as Dedicated Short Range Communications (DSRC) in the context of high-value Intelligent Transportation Systems (ITS) applications. In this report, we summarize the Wireless Access in a Vehicular Environment (WAVE) standardization effort for 5.9 GHz DSRC, its current status, and related issues of the IEEE 802.11p and IEEE 1609 family of standards. We also present an overview of current DSRC development activities in the world context, in the United States, and in California, describing and comparing some of the current commercial implementations. To verify the performance of DSRC prototype radios, we conducted a series of testing in different scenarios. A physical layer simulation and FPGA testbed was developed at the UnWiReD Lab, University of California, Los Angeles, and a software applications programming interface (API) used in tests with different commercial hardware was developed at California PATH, UC Berkeley. The WAVE standards effort, in which we participated, is described, and testing procedures and results are presented. An architecture for DSRC testbeds for safe intersections is reported, focusing on the hardware/software issues, performance and possible future enhancements. Finally, a user's guide to our developed software for testing DSRC/WAVE systems is provided as an appendix.

17. KEY WORDS Wireless Access in Vehicular Environments (WAVE), Dedicated Short Range Communications (DSRC), radio, telecommunications, wireless vehicular networks, roadside infrastructure, testbeds and simulation platforms, 802.11p, IEEE 1609, roadside to vehicle communications, 5.9 GHz Band, Intelligent Transportation Systems Radio, IntelliDrive, VII	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161	
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Disclaimers

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Under Caltrans Task Orders 5214 and 6214, researchers at UC Berkeley and UCLA investigated the testing and evaluation of radio and communication protocol standards for the 5.9 GHz spectrum that has been approved by the Federal Communications Commission for exclusive transportation use. This spectrum allocation is intended for use as Dedicated Short Range Communications (DSRC) in the context of high-value Intelligent Transportation Systems (ITS) applications. In this report, we summarize the Wireless Access in a Vehicular Environment (WAVE) standardization effort for 5.9 GHz DSRC, its current status, and related issues of the IEEE 802.11p and IEEE 1609 family of standards. We also present an overview of current DSRC development activities in the world context, in the United States, and in California, describing and comparing some of the current commercial implementations. To verify the performance of DSRC prototype radios, we conducted a series of testing in different scenarios. A physical layer simulation and FPGA testbed was developed at the UnWiReD Lab, University of California, Los Angeles, and a software applications programming interface (API) used in tests with different commercial hardware was developed at California PATH, UC Berkeley. The WAVE standards effort, in which we participated, is described, and testing procedures and results are presented. An architecture for DSRC testbeds for safe intersections is reported, focusing on the hardware/software issues, performance and possible future enhancements. Finally, a user's guide to our developed software for testing DSRC/WAVE systems is provided as an appendix.

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Caltrans Task Order 6214:

(Continuation of T.O. 5214)

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Final Report

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Keywords: Wireless Access in Vehicular Environments (WAVE), Dedicated Short Range Communications (DSRC), radio, telecommunications, wireless vehicular networks, roadside infrastructure, testbeds and simulation platforms.

Executive Summary

The Wireless Access in Vehicular Environments (WAVE) Amendment P to the IEEE 802.11 Wireless LAN standard is currently in the last stage of sponsor ballot and is expected to receive final approval by fall 2010. Implementations of 802.11p will support the U. S. Department of Transportation's Intelligent Transportation Systems (ITS) Program and the Federal Highway Authority's IntelliDrive^{SM} Initiative. These automotive networking services will operate in a special licensed Dedicated Short Range Communication (DSRC) 5.9 GHz frequency band that has been allocated by the Federal Communications Commission (FCC) for use in transportation, with emphasis on safety of life and public safety. With Task Orders 5214 and 6214, Caltrans sponsored ground-breaking research that has prepared California to take advantage of this exciting new technology.

Section 1 describes a simulation and FPGA-based testbed of the WAVE/DSRC physical Orhogonal Frequencey Data Multiplexing (OFDM) physical layer in the 5.9 GHz band that was designed and implemented as part of Task Orders 5214 and 6214. This testbed demonstrated the use of an integrated set of Commercial Off-the-Shelf (COTS) tools enabling rapid and intuitive progression through development stages. The common simulation and automated hardware testing environment realized time-savings in both development and debugging through the reuse of test benches across several stages of the research and evaluation process. This toolchain and methodology provides a cost-effective method to develop testbeds for conformance testing of vendor products, to evaluate evolving standards specifications, and to facilitate development and testing of novel wireless algorithms in a real-world environment. Descriptions of this testbed and of OFDM model results obtained as part of this work have appeared in the proceedings of ACM WiNTech 2006 and IEEE Tridentcom 2007.

Section 2 of this report describes the DSRC standardization effort, including IEEE 802.11p and IEEE 1609 family standards, in which Caltrans participated as a part of this project. The IEEE P1609 family standards address functionalities above the physical (PHY) and medium access (MAC) layer that have been designed for communications in a ground transportation setting. Current status and related issues of those standards are also discussed in Section 2. While the standards effort has lagged behind the initial expectations of the ITS community, and the initial US DOT projections for deployment were over-optimistic, the work that has been carried out over the past 6 years has explored many important issues and provides a solid foundation for deployment.

In Section 3, we first provide an overview of DSRC development in the world context, in the U.S., and in the California. Since analysis and simulations cannot accommodate the full complexity of practical systems with large numbers of vehicles in close proximity, we conducted radio testing using prototype 802.11p/WAVE equipment. The second part of Section 3 presents our testing procedures and results on DSRC performance. We used inexpensive computer hardware with prototype radios to explore performance issues for multiple On-Board Units (OBUs, radios in the vehicles) approaching a Road Side Unit (RSU). In the third part of Section 3, we describe DSRC testbed architecture for safe intersections. Implications for the future, when the intersection crash problem may be addressed through dynamic red light running countermeasures and other DSRC-enabled systems that “talk” (in a data sense) between the intersection and car are multi-fold. Parts of the research results presented in Section 3 have

appeared in the *Handbook on Vehicular Networks*, in the proceeding of the 1st IEEE International Symposium on Wireless Vehicular Communications, and in the proceedings of the Transportation Research Board, January 2008.

In Appendix A, a user guide and web references are provided for our developed software. This guide has been written to describe the software originally developed as part of Caltrans Task Orders 5214 and 6214. This software is currently running on the Kapsch/Technocomm Multiband Configurable Networking Unit and on the Savari Networks Mobiwave On-board Unit that have been used as part of the Safetrip 21 and VII California projects. Porting of this software to the Denso Wireless Safety Unit is underway as part of the FHWA Exploratory Advanced Research Program "Development and Evaluation of Selected Mobility Applications for VII." This software is also being used as the underlying layer for sending SAE J2735 messages in a joint project with an automobile OEM to study the use of Signal Phase and Timing (SPAT) messages for in-vehicle fuel economy applications. Note that, our WAVE API is documented in a separate user manual available on the software web site.

Table of Contents

Contents

List of Tables and Figures

ITS Band Roadside to Vehicle Communications in a Highway Setting: Final Report

1. A COTS Testbed for Rapid Algorithm Development, Implementation and Test of 5.9GHz OFDM DSRC

The IEEE 802.11 physical layer (PHY in the IEEE nomenclature) testbed for 5.9GHz Orthogonal Frequency-Division Multiplexinsg (OFDM) Dedicated Short Range Communications (DSRC), developed by researchers at the UCLA Wireless Research and Development (UnWiReD) Laboratory (UnWiReD, 2006), is meant to perform conformance testing of vendor products, evaluate developing standards specifications, and allow development and testing of novel wireless algorithms in a real-world environment (Dulmage, MOBICOM, 2006).

In the following subsections we first present the rationale for a testbed which uses an integrated set of COTS tools to

- significantly reduce the volume of tools and expertise required of the wireless algorithm designer by
- reuse subsystem test benches in a common simulation environment across several stages of development
- enable rapid and intuitive iteration through development stages.

We then describe the flexible testbed development environment based on Matlab, Simulink, and Xilinx System Generator, the radio hardware interface using a Xilinx XtremeDSP radio development daughtercard built around a programmable Xilinx FPGA, and research that was carried out under T.O. 5214 and T.O. 6214 on a software-based vehicular channel model. We finally note contributions of this work to WAVE/DSRC development and continuing work by UCLA researchers on WAVE/DSRC.

1.1. Rationale for physical layer radio testbed

In August 2001, the Federal Highway Authority (FHWA) sponsored performance testing of candidate technologies for the Federal Communications Commission (FCC) approved Intelligent Transportations Systems (ITS) frequency. This testing was carried out by the Dedicated Short Range Communications (DSRC) 5.9 GHz Standards Writing Group, a sub-group of American Society for Testing and Materials (ASTM) E17.51 containing representatives of public agencies and of the private sector., The group voted 20-2 to select 802.11a RA (roadside applications), a version of IEEE 802.11a modified to operate at 5.850-5.925 GHz that was demonstrated using Atheros AR5000 chipsets and performed well in a variety of severe multipath and high-speed environments, at distances up to 400 meters (Atheros, 2001). ASTM then produced an initial standard for this technology, “ASTM E2213-03 Standard Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems — 5 GHz Band Dedicated Short Range Communications (DSRC) Medium Access Control (MAC) and Physical Layer (PHY) Specifications” (ASTM 2003).

While the Atheros chips sets performed well on the ASTM testing, the high mobility and the dynamic environment of DSRC applications required a reassessment of the 802.11 PHY receiver architectures. Outdoor radio systems must contend with a considerably different wireless environment than indoor radio systems for which the Atheros chip was originally designed. Two major issues that must be addressed include the typically longer delay spreads in the outdoor environment, the time-varying nature of vehicular channels, and the greater number of sources of interference. A DSRC testbed with highly programmable components was considered desirable to enable modification of physical layer algorithms to realize acceptable PHY performance for a variety of applications and outdoor environments. New receiver algorithms for channel and frequency estimation and tracking can result in significant improvements in performance and throughput, as is currently being claimed for Cohda Wireless technology (Telematics 2009).

The maximum excess delay is the time difference between the first reception of a transmitted signal at the receiver and the last reception. This phenomenon, called multipath propagation, results when a signal travels different paths from the transmitter to the receiver . The shortest path is usually the direct line between the two while longer paths result from the signal reflecting off obstructions in the environment such as buildings or trees. The maximum excess delay is often much different outdoors than indoors due to walls providing large obstructions at close distances. Since walls often cause 30dB of loss for propagation through them, delay spread in indoor scenarios is often limited to paths within the same room. Outdoor environments often have the excess delays a factor of 10 times greater than indoor environments. The 802.11a standard was designed to operate in a delay spread typical of the indoor environment. To combat delay spread, the standard inserts a guard interval before the transmission. The guard interval ensures that no new transmissions will be sent over some time duration. As long as that duration is greater than the excess delay of the channel, consecutive transmissions will not interfere with each other. ASTM E2213-03 and the specifications being developed as part of IEEE 802.11p (see Section 2 of this report) call for halving the symbol rate which doubles the guard interval, but it is not clear if this will ameliorate all of the consequences of the longer, outdoor excess delay encountered in deployment of DSRC applications. If the delay is much larger than anticipated, significant degradations may result. Testbed programmability for DSRC technology allows experiments to be performed in realistic deployments. Results of these experiments can directly impact the direction of the transmit signal and receiver designs for people who build radios for transportation applications.

The UCLA Wireless Research and Development laboratory was well equipped with test and measurement instruments and experience developing two wireless testbeds to facilitate experiments on most aspects of physical layer wireless communications, ranging from individual components such as channel characterization, synchronization, and channel codecs to a software defined multi-antenna wireless system. Ongoing projects within UCLA were leveraged in designing and building an operational DSRC physical layer implementation. UCLA researchers were able to build on their experience in investigating high performance wireless modem technologies in real wideband channels, including a particular focus on OFDM for future wireless applications. Expertise with the physical layer aspects of DSRC was already in place at UCLA at the start of the project.

Modern communications algorithm design requires a diverse set of tools and expertise. From conception to design a rigorous, though not complete, development process can include abstract mathematical analysis, floating-point simulation, bit-true (functional) fixed-point simulation, cycle-true fixed-point simulation, and real-time hardware design and implementation. Each step is distinguished by its own set software tools, design methodologies, and developer expertise. Often there is significant duplication of effort to develop simulation environments, test benches, and verification plans for each stage of development. Comparison of performance and test results between models at different stages is inconvenient at best (e.g. data conversion) and daunting at worst (e.g. parametrizing hardware performance degradation with respect to a floating-point model).

The DSRC testbed developed by UCLA researchers for T.O. 6214 consists of a set of simulation models along with a programmable hardware platform for implementation and test. These models facilitate algorithm development following the general evolution illustrated in Figure 1.

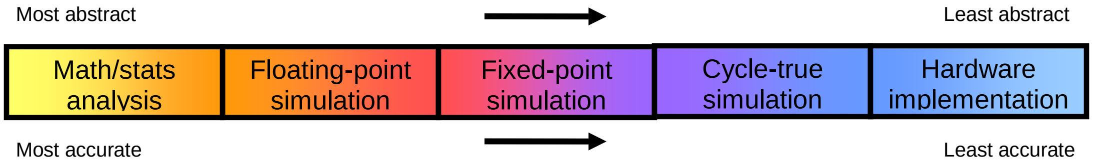

Figure 1 Evolution of physical layer development from algorithm to implementation

The overall goal of this type of testbed design was to keep software/hardware partitioning flexible throughout the development cycle. Evaluation of algorithms with software and simulation has the advantage of being easily re-programmable, with advanced debug capabilities and the resources of a full personal computer environment available for test generation, data storage, and data analysis and display. In contrast, hardware implementations, even FPGA hardware, are relatively static, with limited debug capabilities, even though testing with real hardware and radio transmissions are essential for testing model correspondence to the real world and capturing real-world effects too complex to model. In the testbed that was developed, the overall algorithm design could be arbitrarily partitioned between hardware and software. Testing of the hardware could be carried out either with the fine-grained control of a synchronous interface, or with an asynchronous interface that allowed real-time operation with actual digital/analog and analog/digital conversion to the radio front-end. The synchronous interface, while not real-time, allowed sample-by-sample debugging of the hardware; the asynchronous interface provided high performance block data transfer for real-time experimentation.

The various points of partitioning allowed a single model/testbench to accomplish several goals. Subsystem algorithms and hardware designs could be developed and debugged with a single testbench. Integrated hardware designs could be tested in the same virtual environment used for simulation and development for providing consistent control and monitoring capabilities. The user interface integrated with the testbench could be used to perform both bench and field tests. Once the baseline system was completed, rapid design iterations could be performed, including integrating new floating-point algorithms quickly into hardware implementation.

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1.2. Matlab and Simulink Implementation

The basic testbed design (Dulmage/Tsai/Fitz/Daneshrad, 2006; Dulmage/Tsai/Fitz/Daneshrad, 2007) was modular with loosely coupled subsystems and intuitive interfaces. The testbed software models were implemented using The Mathworks Matlab and Simulink (Mathworks, 2006) products. Matlab and Simulink were augmented with the fixed-point arithmetic toolbox and Simulink fixed-point respectively, tools that facilitate the extension of the simulation environment to direct hardware synthesis of mathematical algorithms. The environment allows the developer to graphically program simulations by connecting together basic functional blocks (e.g. adders, multipliers, logic functions that can be directly implemented in hardware) along with more sophisticated blocks (e.g. matrix decompositions, encoders, modulators). Xilinx System Generator (Xilinx, 2006) augments these functional blocks with structural blocks (e.g. delay elements, registers) from which the developer can create a synthesizable hardware model of their algorithm. Interfacing Simulink's functional blocks with System Generator's structural blocks is straightforward and allows co-simulation of high-fidelity floating-point algorithms with cycle-true, fixed-point algorithms. This allows a highly parameterized, flexible simulation set-up.

The top-level floating-point model is a functional model. Each major component of the top-level is decomposed into major functional subsystems in a top-down design architecture. Components of this model include a transmitter conforming to the 802.11p draft standard, RF filtering, a time variant, multipath fading channel model, and a receiver implementing baseline algorithms. Receiver algorithms that were implemented include frequency offset tracking, simplified soft-output demapper and a soft-input Viterbi decoder. See Figure 2 for a block diagram of the floating point transmitter model.

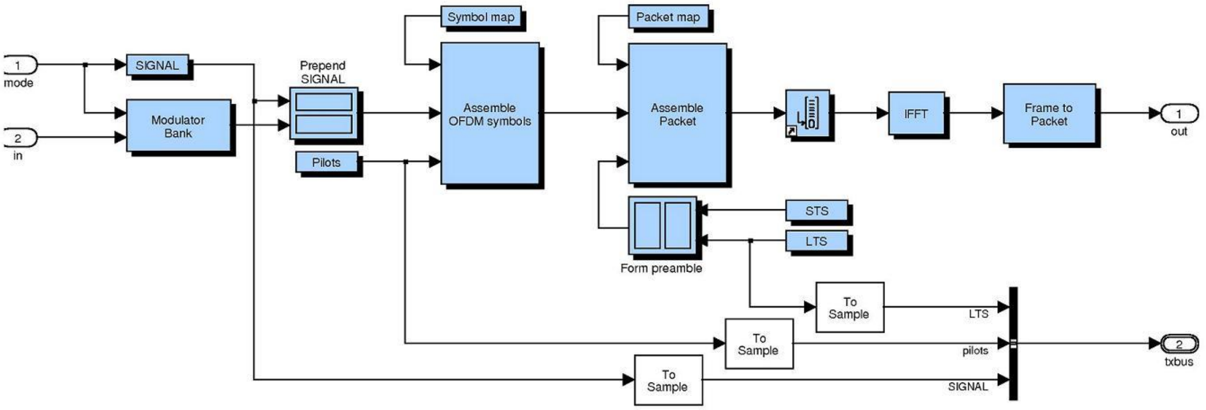


Figure 2: Floating Point Transmitter Model

Measurement and visualization (e.g. spectrum analyzers, BER calculation) facilities are also present at the top-level. Relatively generic interfaces connect the various subsystems. The simulation environment includes DAC/ADC hardware emulation and variable RF impairments (time/frequency/phase offsets). The user interface includes visualization capabilities for a rich set of information, including:

- Received and equalized constellation plots
- Received and equalized signal spectra

- Actual channel and estimated channel responses
- BER, PER, SNR vs. time, BER vs. SNR
- Successful and errored bits within each decoded symbol

See Figure 3 for a screen shot of testbed visualization capabilities.

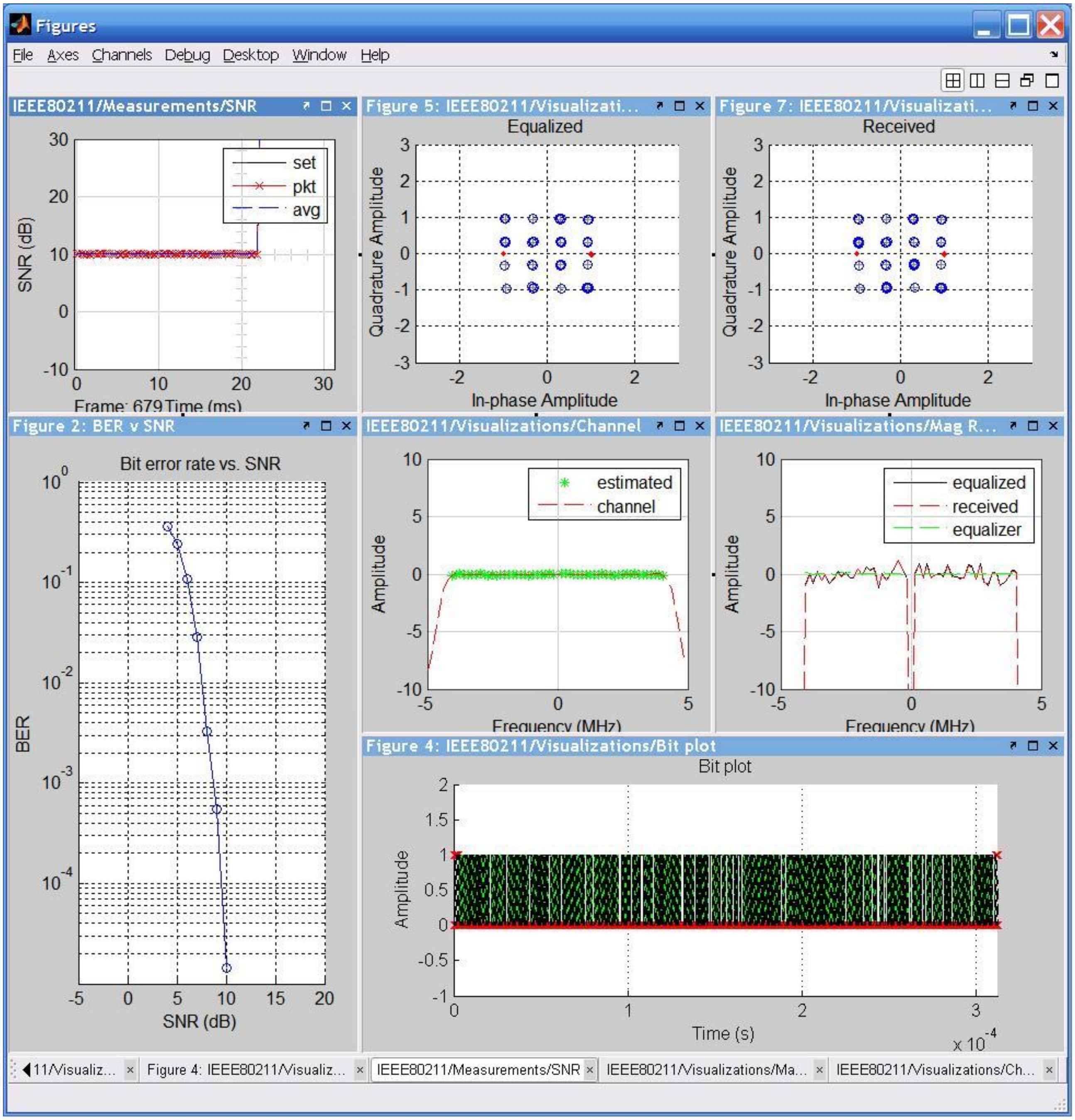
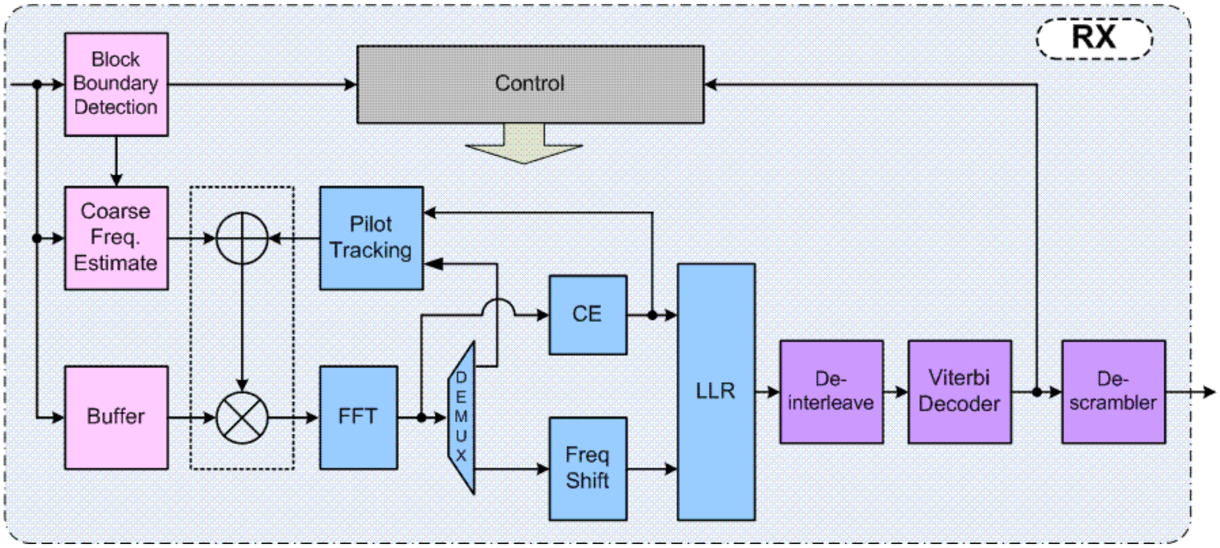


Figure 3 Screen shot of testbed visualization capabilities



In parallel to the floating-point functional model, a top-level cycle-true, fixed-point structural model for a receiver was developed. The fixed-point structural model was synthesized using Xilinx System Generator to a hardware description appropriate to program the FPGA. This hardware implementation would then use the floating-point model as a testbench. The hardware was tested via hardware-in-the-loop simulation with the floating-point transmitter, RF emulation, multipath channel, visualization, and error statistics blocks. Because the synthesized blocks were operating on the high-speed FPGA hardware, accelerated simulations could be run.

Several sub-modules were implemented for the fixed-point receiver model: packet detection/time synchronization, coarse frequency offset estimation, frequency offset tracking, soft-output demapper, and soft-input Viterbi decoder. Figures 5 and 6 illustrate the implementation of the soft-demapper algorithm in the floating-point and fixed-point models, respectively. Their similar layout illustrates the intuitive nature of porting floating-point to synthesizable fixed-point models using the chosen tool set.

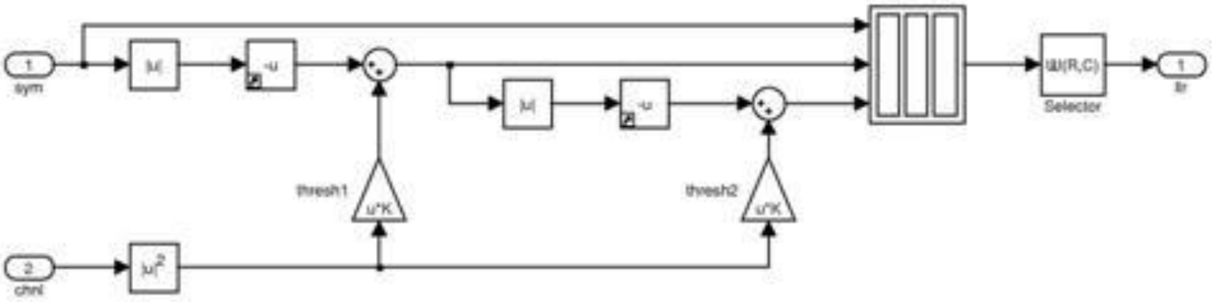


Figure 5 Floating-point model of a soft-demapper algorithm

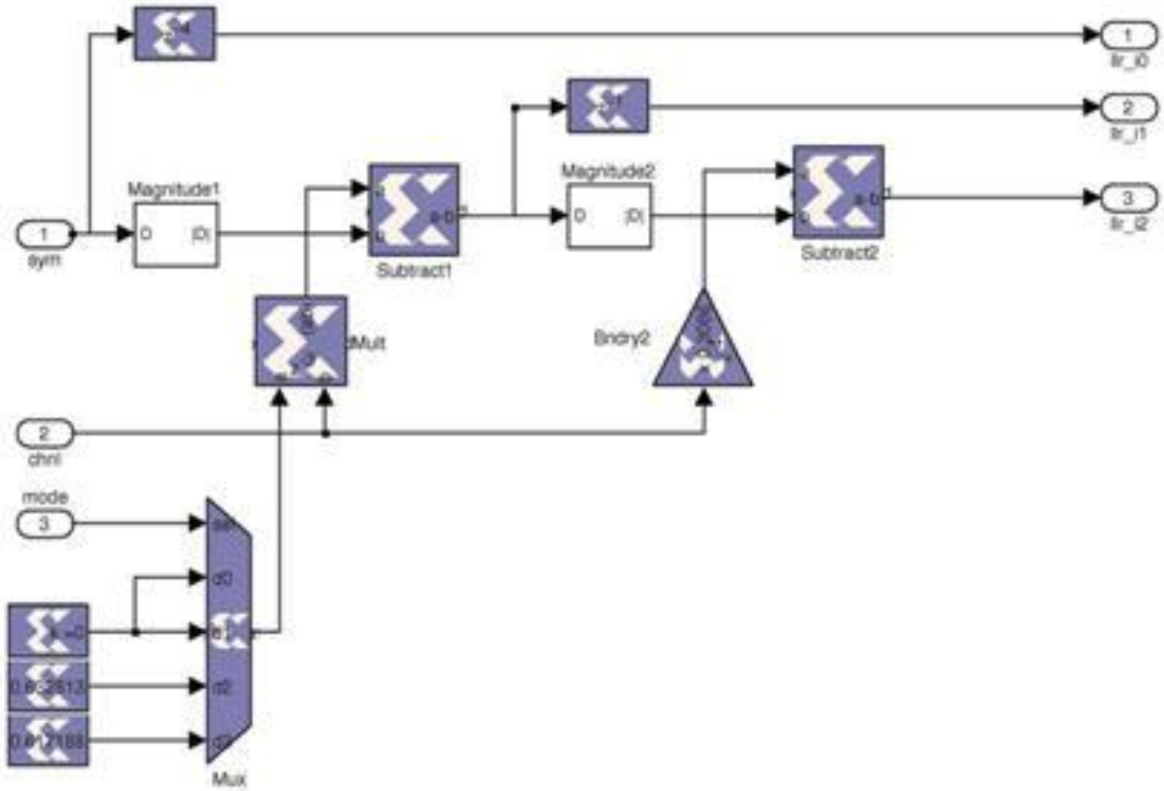


Figure 6 Fixed-point model of a soft-demapper algorithm

Concurrent with the model creation, a design methodology was developed. The methodology proscribes utilizing the floating-point simulation model as a reference with which to provide a (sub)system performance level baseline. The floating-point model also supplies a common testbench with which to exercise and evaluate both the floating-point models and hardware designs. A fixed-point hardware simulation model is constructed from the initial floating-point model in order to quantify performance degradation due to quantization and enable debugging/optimization of the structural hardware implementation. To utilize the same testbench as the floating-point model, input/output interface adaptors may be added. A fixed-point synchronous hardware co-simulation model, synthesized from the fixed-point hardware simulation model, ensures correct synthesis of the algorithms to their implementation on the FPGA and enables more comprehensive performance testing due to more efficient hardware co-simulation. In the final iteration, a fixed-point asynchronous hardware co-simulation model implementing asynchronous (shared-memory) interfaces in the hardware model would allow testing of (sub)systems as they would operate on the hardware in real-time. Asynchronous hardware co-simulation futher improves simulation speed by an order-of-magnitude or more over synchronous hardware co-simulation. Finally, stand-alone software (e.g. the medium access controller) would replace Simulink to drive the hardware using the same shared-memory interfaces as was used during simulation.

Several subsystems were iterated completely through all of the design stages: Viterbi decoder and control logic, FFT/IFFT and control logic, channel estimation, and log-likelihood ratio demapper. Several subsystems were developed through a subset of the design stages: time/frequency synchronization, frequency offset tracking, interleaver/deinterleaver and control logic. The design methodology established a standard procedure for reliable development of hybrid software/hardware testbeds and systems. Several subsystems have already been developed and verified via this procedure each of which contributes to the final goal of a fully functional DSRC prototype radio. Further details on subsystem development and simulation results can be found in the Masters thesis (Dulmage 2008).

Difficulties were found with the Xilinx System Generator development environment in the course of work on the DSRC radio testbed for T.O. 6214. Caltrans-funded UCLA researchers identified and reported several major bugs in the Xilinx development environment. Several of these bugs were fixed in newer Xilinx product releases, but resulted in a considerable loss of time in the project schedule. Researchers on this project were in contact with internal product developers at Xilinx and able to recommend features useful for general FPGA in-the-loop systems.

1.3. FPGA and Radio Hardware

Hardware used for the DSRC testbed was constrained to be low-cost, either COTS or low-cost custom subsystems, and portable. The largest component of the UCLA prototype was a standard 19” rack-mount enclosure, which could easily be made smaller with current commercially available systems. Reprogrammability was a priority. The basic platform was the Xilinx XtremeDSP-II kit designed by Nallatech and consisted of a Xilinx field programmable gate array (FPGA) coupled to dual analog-to-digital converters (ADC) and dual digital-to-analog converters (DAC). The number and cost of on-board FPGA parts can be tailored to the complexity of the system to be developed. The board also contained 4MB of off-chip memory accessible through the FPGA. Embedded or soft-core processor support could also be included on the same board for an integrated implementation of the IEEE 802.11 MAC layer. Different hardware implementations were achieved through automatic synthesis using Xilinx ISE tools and Xilinx System Generator.

The FPGA board was hosted on a PCI motherboard and housed in a standard PC. A high-speed interface to the PC is needed for development, test, and control; USB, 100Base TX Fast Ethernet, and PCI were available interfaces at the time. 1GB TX and PCIe interfaces are available on modern boards. The ADC and DAC ports were readily accessible from the back panel of the PC. The custom radio frequency (RF) front-end box converted signals to and from the FPGA board in two stages, and operated in the DSRC band from 5.85 GHz to 5.925 GHz. Operating frequency and transmit and receive gains were programmable from front-panel interfaces on the RF box.

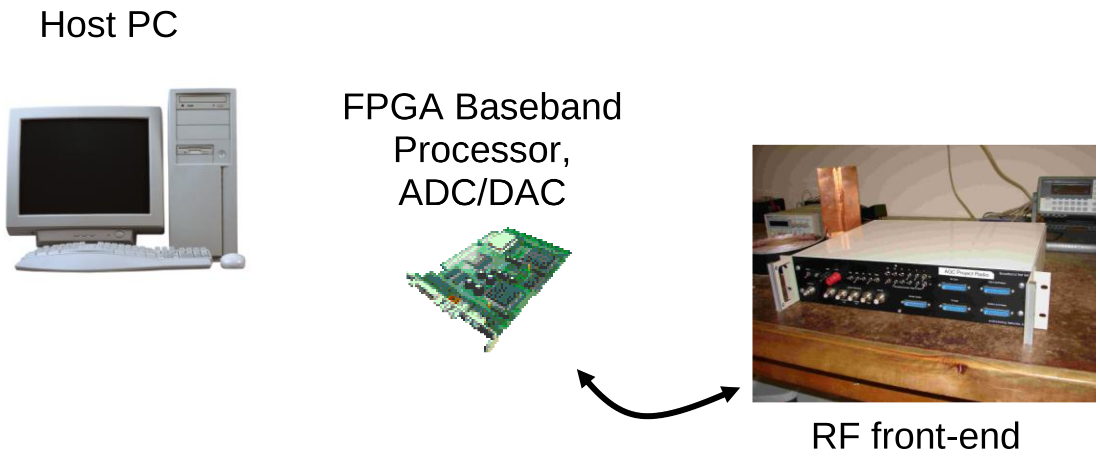


Figure 7 Hardware components of the physical layer testbed.

1.4. Development and Simulation Results

The DSRC testbed work was continued in a master's thesis "IEEE 802.11 OFDM Model for Algorithm Development, Implementation, and Test," (Dulmage 2008) extending and generalizing the original design work, and in papers on channel modeling in the non-isotropic scattering environment of the open highway (Dulmage/Fitz 2007a, 2007b). During the course of the testbed work, it became clear that the applications of the testbed were much more general than 802.11p DSRC. The testbed had the potential to become a general purpose, hybrid software-hardware development platform capable of supporting applications ranging from software simulation to hardware field-testing .using a single development environment. The testbed combined lower performance, more general purpose processing engine (basically a personal computer or PC) with a high performance but less arbitrarily reconfigurable hardware device, in this case a field-programmable gate array (FPGA) board, resulting in both a highly flexible and highly accessible system.

The thesis provided a variety of preliminary results and suggested many areas for further investigation using such a test bed. The considerable affect of clipping noise on the channel estimation was shown. Future work could elucidate the nature of the degradation (frequency-domain response, relationship to input signal, etc.) and find algorithms robust to clipping noise and/or mitigation techniques. A procedure was outlined to compute the fixed-point dynamic range and scaling necessary to avoid certain degrading affects on the linear soft-metric demapper algorithm. Further exploration could determine a generalized framework with which to analytically compute fixed-point parameters to ensure some level of performance for linear functions. Several aspects of the system performance were explored over a variety of channels, and channel estimation emerged as a particularly important aspect of performance. In time-invariant tests, performance differed significantly depending on the channel characteristics. Future work could determine the channel properties that most affect bit-interleaved coded modulation (BICM) systems and suggest design parameters (e.g. code rate, interleaver design, symbol constellation) to achieve the best performance based on those channel properties. The affects of time-variant channels were also explored. Future work could explore the significance of the loss of channel estimate coherence with the time-variant channel over long packets. The affects of envelope vs. phase variation would suggest potential mitigation techniques such as tracking or prediction algorithms. Special channel coding may enable greater exploitation of diversity across amplitude or phase depending on their characteristics.

1.5. Channel Model Research

The papers on a "Non-Isotropic Fading Channel Model for the Highway Environment" (Dulmage/Fitz 2007a, 2007b) investigate the properties of several non-Jakes Doppler spectra proposed for the vehicle-to-vehicle environment. The high-speed, mobile-to-mobile scenario presents a unique wireless environment. The IEEE 802.11p/D1.0 (WAVE) draft standard document described a channel model recommended for system development and test. The model was derived from channel sounding experiments performed in an open highway environment (Acosta/Ingram/Tokuda 2004). The draft standard specified a 10-tap multipath fading model with the majority of taps exhibiting Rician fading. The diffuse Doppler spectrum for each tap results from the non-isotropic nature of the environment and does not match the classic Jakes spectrum. The exploration in (Dulmage/Fitz 2007a, 2007b) of the alternative Doppler spectra identifies their properties and suggests a method of realization using a sum-of-sinusoids (SoS) channel model.

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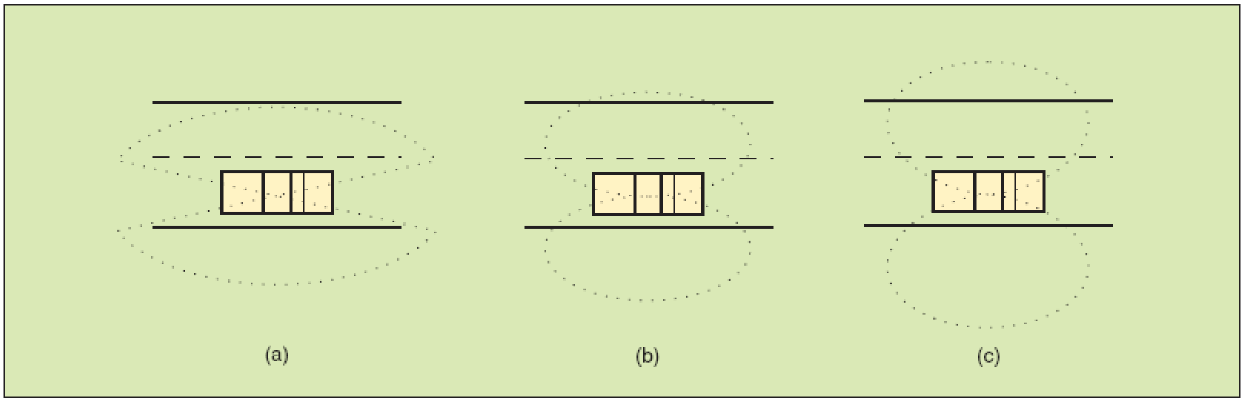


Figure 8 Angle-of-Arrival distributions for (a) JakesX, (b) flat, and (c) round spectra. Vehicle and roadway included for scale reference.

Motion in the wireless environment causes transmitted signals to experience Doppler shifts as a function of the angle between the signal path and the direction of motion. Signals arrive at a receiver after having experienced reflections from potentially moving scatterers at a variety of angles. The superposition of these multipath components with a range of Doppler shifts and received powers manifests as a Doppler spectrum at the receiver. The exact shape of the Doppler spectrum is a function of the wireless environment.

The probability density functions for the angles-of-arrival of the flat and round Doppler spectra are non-standard distributions. As such no generation functions specific to these distributions are available. Figure 8 shows the angles-of-arrival distributions derived in (Dulmage/Fitz 2007b) using randomization techniques for several non-Jakes spectra considered in highway scenario channel models. The classic Clarke channel model was modified to generate fading signals corresponding to the non-isotropic scattering profiles. The theoretical correlations, level-crossing-rates, and average-fade-durations were derived. The simulation results matched well with the theoretical ideal channel. The channel model enables efficient, high fidelity simulation of channels observed in the vehicular environment. This facilitates the investigation of DSRC system performance in realistic channels.

1.6. Contributions and Future Work

The tools and architecture described above allow designers to analyze algorithms and implement simulations at a high level reducing the need for programming expertise (though such expertise may be helpful for advanced modeling with Simulink) and hardware design expertise (e.g., specialized skills such as using VHDL). Learning many disjoint, often incompatible development environments is also avoided. Most importantly, the ease of integration of the functional floating-point, fixed-point, and structural models enables the incremental evolution of algorithms using a common simulation framework.

The use of Xilinx System Generator as the basis for the models allows the designs to be easily ported to any Xilinx part supported by the company. This reduces costs for part-specific design revisions both in time and administration. Cross-product compatibility also facilitates the use of more complex algorithms as more powerful FPGAs become available. Nallatech provides a variety of ready-to-use FPGA boards with integrated peripheral resources and interfaces. Xilinx partnership with Nallatech alleviates many compatibility issues involved in porting designs between boards. This allows the algorithm designer the flexibility to select the right amount of processing resources for a given design without having to explicitly design the board according to the processing needs.

Bit-error-rate results have been obtained for the current floating-point and cycle-true models over a variety of fading channels. We have been able to integrate cycle-true, fixed-point implementations of algorithms on the programmable hardware in co-simulation with the floating-point model. This allows isolation of individual algorithms for performance comparisons to the floating-point versions. It also enables us to easily integrate hardware acceleration into our simulations.

While Xilinx provides simple facilities for integrating the FPGA into simulations and software test benches our goal is to produce a library of high-performance, flexible, ready-to-use interfaces to various board resources such as internal and external memory, ADC/DAC and multiple FPGAs. These interfaces, of course, have general applications beyond our current testbed.

The DSRC/WAVE physical layer testbed enables theoretical performance evaluation of a standard 5 GHz OFDM system under a variety of use environments and hardware impairments. Baseline performance results can be used to evaluate the sufficiency of the 802.11p/WAVE standard specifications. Baseline performance results can also be used to quantify the degradation from theoretical optimum performance due to fixed-point, hardware implementation of subsystems of commercial products evaluated for standards conformance.

Other contributions are related to the general purpose functionality of the design, which provides a highly parameterized, comprehensive OFDM simulation model which can be leveraged with potentially minor changes to other OFDM-based wireless projects (such as WiMax). Testbench subsystems for RF impairments, channel model and visualizations are further applicable to a wide-range of mobile wireless research. The configuration and run-time capabilities of this model are suitable for extensive investigation of the affects of a variety of signal parameters and impairments. Visualizations and measurements can be disabled to enable fast batch simulations.

The system model is also useful for demonstration and illustration of concepts during educational instruction. The modularity of subsystems facilitates substitution of alternative algorithms for performance comparison, proof of concept testing, and research. We do not know of any other OFDM system model with comparable accuracy to the standard, array of configurable options, run-time control capabilities, or visualization options.

Important Caltrans-funded DSRC/WAVE work continues at UCLA. In one recent papers, the use of Received Signal Strength (RSS) to estimate distance accurately on systems using location aware applications is studied.(Dulmage/Cioffi/Fitz/Cabric 2010). In another paper, based on extensive simulations of IEEE 802.11p, a new metric, the normalized empirical coherence time (NETC) is used to designate the minimum time (as a percentage of signal duration) over which the system achieves some performance threshold (Dulmage/Fitz/Cabric 2010). This metric is explicitly a function of modulation, packet duration and the traditional coherence time, and could be used in place of the latter when determining how to constrain packet duration so that channel variation has negligible impact on performance.

2. Standards Development for Wireless Access in Vehicular Environments (WAVE)

2.1 Introduction

Intelligent Transportation Systems, empowered by wireless communication, are expected to significantly improve the safety and efficiency of our transportation network. The idea is to inter-connect all the physical components of a transportation system in cyber-space. Vehicles equipped with wireless transceivers enabled for Dedicated Short Range Communication (DSRC) can exchange information either in vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) fashion. Since V2I communication requires an initial infrastructure investment before deployment, V2V communication among vehicles organized in Vehicle Ad Hoc Networks (VANETs) is likely to be deployed first. However, new safety, navigation, and automation applications in vehicular environments as envisioned in the IntelliDrive^{SM} initiative ((USDOT/IntelliDrive^{SM} 2010), will be greatly enhanced by the addition of the information available to the infrastructure, both from roadside sensors and traffic management centers. The ubiquity of cellular communications, which can reasonably be expected to provide some access to infrastructure information to every vehicle in the near future, enables a multitude of possible communication architectures and applications.

The operation of Wireless Local Area Networks (WLAN) on motor vehicles in a highway environment presents many challenges. Ideally, the same on-board equipment used for toll collection should also be available for use by roadway safety applications such as vehicle collision avoidances, and for other applications such as traveler information, emergency services or commercial data services. Some of these applications may require extremely short times, on the order of 50 to 100 milliseconds, to complete a transaction, while for other applications, extremely high data rates or long operating ranges may be required.

Before deployment of applications dependent on V2V or V2I communications can occur, standards must be developed to allow interoperability between different automobile manufacturers and different DSRC equipment manufacturers. Caltrans Task Orders 5214 and 6214 funded participation in standards development at the most basic layers of the wireless network stack: an amendment to the IEEE 802.11 Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, and a new family of IEEE standards providing networking services for Wireless Access in Vehicular Environments (WAVE), IEEE 1609. This report summarizes the history and current status of this standard development at the lower layers of the networking stack. It does not deal in detail with upper layer standards such as SAE J2735, a message set dictionary (i.e., common languages for DSRC applications to understand each other) that describes DSRC message content (SAE J2735 2009).

2.2 The FCC-approved DSRC frequency band

Since the mid-1990s, transportation researchers and the US Department of Transportation have been working towards future use of DSRC in a spectrum dedicated for transportation purposes only. In 1997, the Intelligent Transportation Society of America (ITS America), on behalf of the transportation industry, petitioned the FCC for a specific band of frequencies at 5.9 GHz. In 1999, the FCC granted the petition with the stipulation that public safety uses would have priority, but postponed defining the rules on how and to whom the spectrum would be licensed. A standard for the physical and medium access control layers in this DSRC band, E2213-02 - Standard Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems, was defined by the American Society for Testing and Materials (ASTM) International in 2002 (ASTM, 2002), and in 2004 the FCC published rules and standards for use.

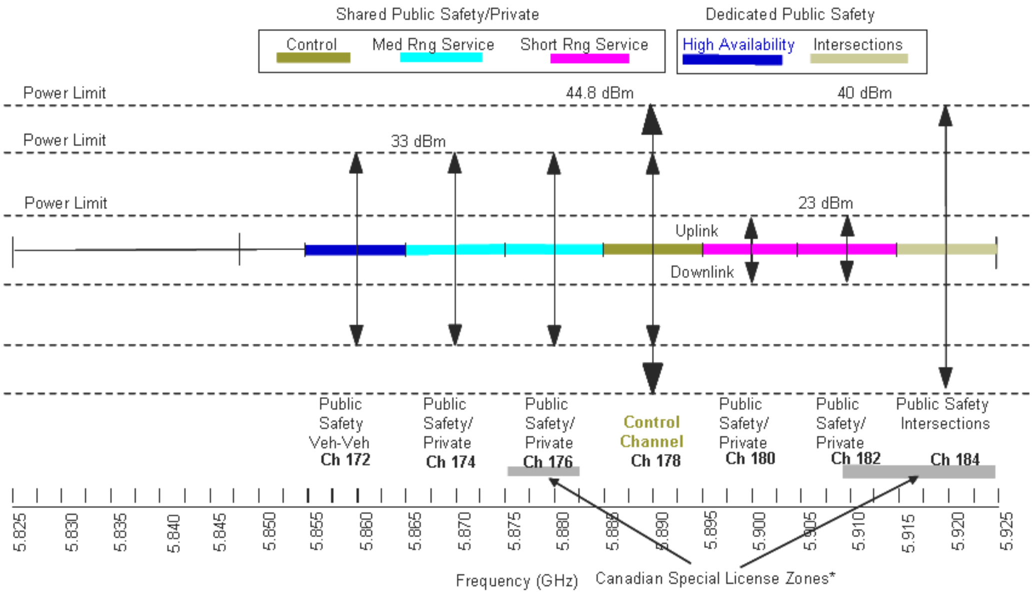


Figure 9: FCC DSRC channel allocation

The FCC rules stated that DSRC frequencies should be used “primarily” for safety purposes, but left the eligibility requirements for licensing open in order to encourage development of new services. The DSRC band lies between 5.850 and 5.925 GHz, and includes 7 available 10 MHz wide channels. Both public safety and non public-safety users are eligible for licensing on all channels, with limited geographical coverage for each roadside installation. See Figure 9 for an illustration of planned DSRC channel allocation.

It is important to distinguish between the previous DSRC standard in the 915 MHz range, which was used primarily in electronic toll collection applications, and the Wireless Access in the Vehicular Environment (WAVE) standards being developed for the new 5.9 GHz DSRC band. The previous DSRC standard had a range of less than 30 meters, a data rate of only 0.5 Mbps, and operated on a single unlicensed channel. The WAVE technology has a range of up to 1000 meters, data rates from 6 to 27 Mbps, and licensed multi-channel operation. Whereas older DSRC applications were limited to short-distance applications with a command response communication model, the new WAVE technology is being designed to support general Internet access and special low-latency short messages for vehicle safety applications as well as the existing command-response applications. A further difference is the open architecture and standard protocol being developed for WAVE devices, compared to the custom chip sets of previous systems.

2.3 Amendment P to IEEE 802.11

The physical layer for devices in the FCC-approved DSRC frequency band is based on IEEE 802.11a Orthogonal Frequency Division Multiplexing (OFDM), so that existing 802.11a WI-FI chip architectures can be used as the basis for inexpensive WAVE implementations and deployment. Using existing WI-FI chip architectures has great advantages for economies of scale in the production of WAVE devices, taking advantage of the large market for consumer WI-FI.

There are also reliability advantages in using a proven commercial architecture. Changes that are required to support WAVE, in addition to the basic change in frequency from the unlicensed 802.11a channels to the 5.9GHz DSRC channels, include adjustments to the Physical Layer (PHY) for the rapid changes in distance between wireless stations during high-speed travel and changes needed to the Medium Access (MAC) layer to deal with the short communication latency required to exchange time-critical safety information between vehicles.

2.3.1 Fundamentals of IEEE 802.11

IEEE 802.11 was originally developed to provide a "wired-equivalent" wireless network that could provide reliable transmission to higher layers of the network stack. As such the 802.11 standard was written to include authentication and association features that require handshaking between nodes that are part of a Basic Service Set (BSS) before any data communication is allowed to occur, mimicking the privacy and security of a wired Local Area Network (LAN) using Ethernet. This handshaking precludes the short communication latency when vehicles come in range of each other that is required for V2V and V2I communications.

From the beginning 802.11 chip sets have been able to go into "promiscuous" mode and pass all communications received to higher layers of the networking stack, but this has not been part of the operation of these chip sets according to the standard. The fundamental necessity for use of these radios in vehicles for safety applications is to relax this constraint. Early testing of existing 802.11a chipsets by Atheros (Atheros, 2001) and others (Armstrong, 2008) showed adequate performance of the PHY at vehicle speeds, so changes to the 802.11 PHY as part of Amendment PHY have been relatively minor. Physical layer changes to 802.11a OFDM that are required to support WAVE include:

- Support for the higher frequencies, since the 802.11a band stops at 5.825 GHz, just below the DSRC channels.
- Adjustments to the physical layer for the rapid changes in distance between wireless stations during high-speed travel. These include the use of 10 MHz channels and consequent tighter margins for adjacent channel rejection.

While there is reluctance among some chip manufacturers to support the tighter margins, and some uncertainty among researchers about whether these changes will be sufficient to provide reliable communications at highway speeds, the physical layer emendations do not seem to have been controversial to the 802.11 Working Group as a whole.

The 802.11 Medium Access Control (MAC) layer is typically implemented partially in software and partially in firmware; the physical layer (PHY) particular to the radio frequency is typically a combination of firmware and hardware. Amendments to the standard have included a variety of features to improve quality of service and security, as well as to extend the standard to different parts of the spectrum, and are very complex. The current version of the standard is over 1,000 pages. The descriptions in the standard of the MAC Layer Management Entity (MLME) and the Station Management Entity (SME), as well as the Service Access Points between different layers and entity within an 802.11 radio (called a station or STA) are conceptual rather than a strict specification of internal functions. While implementers often use the descriptions of these entities as a guide, only information that is exchanged between STAs or that is specified in a Management Information Base (MIB) variable for configuring the STA is normative. For this reason, it is quite difficult to use the 802.11 MAC standard as a guide to implementation "from scratch” of the required capabilities, and existing 802.11 chipsets represent considerable intellectual property.

2.3.2 IEEE 802.11p History and Current Status

The initial drafts of the IEEE 802.11p amendment were system specifications written from the point of view of the Intelligent Transportations Systems (ITS) community, not communications standards designed to specify the minimum requirements for interoperable systems. These initial drafts were written by ITS experts, and there was a culture clash between their expectations and that of the communication experts who dominate 802.11. There was also difficulty in harmonizing with the ASTM standard (ASTM, 2002) and the FCC rulings specifying 7 bands. These rules apply to the U.S. only, and IEEE is an international standard. Additional problems were caused by the difficulty of writing standards in advance of any implementations of applications or networking services. IEEE 802.11 was initially designed with respect to existing higher networking layers based on wired Ethernet. As different groups developed requirements for possible DSRC networking applications, the boundary between what would be implemented in 802.11 and what would be implemented in the higher networking layers being specified in the IEEE 1609 family of standards was fluid.

Table 1 shows how revised drafts made by IEEE 802.11 Task Group P gradually gained approval to pass Letter Ballot, the first and most important stage of approval for inclusion in IEEE 802.11. Draft 1.0 was 59 pages and included diagrams for how to install WAVE hardware in vehicles as well as a special appendix on WAVE in North America.

Recirculation TGp Draft 8.0	Approve 89%	Wed Aug 05, 2009
Recirculation TGp Draft 7.0	Approve 92%	Fri Jun 19, 2009
Recirculation TGp Draft 6.0	Approve 89%	Tue, Mar 31, 2009
Recirculation TGp Draft 5.0	Approve 85%	Fri, Dec 05, 2008
Letter Ballot TGp Draft 4.0	Approve 79%	May 3, 2008 (passed, > 75% approved)
Letter Ballot TGp Draft 3.0	Approve 74%	Sep 12, 2007 (failed)
Letter Ballot TGp Draft 2.0	Approve 67%	Jan 5, 2007 (failed)
Letter Ballot TGp Draft 1.0	Approve 59%	Apr 11, 2006 (failed)

Table 1: Task Group P IEEE 802.11 letter ballots

Gradually the vehicle specific scenarios and specifications were transferred to an Appendix, and eventually eliminated altogether, and Task Group P produced drafts that took into account the style and conventions of 802.11 as a whole.

The overall ITS concept for using WAVE communications involved advertisement to neighbors of ITS services available. In the context of IEEE 802.11, the question of what kind of management frame would be used to communicate this information provoked much controversy. Initially the use of a special kind of management frame called an Action Frame was proposed.

These were proposed to be used to form a special kind of intercommunicating WAVE Basic Service Set. This drew criticism from the 802.11 Working Group that since many of the fields that were being communicated were part of the Beacon Frame that was used to establish ordinary 802.11 BSS communication, WAVE communication should use Beacons. A revised draft was prepared with this change.

However, the idea of a WAVE BSS actually represented a confusion with groupings of networked services that really ought to be provided at the IEEE 1609 higher layers, not in the 802.11 MAC. The 802.11 BSS concept was firmly connected to the authentication and association operations that would make low latency operation impossible. The next major advance in the development of the draft was to eliminate the concept of a WAVE BSS or of a special WAVE mode, and replace it with simply allowing data frames to be exchanged outside of the context of a BSS whenever a MIB variable is set to allow this to occur.

Elimination of the WAVE BSS concept from the 802.11p draft resulted in considerable simplification and clarity. However, now Task Group P received feedback from other members of the 802.11 Working Group that it was not appropriate to use a Beacon to send WAVE Service advertisements and timing information when no BSS was being formed. The essential needs for coordination and maintenance of security by the IEEE 1609 higher layers between different WAVE stations are a mechanism to advertise WAVE services and a mechanism to send global timing information. The current draft uses the existing Vendor-Specific information element to encapsulate the WAVE service advertisement, and uses a new management frame for Timing Information. The key feature of using a special management frame is that it, like the Beacon Frame, can be sent with hardware insertion of the current 802.11 timestamp into the frame at the moment it is sent, so that the timestamp can be read at the receiver with no intervening delays from queuing or higher layer processing in the network stack. Along with information that specifies the offset of the timestamp from a WAVE STAs global time (expected to be obtained from a reliable source like GPS), this Timing Information can be used to reconstruct the sender's global time for the message at the receiver.

As part of Task Orders 5214 and 6214, Caltrans funded California PATH researcher Dr. Susan Dickey to attend IEEE 802.11 Working Group sessions. Dr. Dickey began attending the sessions in January 2006 and became secretary of Task Group P in May 2007. As secretary, she made a considerable contribution to the discussions and functioning of the Task Group. In Fall 2009 Task Group P resolved the last remaining comments on the Letter Ballot Draft 8.0, formed a Sponsor Ballot pool and begin the Sponsor Ballot process for final polishing of Amendment P. As of March 2010, after the few comments for the second Sponsor Ballot recirculation were resolved, the 802.11p Sponsor Ballot Comment Resolution Committee received conditional approval to submit the 802.11p Draft 10.0 to the IEEE 802 Review Committee (RevCom). Final approval of the 802.11p Draft by RevCom may occur as early as June 2010.

2.4 IEEE 1609 Family of WAVE Standards

Four of the IEEE 1609 family of WAVE standards have so far been passed for trial use.

- **IEEE P1609.1 Resource Manager** – As currently written for trial use, this provides application-level services heavily based on legacy 900 MHz toll tag reading mechanisms.

- **IEEE P1609.2 Security Services for Applications and Management Messages** – defines secure message formats and processing, the circumstances for using secure message exchanges and how those messages should be processed based upon the purpose of the exchange.
- **IEEE P1609.3 Networking Services** defines network and transport layer services, in support of secure WAVE data exchange, as well as Wave Short Messages, which provide an efficient WAVE-specific alternative to IPv6 (Internet Protocol version 6) for direct use by applications.
- **IEEE P1609.4 Multi-Channel Operations** provides enhancements to the IEEE 802.11 Media Access Control (MAC) to support WAVE operations.

The earliest of these was passed in December 2006 and the latest in September 2007. There is a two year trial period after passage for trial use, during which prototype systems are to be built and evaluated. At the end of 18 months after passage, IEEE begins collecting comments on the standards, and at the end of the trial use period the standard will be either confirmed, revised or dropped.

Currently the IEEE 1609 Working Group is involved in active revision and addition to the standards, based on experience of various groups with testbeds and DSRC WAVE prototypes. Full use versions of 1609.3 and 1609.4 were put out for the first sponsor ballot in March 2010. The fact that different members of the family were approved for trial use at different times has caused some problems with consistency that are being addressed during this revision. Problems with stability of the standards were also induced by the changing assumptions at the 802.11p level of how much functionality would be included in the 802.11 MAC. As more prototypes and products are implemented and tested, real requirements are fed back into the IEEE 1609 standards process, which are currently being rewritten for full use.

Under Task Orders 5214 and 6214, Caltrans funded the participation of PATH researchers Dr. Susan Dickey and Somak Datta Gupta in the IEEE 1609 Working Group standards revision process. Dr. Dickey has been involved since fall of 2005, and has functioned as the secretary and keeper of the errata lists. On consultation with colleagues at PATH, she submitted the following list of bullet points to Tom Kurihara, 1609 Working Group chair, for consideration during the revision at the end of the trial use period:

- Include mechanism to handle priority of communications not just on the air link but throughout backhaul communications.

- Include possibility of communication filtering and certificate handling at RSU, to deal with restricted backhaul communication bandwidth.

- Allow DSRC communication between RSUs and stationary sensor processors for the purpose of safety and traffic control applications.

- Provide a mechanism for multihop routing vehicle-to-vehicle, with possible gateways at RSUs.

- Design transparent certificate handling procedures that preserve security without enforcing proprietary monopolies for services.

- Explicitly allow that some applications which do not exchange data with immediate roadside consequences (e.g. probe data applications) may not require certificates.

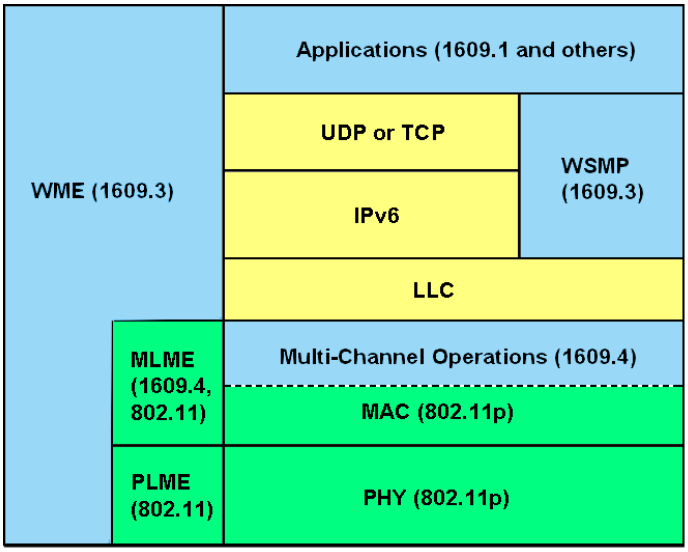
•Re-evaluate provider/service ID and context mark terminology and mechanisms, to make usage and terminology more sensible and more consistent with existing network middleware.

•Consider the possibility of ensuring the ITS band mandate for low latency safety communications be dedicating one channel for this purpose, and, assuming two radio configurations are possible, running 1609 protocol with less critical communications on the remaining channels.

Somak Datta Gupta of California PATH is actively involved in a complete rewrite of 1609.1 with a different emphasis as described in section 2.4.2.6. In the following subsections, we first summarize the characteristics of the 1609 trial-use standards, and then discuss issues in the on-going revision process.

2.4.1 IEEE 1609 Trial Use Standards

The layers of the networking stack associated with the different IEEE 1609 WAVE standards are illustrated in Figure 10 below.



Acronyms

WSMP: WAVE Short Message Protocol
UDP: User Datagram Protocol
TCP: Transmission Control Protocol
IPv6: Internet Protocol Version 6
LLC: Logical Link Control
MAC: Medium Access Control
MLME: MAC Layer Management Entity
PHY: Physical Layer
PLME: PHY Layer Management Entity
WME: WAVE Management Entity

Figure 10: WAVE standards (from IEEE 1609 trial use standards)

A legacy system for toll tag reading in the previous 900 MHz DSRC standard was originally the basis for 1609.1. This became almost completely irrelevant to planned implementations for 5.9 GHz DSRC. At the higher levels of networking and application services, the 1609.1 DSRC Resource Manager trial use standard described the application level services and interfaces designed to support command-response applications of the style supported under the old DSRC standard and currently used by Electronic Toll Collection (ETC) applications, thus providing an easy transition to WAVE technology for the installed base of ETC applications. However, for new applications based on more modern models of programming and network middleware, this method is unnatural and inflexible, so this standard has been made optional.

Since 1609.1 was approved first, there is an inconsistency in the use of data fields that are called Application Context IDs and Context Marks in 1609.1 and Provider Service IDs and Context Marks in 1609.3.

The P1609.2 Security Services for Application and Management Messages trial use standard defines secure message formats and processing of secure messages, within the DSRC/WAVE system, defines methods for securing WAVE management messages and application messages, with the exception of anonymity-preserving vehicle safety messages, and describes administrative functions necessary to support the core security function. This method is certificate-based, cleverly avoiding the latency of handshaking, but introducing problems of certificate distribution.

The 1609.3 Networking Services trial use standard defines services operating at the network and transport layers to support vehicle-to-vehicle as well as vehicle-to-roadside and roadside-to-vehicle communication using the 5.9 GHz DSRC/WAVE mode. In particular, P1609.3 describes a WAVE Short Message protocol (not based on the IP suite of Internet protocols), that can be used for low-latency vehicle-to-vehicle communication, in conjunction with IP protocols for other applications. It also defines application registration services that so that applications may announce their services to neighboring stations, as well as registering application priorities for use by lower layers.

The 1609.4 Multichannel Operations trial-use standard describes multi-channel wireless radio operations using the WAVE mode at the MAC and physical layers, including the operation of control channel and service channel interval timers, parameters for priority access, channel switching and routing, management services, and primitives designed for multi-channel operations. The MAC contains two EDCA entities (from IEEE 802.11e QoS enhancement) for control channel and service channel respectively (see Figure 11). The basic multi-channel operations scheme is to have every station return to the Control Channel to listen for WAVE service announcements and WAVE short messages for a part of a fixed interval and the switch to service channels as desired for IP traffic for the rest of the interval. Note that even if some stations are able to have two radios and dedicate one to the Control Channel, if any stations are switching between Control and Service, all stations must do their Control Channel broadcasts during the interval when the single radio stations are listening. There are still many unanswered questions in this area about the best possible channel scheme to ensure low latency, have reasonably good utilization of available bandwidth, and keep the radios inexpensive, and these questions are an active area of discussion at the IEEE 1609 Working Group meetings (see Kenney 2009, Hong/Rai/Kenney 2009, Hu 2009).

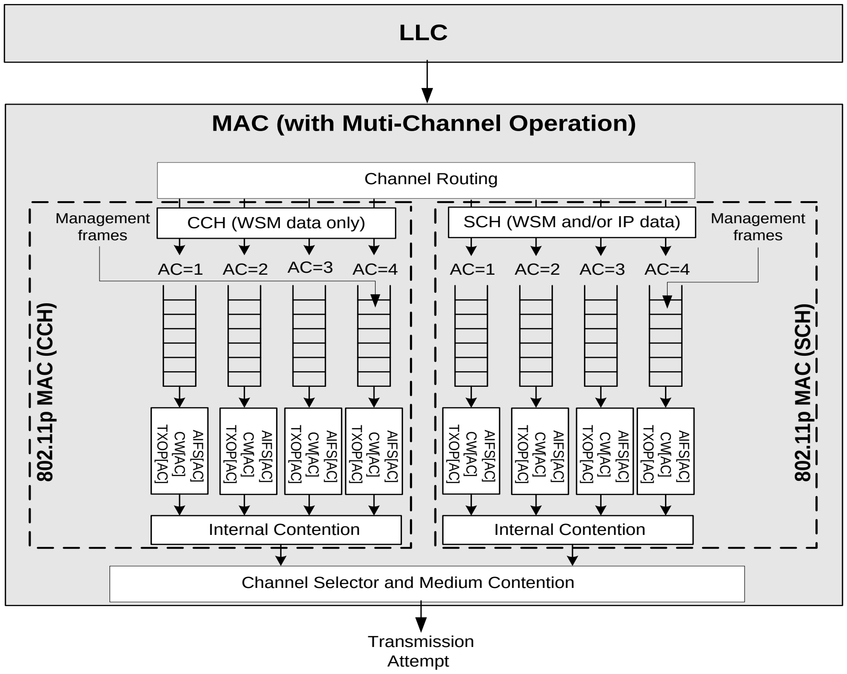


Figure 11: Two EDCA entities in MAC layer (from IEEE 1609.4 trial use standard)

An alternative view of 1609 protocol stacks is also shown in Figure 12, taken from a recent presentation at the 1609 Working Group by John Moring of Kapsch/Technocom: (Moring, 2009a)

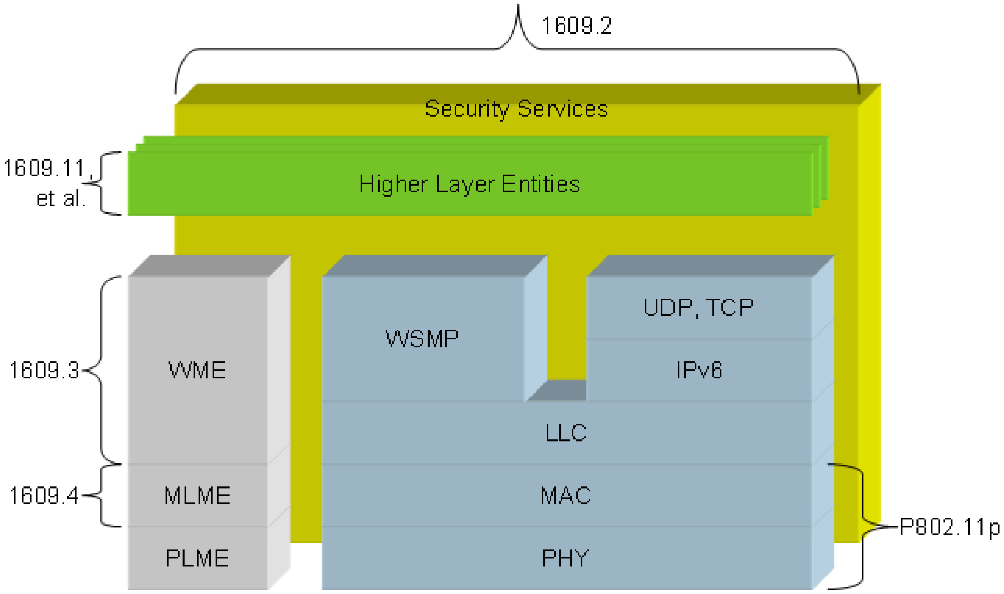


Figure 12: Alternative view of WAVE standards (from Moring's presentation)

2.4.2 Current issues in IEEE 1609 WAVE

In this section, we describe open issues and current development in WAVE standards regarding the networking services (IEEE 1609.3) and multi-channel operations (IEEE 1609.4), including the distribution of timing information, vendor specific action frame, transmission power constraint, channel switching, and service initialization decision making. We also describe open issues regarding the resource manager (IEEE 1609.1), electronic payment via WAVE (IEEE 1609.11), and security algorithms (IEEE 1609.2).

2.4.2.1 Timing Information

In the trial use standard of IEEE 1609.4, timing information is provided only by the service provider, and (based on information from the provider) a user can then estimate UTC (Universal Coordinated Time). A common practice is to assume Gaussian noise and use a Kalman filter to get a mean and variance of UTC time estimates. Initially, the possibility of using WAVE stations (STAs), that are not providers, to provide only timing information. A STA may want to obtain a more accurate update but doesn't want to wait until it gets into coverage of a provider. If there are other STAs around that have UTC, then it may get timing information from them. This information flow may be operating only on an SCH. Figure 13 shows the path of timing information flow from a service provider to a user in the trial standard. There may also be cases, e.g. 1609.1, of devices which don't want WSA but may want UTC to a coarser accuracy than that required for sync. Figure 14 shows a design from a timing provider (not necessarily a service provider) to a timing user; for more details see (Moring, 2009b).

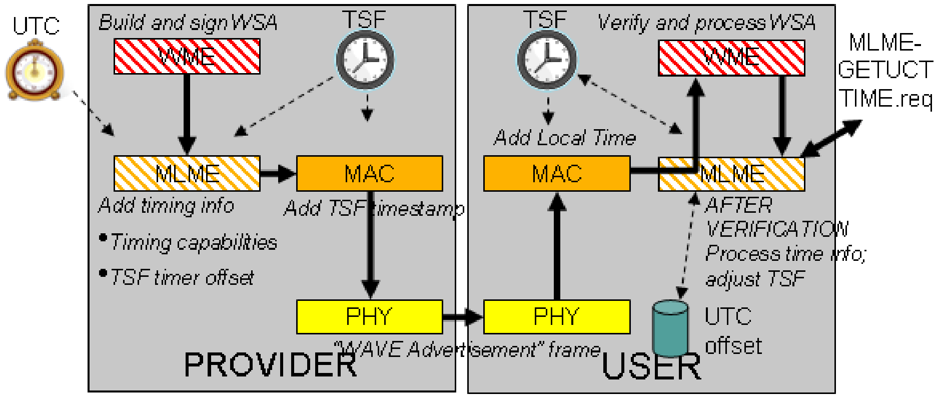


Figure 13: Flow of timing information using WSA in trial use IEEE 1609.4

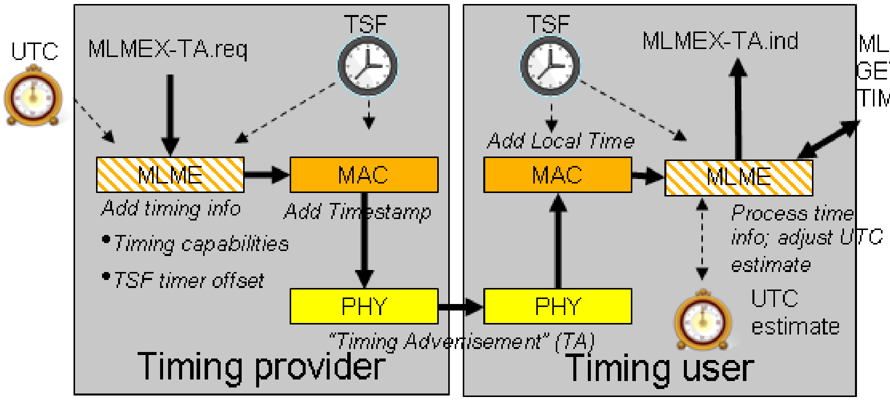


Figure 14: Flow of timing information from a timing provider proposed by Morning

2.4.2.2 Vendor Specific Action Frame

In the trial use standard of IEEE 1609.3, all WAVE management information was distributed via a "WAVE Announcement" frame. Time Advertisement (TA) frame contains the critical Timestamp field set by 802.11. A type of frame, called *Vendor Specific Action* (VSA) frame, is proposed to include WAVE Service Advertisements and perhaps other announcements, e.g., regulatory information, country of operation, channel sets in use, transmit power constraints, and device configuration info per 1609.1. Table 2 lists all types of requests provided by IEEE 1609.3 (Moring 2009c).

Service Request Type	**Primary Purpose**	**Channel/interval assignment**	**Message Generation**
Provider	Service advertisement/ SCH participation	WSA on CCH in CCH interval; service on SCH in SCH interval	VSA frame containing WSA
User	Service notification/ SCH participation	SCH in SCH interval, plus optionally SCH in CCH interval	none
WSM	Received message routing	none	none
CCH	Control channel participation	CCH in CCH interval	none
Management data	Management data distribution	CCH or SCH; CCH or SCH interval or both	VSA frame
Timing advertisement	Time distribution	CCH or SCH; CCH or SCH interval or both	TA frame

Table 2: Types of requests provided by IEEE 1609.3

To streamline the sending of WAVE management information via the VSA, generic VSA SAP (Service Access Point) is proposed to be included in 1609.3 WME, which schedules the announcements in concert with data plane services. This allows “other” management entities, e.g., 1609.1, to exchange info via management frames. Figure 15 shows the flow of VSA messages. Data routed to receiving entity via new Management ID in the Organization Identifier. WME may still exchange *WAVE Service Advertisements* (WSAs) via interaction through MLME.

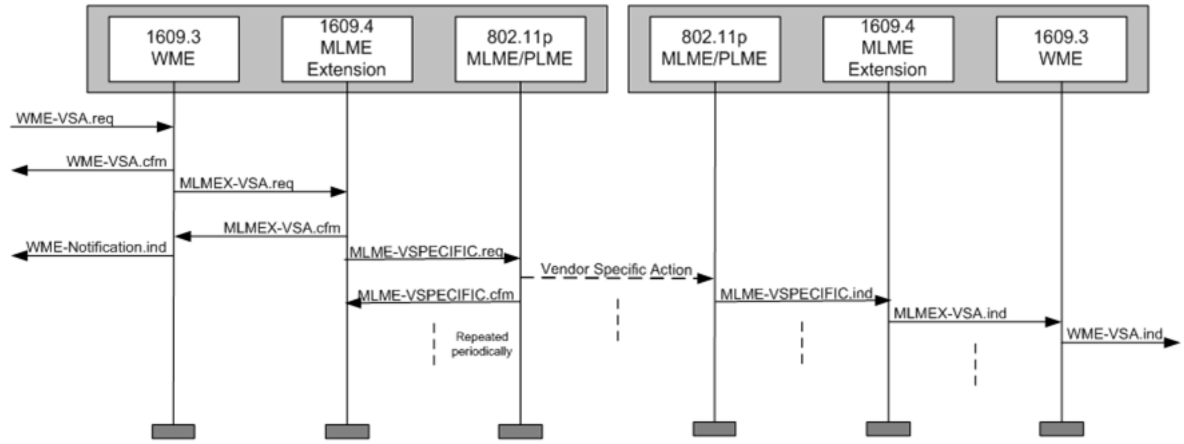


Figure 15: An example of flow of Vendor Specific Action (VSA) messages

A generic VSA SAP is also provided at 1609.4 MLME. This allows opaque management information to be sent and received on SCH or CCH. However, the 1609.4 performs no processing on content, including WSAs. The Vendor Specific Content is completely under control of the management entity identified by Management ID (in this case 1609.3 WME), including any security processing. Figure 16 shows the format of VSA that contains a WSA.

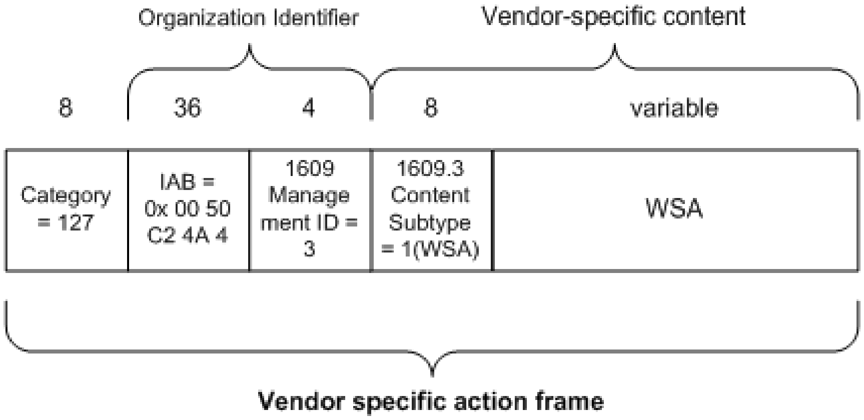


Figure 16: Format of Vendor Specific Action (VSA) that contains a WSA

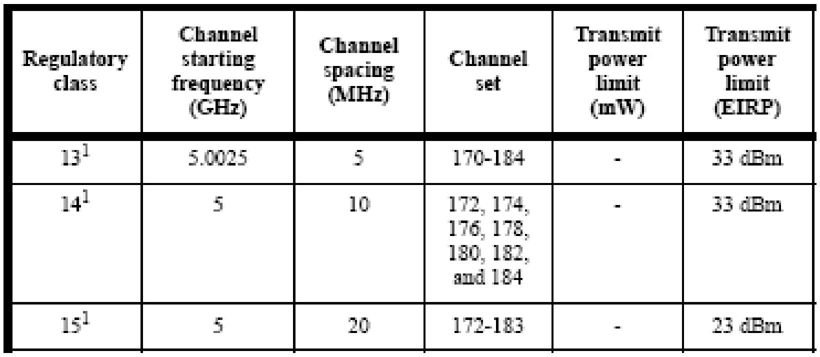
2.4.2.3 Transmission Power Constraint

IEEE 1609 allows higher layers to set transmit power on individual messages, e.g., the transmission power for WAVE short messages (WSMs) can be set on a per frame basis. However, there are regulatory constraints limiting the maximum transmission power. Thus, it is important to make sure the 1609 stack does not transmit at illegal power levels. In trial use standard, WAVE distributes *Transmit Power Level* for each SCH in the WSA.

To prevent such illegal transmissions in SCH, the 802.11 MAC/MLME should prevent transmissions from exceeding the allowed maximum, even if requested by higher layers. For CCH, trial use standard does not distributed power constraints for the CCH. It is thus proposed to include this power constraint in the *Channel Info* of the WSA and to include this feature in 1609.3 and 1609.4. That is, Providers may broadcast regulatory information in WSA, including *Country String* in WSA header and Power levels in *Channel Info*. Users override default power limits on receipt of valid WSA. Meanwhile, Users retain latest received *Country String*, and Users revert to default power levels on leaving Provider coverage; for more details see (Moring 2009d).

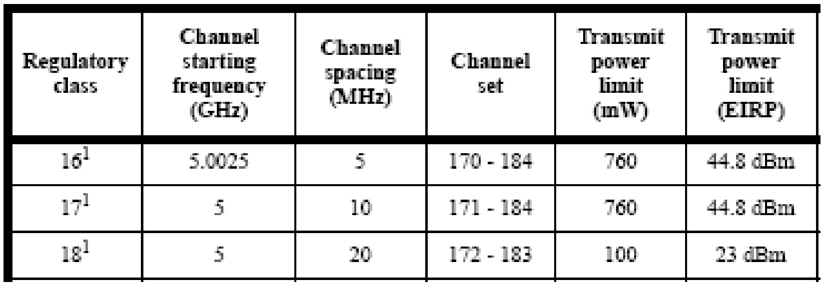
2.4.2.4 Channel Switching and Time Alignment

In 1609, channel information is used in several places. First, in WSA, channel information is carried for each advertised service. This channel information is provided by higher layers at Provider, accepted by User, indicating channel number, power, rate, EDCA parameters. Second, in *Transmitter Profile*, it is registered with lower layers for each channel carrying traffic IP and the same channel information is carried in WSA. Third, in WSM, channel number and other parameters are provided by higher layer at transmitter. Forth, in 1609.4 MIB, channel list identifies usable channels, including CCH. Finally, in 1609.3 MIB, channel number is included in *Available Service Information* (from received WSA) and *User/Provider Service Information* (from higher layer). It is proposed to use both country string and channel number to identify a regulatory class. Table 3 and 4 show the regulatory classes used in U.S.A. and Europe. Table 5 shows the idea of using both country and channel number information to identify a channel.



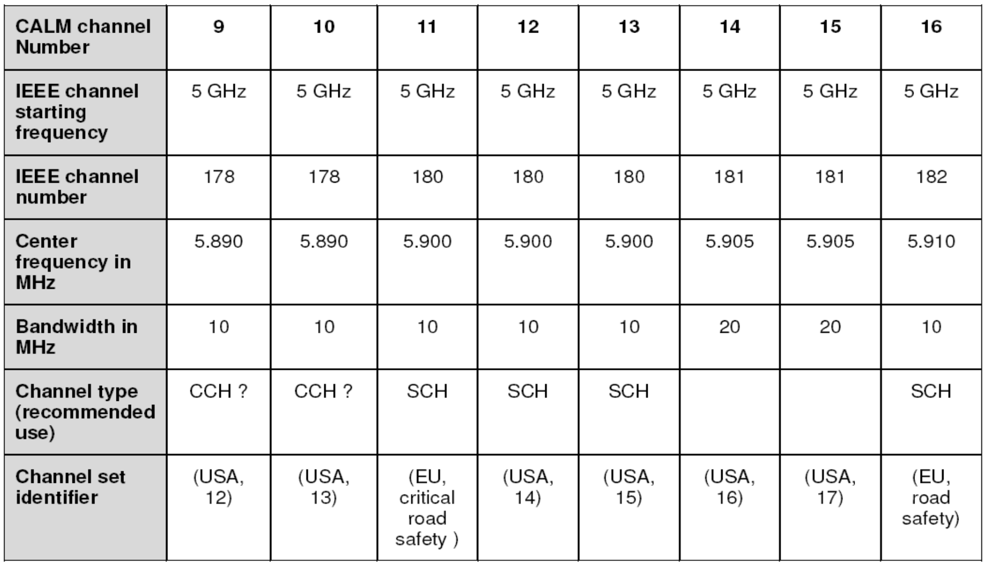
Regulatory class	Channel starting frequency (GHz)	Channel spacing (MHz)	Channel set	Transmit power limit (mW)	Transmit power limit (EIRP)
13[1]	5.0025	5	170-184	-	33 dBm
14[1]	5	10	172, 174, 176, 178, 180, 182, and 184	-	33 dBm
15[1]	5	20	172-183	-	23 dBm

Table 3: Regulatory class and channel number in U.S.A.



Regulatory class	Channel starting frequency (GHz)	Channel spacing (MHz)	Channel set	Transmit power limit (mW)	Transmit power limit (EIRP)
16[1]	5.0025	5	170 - 184	760	44.8 dBm
17[1]	5	10	171 - 184	760	44.8 dBm
18[1]	5	20	172 - 183	100	23 dBm

Table 4: Regulatory class and channel number in E.U.



CALM channel Number	9	10	11	12	13	14	15	16
IEEE channel starting frequency	5 GHz	5 GHz	5 GHz	5 GHz	5 GHz	5 GHz	5 GHz	5 GHz
IEEE channel number	178	178	180	180	180	181	181	182
Center frequency in MHz	5.890	5.890	5.900	5.900	5.900	5.905	5.905	5.910
Bandwidth in MHz	10	10	10	10	10	20	20	10
Channel type (recommended use)	CCH ?	CCH ?	SCH	SCH	SCH			SCH
Channel set identifier	(USA, 12)	(USA, 13)	(EU, critical road safety)	(USA, 14)	(USA, 15)	(USA, 16)	(USA, 17)	(EU, road safety)

Table 5: Channel identification using country string and regulatory class

In addition, in trial use 1609.4, a channel switch is accomplished via MLME sending, but *dot11CurrentFrequency* (in 802.11p) does not uniquely identify a channel. In 802.11 MIB (Management Information Base), *dot11CurrentFrequency, dot11CountryString, dot11ChannelStartingFactor,* and *dot11PhyOFDMChannelWidth* are available. These four parameters are necessary and sufficient to specify a unique Regulatory Class as defined in 802.11 Annex J. The *Country String* is configured in the MIB and can be updated via the WSA. The *dot11CurrentFrequency* is set at each channel switch. The *dot11ChannelStartingFactor* and *dot11PhyOFDMChannelWidth* are set at each channel switch.

Time alignment is another important issue. Some devices may need to switch channels on channel interval boundaries to participate in multiple services. Some devices base security verification of received messages on knowledge of time. Some of these same devices may not have a local absolute timing source. Figure 17 illustrate this channel switching behavior. To above purposes, WAVE must provide an over-the-air time synchronization option with better than 1 ms accuracy. It is thus proposed to design devices that periodically transmit timing information. With received information, receiving devices may derive time synchronization adequate for switching within the guard intervals occurring on channel interval boundaries. See more details in (Moring 2009e, 2009f).

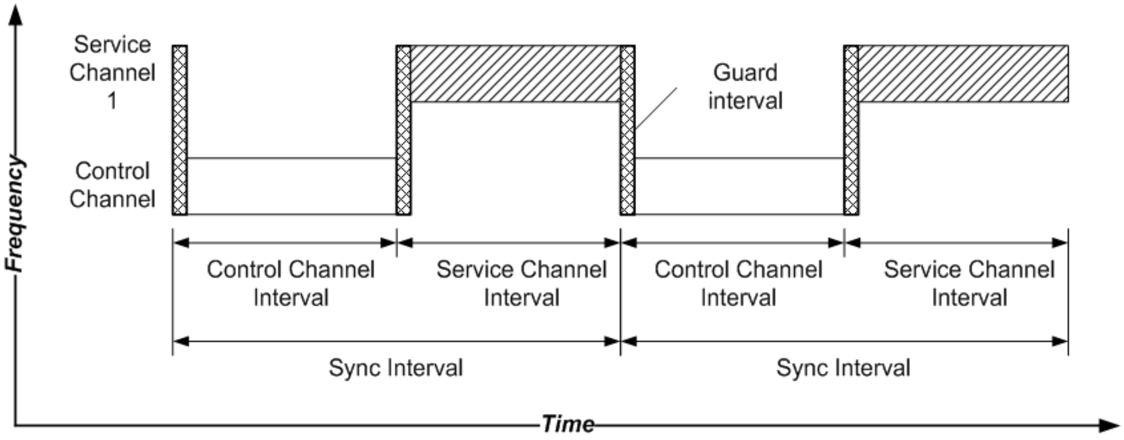


Figure 17: Time alignment and channel switching in time/frequency domains

2.4.2.5 Service Initialization Decision Making

In current design of IEEE 1609, *service link quality assessment* is used as a basis for service initiation decision. For example, a vehicle would consider starting a service only if it successfully receives 5 WSAs in a row or the signal quality of the received WSAs are consistently good. At the 1609 Working Group meeting in August 2009, Daniel Jiang of Mercedes-Benz Research and Development North America proposed to include *service provider location information* in WSA (Jiang 2009). By comparing provider location information and self location information, a vehicle can decide the distance to service provider and decide when to start services. This method is simple and straightforward. This also enables optimizations based on vehicle path considerations. See details in

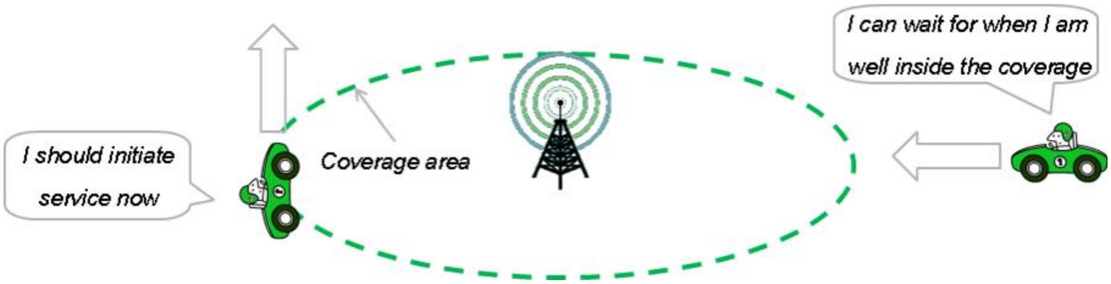


Figure 18: Service initialization based on location information proposed by Jiang

2.4.2.6 Resource Manager

One of developing concepts for 1609.1 is to support low-end devices, e.g., intelligent cones. Those low-end devices may include a single application or limited applications. Those devices are not service providers, and they are not autonomous, i.e., they are managed. It is proposed to add new functionalities in 1609.1 to support over-air management of those low-end units, e.g., their sleep mode, the triggering on message or event, etc. Alastair Malarky of Mark IV has taken the lead in producing an initial draft. (Malarky 2009). It is proposed that specific RSEs/OBEs may configure low-end units using over-air management, including 802.11 and WME defaults, device identity, sleep settings, trigger settings, and activation of application on unit. Besides, RSEs/OBEs can also request device configuration/status.

For low-end devices, their 1609.1 Identities include physical and logical identities. For the physical identity, its *Vendor Identity* is permanent and globally unique. For the logical identity, its *Session Identity* is assigned by its Management device. This session ID is used for higher layer access on Management device and is only used over the air. This session ID allows for anonymity. This identity is in protected data fields. This kind of over-air-management is done by using 802.11 Vendor Specific Action frame.

Specifically, to save energy consumption, those low-end devices can be configured to “sleep” with timeout and triggers. Those devices support *Wake on message* capability so that they resume operations upon receiving control message and application message. Those devices also support *Wake on external trigger* capability so that they can be activated by physical ports on device or feedback signals from a sensor or loop detector.

2.4.2.7 Toll Transaction

A new standard IEEE 1609.11 is in development for electronic payment over WAVE, e.g., toll transactions; an outline was proposed at the June 2009 IEEE 1609 Working Group meeting by Justin McNew of Kapsch Technocom (McNew 2009). In this outline, the concept of *Application* contains an *Application Core* and the *WAVE Interface Application Layer (WIAL)*. The Application Core mains application-specific processing which WAVE might be unaware of. The WAVE Interface Application Layer (WIAL) performs application-specific interfacing with Application Core and the WAVE Stack. *Payment Service* provides services for Application Core or WIAL, depending on the system. Figure 19 illustrates this concept.

Two basic payment options were identified. They are *User and network preapproval* (i.e., “Preapproved” scenario) and *User approval of at time of invoice and network approval at time of payment* (“Invoice” scenario). Both Payee and Payer Payment Service should support operations for encryption and decryption of octet sequences. For the “Pre-approved” scenario, user approves payments in advance of over-the-air transaction. Payee generates receipt and sends account information to central payment entity offline. For the “Invoice” scenario, end user approves invoice (e.g. via HMI). Payee may send payment information to a central payment entity or entities. The “Pre-approved” scenario and the “Invoice” scenario are shown in Figures 20 and 21 respectively.

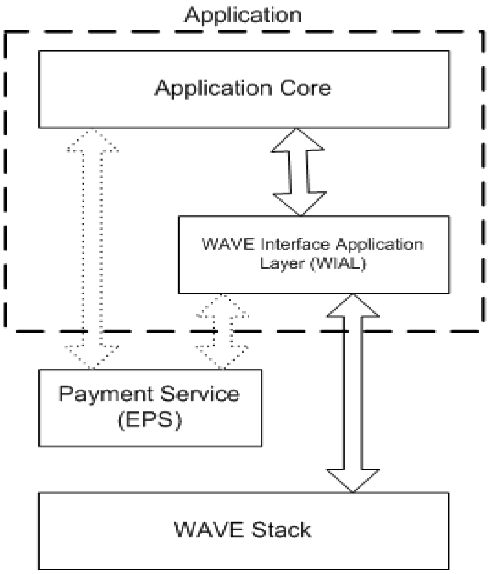


Figure 19: An application is composed of application core and WIAL in 1609.11

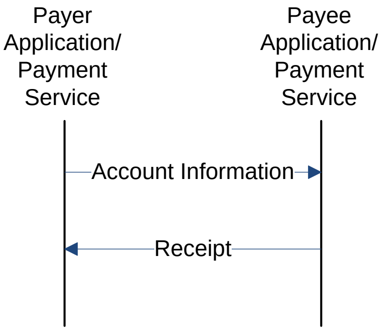


Figure 20: Illustration of "Pre-approved" scenario in 1609.11

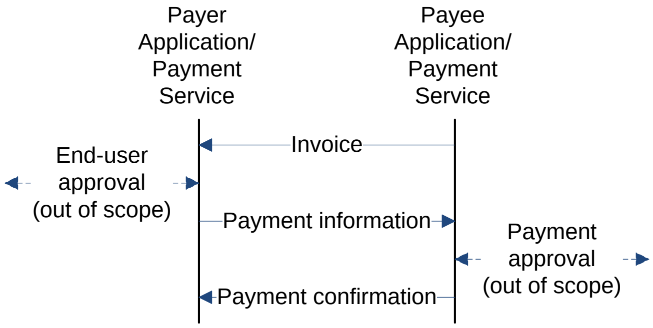


Figure 21: Illustration of "Invoice" scenario in 1609.11

2.4.2.8 Security

Some studies of the security algorithm in trial use standard 1609.2 indicate that it may be too expensive in terms of hardware capability to carry out the required computations. New algorithm have been proposed to reduce the computation requirements. A presentation by Andres Weimerskirch at the February 2009 meeting gave an excellent exposition of these issues, from the point of view of the Vehicle Safety Consortium group of automotive manufacturers (Weimerskirch 2009).

The objective of the privacy algorithm is to ensure security of WAVE operations while avoiding long-term tracking via infrastructure. For example, security algorithms need to handle change of all identifiers of the vehicle: MAC address, J2735 sender ID, certificate, etc. More specifically, security for WAVE should address the following: First, an application should only accept a valid message from a valid unit, within the intended reception time, within valid geographic location. Secondly, devices should not be locked out of the system, which might results in failure of important applications. A good algorithm should satisfy both requirements.

	1609.2 ECDSA	**TESLA**		**TADS**	
Authentication generation	6.5 ms* (ECC-224) / 10 ms (ECC-256)	1.5 ms		8 ms* (ECC-224) / 11.5 ms (ECC-256)	
Authentication verification	26 ms* (ECC-224) / 39 ms (ECC-256)	1.5 ms		1.5 ms (TESLA) / 40.5 ms (ECDSA-256)	
CPU Load for 2 OBEs at 10 messages per second: Signing / Signing + Verifying	13% / 67%	3% / 3.8%		14.3% / 21.7%	
Latency: Min. / Max.	61 ms / 90 ms	*piggy-back*	*separate*	*piggy-back*	*separate*
		91 ms / 123 ms	26 ms / 28 ms	116 ms / 145ms	40 ms* / 42 ms*
OTA packet size (send certificate with each 3rd message and using ECC-256)	115 bytes	102 bytes	167 bytes	141 bytes	210 bytes

Table 6: Performance comparison on OBU at 400MHz (reported by VSC-A)

Currently in 1609.2**,** *ECDSA* (Elliptic Curve Digital Signature Algorithm) is supported to change certificate/MAC/sender ID during service channel and have it available at beginning of control channel. Other authentication protocols for V2V safety applications have been presented. For example, *TESLA* (Timed Efficient Stream Loss-tolerant Authentication) is computationally efficient than ECDSA. TESLA change certificate/MAC/sender ID during service channel and have it available at beginning of control channel. It tries to disclose TESLA key during the same CCH interval in which the TESLA message was broadcast. This is already implemented by generating and broadcasting heartbeat messages at the beginning of the CCH interval. However, this algorithm increases delay. The *TADS* (TESLA Authentication and Digital Signatures) combines benefits of TESLA (computational efficiency) and ECDSA (low latency on demand, non-repudiation). However, TADS increases bandwidth overhead. Another algorithm, *Verify-on-Demand*, only verifies messages that have actual impact and it's compatible with current 1609.2 standard. The performance of ECDSA, TELSA, and TADS is compared in Table 6. The optimal algorithm that balances those factors is still under investigation.

2.5 Summary

Looking at the DSRC standards effort, IEEE 802.11p specifies high-speed short-range wireless communication among vehicles and surface transportation infrastructure. Similar to IEEE 802.11a, 802.11p radio is based on matured Orthogonal Frequency-Division Multiplexing (OFDM) technology. The 802.11p MAC layer functionality is slightly modified to include provision for rapid communication of DSRC devices with no need for authentication or authorization processes as in the original 802.11 standard. In addition to the 802.11p standard, IEEE 1609 defines higher layer functionalities such as networking and multi-channel operations for VANETs. As part of these standards, a new type of message, WSM (WAVE Short Message) is defined in 1609.3, which supports frame-by-frame power and modulation assignment and thus provides new possibilities for cross-layer optimization. To ensure that DSRC applications are inter-operable, other standards may be employed in this architecture For example, SAE J2735 is a message set dictionary (i.e. common languages for DSRC applications to understand each other) that describes DSRC message content. The standardization effort has been equally supported by industry and government entities.

The Wireless Access in Vehicular Environments (WAVE) proposed Amendment P to the IEEE 802.11 Wireless LAN standards (the specifications underlying WI-FI and the related IEEE P1609 family of standards for higher-level networking and applications services, have been designed to meet these challenges. Implementations of these standards will support U. S. Department of Transportation's Intelligent Transportation Systems (ITS) Program and the Federal Highway Authority's Vehicle Infrastructure Integration Initiative. These automotive networking services will operate in a special licensed Dedicated Short Range Communication (DSRC) frequency band that has been set aside by the Federal Communications Commission (FCC) for public safety use.

3. Architecture and Design of Vehicle-Infrastructure Testbeds for Dedicated Short-range Communication

3.1 Overview of DSRC Development

3.1.1 Introduction to Vehicle-Infrastructure Cooperation

The inclusion of the roadside element is a logical extension of Vehicular Ad-hoc Networks (VANET), from the perspective of those with vehicle-centric and also those with infrastructure-centric network applications backgrounds. Consider that stationary motes – or roadside equipment (RSE) – intersect moving cars, and represent the edge of and therefore access to an extensive landside network, replete with existing, or with vehicle-infrastructure cooperation (VIC) replete with *new* user services. The idea of onboard equipment (OBE) and RSE connecting offers a plethora of information-based applications and, important to the traveler, a plethora of information-based services. And what is this plethora of services? Mobility applications should have the basic attribute to deliver dynamic traveler information and may include:

- Traffic and travel conditions, including route specific travel times and delays
- Route assistance and route diversion
- Map database assistance
- Adverse weather information
- Multi-modal trip planning: transit connections, fare information, schedules, and real-time bus/train arrival information, airport and port authority information
- Parking information, to include transit and commercial vehicle parking
- Signal phase timing information (for signal coordination)
- Road surface conditions

Moreover, safety services may include:

- Vehicle-based sensor and communication systems, to include vehicle-vehicle communications
- Cooperative intersection collision avoidance systems, to potentially include signal violation warnings
- Merge assistance systems
- Rear-end collision warning systems
- In-vehicle signing for both static and dynamic and dynamic advisories
- Transit applications such as precision docking and automation

These applications lists are not comprehensive; they are merely a list, and given VIC as an enabler, transportation services that depend on telematics would have the attribute of real time or on-demand information – and the list may grow as large as the marketplace of useful service and application providers and willing subscribers (and their road authorities) allow. Another dimension to this marketplace is provision of on-demand infotainment, as the delivery of these products to vehicles may provide economic incentive to build an infrastructure that provides additional mobility services and to some, the safety imperative.

The real question, then, is how do these services begin to be delivered? A key to the answer will be the existence of RSE which are in two-way communication to cars, or VIC. Given VIC and the existence of a backhaul network to landside operations there can be delivery to and from *the first equipped vehicle* of existent telematics and infotainment services, e.g., travel time information. Subsequently, as OBE-equipped vehicles proliferate, market-penetration-based services available by information exchange between vehicles and the stationary RSE become more real. Take for example, the VII California test bed along North-South corridor in the San Francisco Bay Area, circa 2007: a "mere" presence of 12 RSE intersects an average of 400,000 vehicles a day, traveling three major routes, two limited access freeways and one major signalized arterial. Presuming applications delivered from these RSE provide some benefit to travelers, there is no need to await market penetration to allow acceptable peer-to-peer connectivity and VANET.

In fact, a compelling aspect of having some installation of RSE is that the roadside component and services it may provide could engender bringing OBE into vehicles; what may make this even more compelling is that these OBEs brought into vehicles may not only be automotive company installations, they could be handheld consumer electronic devices that make this short- and medium-range connectivity: mobile phones, perhaps equipped with WiFi or even Dedicated Short Range Communication (DSRC). Imagine dynamic route advisories given to drivers to route themselves out of traffic jams; imagine windshield wiper data giving roadway authorities insight to a moving storm front; imagine the wealth of services that could enhance travel, traffic management and indeed, transportation efficiency and our quality of life.

However, the real DSRC case is safety, and how to deliver the quality of service – that is, low latency and highly available – safety-of-life messages necessary to enact an OBE-to-OBE or OBE-to-RSE/RSE-to-OBE wirelessly-delivered safety message. In this case, the entire network need not be present; rather, the edge of the network car-to-road or road-to-car can exchange detailed in-vehicle information which can be displayed in a nearly immediate and indeed urgent manner to the driver. Imagine an intersection that warns the inattentive driver that the yellow phase will imminently turn to red – and prevent a red light violation; imagine a car that brakes hard or conversely one that brakes moderately, with that safety information communicated via DSRC to the car or string of cars behind such that onboard processors and displays could provide or not provide a warning; imagine again the wealth of services that could enhance safety and along the way also increase transportation efficiency.

The arguments above, one a mobility and efficiency argument and another a safety argument, have led institutions in the United States to mobilize around the 75 MHz of free unlicensed bandwidth from 5.85 – 5.925 GHz and to begin to standardize and institutionalize Dedicated Short Range Communications (DSRC). This, until recently, has been the thrust of the United States efforts in VIC, and this is the starting point of this chapter. However, in order to impart a better understanding of the state of VIC, we will begin a bit more broadly by briefly covering the worldwide context, then describe more pointedly the case in the United States (and probably by *de facto* precedent all of North America). We will describe some of the emergent research with DSRC, some of the conceptual applications, and then we will point toward a possible future that transcends a "just DSRC" wireless paradigm, in work enabled by the United

States Department of Transportation (US DOT), California Department of Transportation (Caltrans) and conducted by the authors. This potential future comes full circle, placing work across many regions of the world into the same trajectory, by recognizing the proliferation of consumer handheld devices in the world and therefore taken by travelers on most trips, and then by leveraging multi-band attributes beginning to appear on these devices and finally transitioning into a world where applications, safety and mobility alike, may be ubiquitously applied across the heterogeneous base of portable consumer devices.

In this section, we first discuss the development of VIC in the Europe, Japan, and the United States. We discuss the current VIC communication technology in the United States and present results on its performance derived using our VII California Testbed. Finally we conclude with our reading of the future of VIC.

3.1.2 Development during 2004-2008

3.1.2.1World Context

The idea of VIC captures the imagination worldwide, and it is interesting to observe the regional and in some cases nation-by-nation ideas and means to instantiate them into a true VIC deployment, and in all dimensions: in wireless communication frequency, in degree of infrastructure at the roadside, in complexity of onboard equipment, in timeline to deployment and in applications or services considered. Clearly, transportation needs, legacy infrastructure and existent policy and other institutional arrangements dictate the degree and ubiquity of ideas.

While there are several world-regional ideas, in this section we describe the European Commission’s Continuous Air interface for Long and Medium distance (CALM) and the Japanese SmartWay efforts. The description is topical and brief, as the primary message is that despite the focus on this chapter on VIC in the United States, there are indeed other ideas, efforts and flavors underway to effect VIC. These ideas – and CALM and SmartWay in particular – have recently influenced thinking and policy in the United States, namely the work therein has posed the questions, “Is there a better way?” and “Isn’t better defined as deployment sooner, not in the distant future?” These are excellent questions and continually asked, they will always point toward new and more relevant research.

The Continuous Air interface for Long and Medium distance (CALM) is integral to the European Commission’s Cooperative Vehicle-Infrastructure System (CVIS) effort, as it provides both an architecture and a means to interweave existing protocols such that multiband communications may occur simultaneously, and in principle seamlessly. Therefore, in essence, transportation applications may be delivered to a consumer device which has, for example, a 3G communication channel. As market forces drive the consumer device to more and more connectivity, such as 4G (such as WiMax), WiFi or even IEEE 802.11p DSRC, the handheld device operating under the CALM architecture will be able to still enact two-way communication.

Therefore, CALM aims to integrate into an intelligent agent that arbitrates between and provides security between nearly 25 different standards, many still in progress, and if and when those standards roll out, CALM-compliant handheld platforms may be a communications link-neutral or -independent applications environment. Via CALM and potentially as applied by

CIVIS, the transportation system manager will receive traffic probe data, and the traveler will in turn receive local map data and that hoped-for plethora of various other services.

In October, 2007, several years' work in leveraging existing infrastructure and programs, "Smartway 2007" was demonstrated by the Ministry of Land, Infrastructure and Transport and the Transport National Institute for Land and Infrastructure Management. Smartway was hosted on the Tokyo Metropolitan Expressway and was the culmination in delivering a prototype of what the Japanese call an "on-board ITS experience". It delivered in demonstration fashion an ensemble of mobile services, either via integrated center console driver interface or through an aftermarket audio-only version. Central to Smartway is VIC, as services were all delivered by wireless. Services delivered fall under three categories:

- Near real-time driver assistance
- In-vehicle messaging
- Two-way communication, which enables e-payment or tolling.

In Japan, there are unique technological and institutional underpinnings and years of public- and private-sector investment the Japanese surface transportation system. To wit, virtually every new car sold in Japan is equipped with an in-vehicle navigation system additionally equipped with a Vehicle Information and Communication System (VICS) component. Therefore, as a significant Smartway enabler, road and congestion state information for major arterials and limited access highways is aggregated by the Japan Road Traffic Information Center, transported to the VICS Center, then delivered by optical (IR) beam or 2.4 GHz radio beacon back to cars. The widespread adoption of VICS has allowed cars to serve as probes, which multiplies the efficacy of this system.

As a second significant Smartway enabler, at the time of the demonstration, approximately 75% of all cars using toll roads in Japan were equipped with 5.8 GHz DSRC-based Electronic Toll Collection (ETC), developed to Japanese standards and implemented by most expressway authorities in Japan. This particular DSRC range is 30 meters, sufficient to accomplish its primary purpose providing the short range communications link for an automated tolling transaction.

Therefore combining the two enablers, or fusing VICS and ETC onto one OBE, allows probe information already available from VICS to be sent via DSRC from the infrastructure to the vehicle and vice versa. This new OBE serves as a gateway for telematics applications to be delivered from the roadside to the vehicle and then displayed in the VICS-equipped navigation unit. Importantly to VIC deployment, hardware development with such a system based on this unique Japanese legacy was not difficult. Essentially, the primary tasks are to develop applications delivered through the landside portion of the network and deliver by existing communication means to the Smartway OBE and to the customize user interfaces. Thus, a total of eight Smartway applications were demonstrated:

- Milepost ('positional') Information: Delivery of Changeable Message Sign- and overhead sign panel-equivalent in-vehicle signage of distance to exits or significant destinations.
- Audio Messaging: Link times provided through in-vehicle auditory means, e.g, "10 minutes to Exit A."
- Merging Assistance: Visual and audio information provided at merge point when other vehicles, perhaps occluded, merge onto the mainline or vice versa.

- Information on Conditions Ahead: Visual and audio information – to include a still-frame video detection camera output – of congestion on the upcoming roadway. In Japan, the particular siting would be at tunnel entrances or other known bottlenecks, e.g., "Current traffic flow ahead of Gaien entrance about 1 km ahead" as caption to a surveillance camera image."
- Parking Lot Payment: E-transactions conducted via credit card-through-DSRC transaction at a parking lot adjoining the Metropolitan Expressway
- Internet Connection: Delivery of http via 5.8 GHz DSRC brought to the vehicle within the aforementioned parking lot. Internet content is carefully controlled in the demonstration, but the attendee can envision the freedom of the internet through this demonstration.
- Road Alignment: Use of an onboard map database, which when combined with vehicle speed, enable delivery of curve overspeed warnings, e.g., "Sharp curve ahead! Drive carefully."
- Obstacle Warning: Particularly important with upcoming blind curves, visual and audio information on stopped vehicles around the bend of the curve is provided, e.g., "Congestion ahead! Drive carefully."

3.1.2.2VIC in the United States

The roots of DSRC in the United States may be formally traced to 2003, when the Federal Communications Commission (FCC) adopted what is termed a Report and Order that provided licensing and service rules for DSRC in the ITS Radio Service. This enabled free, licensed use of the 5.850-5.925 GHz frequency range, primarily for use in safety but also for other transportation and commerce applications. It was originally conceived as a general purpose RFID technology. In making implementation decisions, however, it was quickly recognized that the IEEE 802.11 wireless local area networking technologies represented a better base for DSRC. In particular, DSRC came to be based on the IEEE 802.11a OFDM sub-family which over time came to be the dominant home and enterprise wireless LAN product. The economies of scale obtainable by piggybacking DSRC on 802.11a made this case compelling during the standards discussions at the time.

There emerged three sets of standards and concomitant application ideas *(1-3)*. The wireless standards are those within the IEEE 802.11 Wireless LAN family, with the DSRC spectrum and band plan comprising IEEE 802.11p, then a transition to the enabling IEEE 1609 standards for Wireless Access in Vehicular Environments (WAVE) – the resource manager, or 1609.1; security services and management, or 1609.2; networking services, or 1609.3; and finally, multi-channel operations or 1609.4. It is the combination of these standards and particularly the last, or IEEE 1609.4 that enables channel switching and a control channel scheme, wherein safety services may be primarily provided, but other channels in the IEEE 802.11 band plan to be switched to during non-critical (to safety) periods.

The final or top layer standard would be the application layer, SAE J2735, under development by the Society of Automotive Engineers, DSRC Technical Committee. Because the focus of this chapter is on the potential transportation applications from VIC, we choose to quote the emergent SAE J2735 Standard, as that states the case and frame the antecedent and additional IEEE standards within the end-use or applications domain. The stated case is a safety case:

Safety applications, in particular, must be interoperable between vehicles from different manufacturers and between vehicles and roadway infrastructure within all the areas where the vehicle is likely to travel. This requirement for interoperability is also relevant to contemplated mobility applications. This SAE Standard specifies initial representative standard message sets, data frames and data elements that allow interoperability at the application layer without the need to standardize applications. This approach supports innovation and product differentiation through the use of proprietary applications, while maintaining interoperability by providing standard message sets that can be universally generated and recognized by these proprietary applications.

The message sets specified in this SAE Standard depend upon the lower layers of the DSRC protocol stack to deliver the messages from applications at one end of the communication system (for example, in a vehicle) and the other end (for example, in another vehicle). The Standard then describes how the aforementioned lower layers support, at the top, ground transportation and in particular safety applications.

The WAVE communications system is designed to enable vehicle-to-vehicle and vehicle-to/from-infrastructure communications in order to provide a common platform to achieve the safety, mobility and commercial priorities... Interoperability is a fundamental requirement of this common platform, and WAVE is designed to provide the required interoperable wireless networking services for transportation. As well, the WAVE system uniquely supports the high-availability, low-latency communications requirements of vehicle safety applications, such as pre-crash collision mitigation, intersection collision avoidance and cooperative collision avoidance.

The physical layer (PHY) of the WAVE system is defined in IEEE P802.11p. In general, the WAVE PHY provides a control channel (CCH) and multiple service channels (SCH). The range of this system is generally considered to be line-of-sight distances of less than 1000 meters. The PHY has been optimized to support usage by vehicles traveling at highway speeds. IEEE P1609.4 provides enhancements to the IEEE 802.11 medium access control (MAC) that support WAVE safety, mobility and private applications in a multi-channel system by specifying mechanisms for prioritized access, channel routing, channel coordination and data transmission.

The upper layers of the network stack, up to the application layer, are defined in IEEE P1609.3. There are two pathways through the WAVE upper layers above the LLC layer: the Wave Short Message Protocol (WSMP) stack and the UDP/IP stack. IEEE 1609.3 describes networking services for applications running over either of these stacks, as well as describing the operation of the WSMP stack. Transmissions on the CCH are limited to WAVE Short Messages (WSM). Either WSMP stack or UDP/IP stack may be used for communications on SCHs. The WSMP stack is generally used for broadcast applications.

IEEE P1609.2 defines secure message formats, and specifies how these secure messages are processed within the WAVE system. These security services are designed to protect messages from attacks such as eavesdropping, spoofing, alteration and replay, while respecting end users' rights to privacy. The messages covered in IEEE P1609.2 security procedures include WAVE management messages and application messages, but do not include vehicle-originating safety messages. Security services for vehicle-originating safety messages have not yet been specified in any standard, but will be required before vehicle safety applications can be deployed.

These enabling standards have been regarded as an essential and parallel complement to the US DOT's Vehicle-Infrastructure Integration (VII) Program. Their adoption was considered integral to interoperable system of vehicles and the roadside holds significant promise roadway operations and safety. This promise captured interests of local, regional and state stakeholders in tandem with interest from the US DOT and, in particular, the automotive industry. They fed a vision of a roadside-based network delivering low-latency, highly reliable data communications to support safety and mobility services to users.

Indeed, the integrated transportation data network would be of unprecedented scope and complexity – and that complexity was imagined: the fully deployed system would include onboard equipment (OBE) installed on every new vehicle manufactured after a specified date and RSE installed at all signalized intersections in major urban areas, at primary intersections in other areas, at all highway interchanges and along major intercity and many rural highway. This coverage would be extensive, as the proposed VII system would cover all urban roads within 2-minute travel times, 70% of all signalized intersections in 454 urban areas; and as a vehicle OBE complement to this network of RSE, up to 15 new million vehicles per year would be DSRC- and therefore VII-equipped. This has been likened to an unprecedented marriage between industries and the public sector to a scale hitherto not imagined, especially in the transportation sector.

In addition to the across-the-board recognition that high QoS safety applications would be an important development, an allure to the automotive industry would be the delivery from an essentially 'free' wireless network (that is, if one discounts the tax dollars that may ultimately pay for it) would be available to deliver telematics and infotainment content to drivers. An additional allure to roadway operators and planners is that VII would make it possible to collect transportation operations data of great breadth and depth, to implement sophisticated traffic safety systems, and to manage traffic flows with previously unthinkable precision. From this vision, the process of developing the answers to such an ambitious endeavor would consume considerable time and effort at the US DOT level, that is, the VII program. In addition, lessons for deployment might be learned from regional efforts, notably in Florida, Michigan and California and most certainly in the forthcoming US DOT VII Proof of Concept experiments.

3.1.3 Making the US Technology Work – VII California Testbed

It is imperative to note that within the push-pull between national and more local interests, a literal and figurative divide emerged: differences between deployment models and their applications became increasingly obvious. Would the US DOT "big bang" prevail? Or would local or regional needs grow separate regional areas where some type of VIC would locally manifest?

Focusing on California, State and regional stakeholders have specific transportation infrastructure, operating policies and needs than what may be universally addressed with a national VII program. These needs led to a partnership between the California Department of Transportation (Caltrans) and the San Francisco Bay Area Metropolitan Transportation Commission (MTC). Caltrans and MTC began addressing these needs with a multiyear effort to develop, demonstrate and deploy a VII tested in a key corridor in Northern California with a formal program testbed design, development, installation, associated engineering. This corridor is comprised of roughly ten-mile segments of two routes North of Palo Alto and South of the San

Francisco Airport. It encompasses two highways: State Route 82 and US 101. This selection addresses both a high-volume freeway (US 101) and a major arterial complete with signalized intersections (SR 82), shown below in Figure 22.

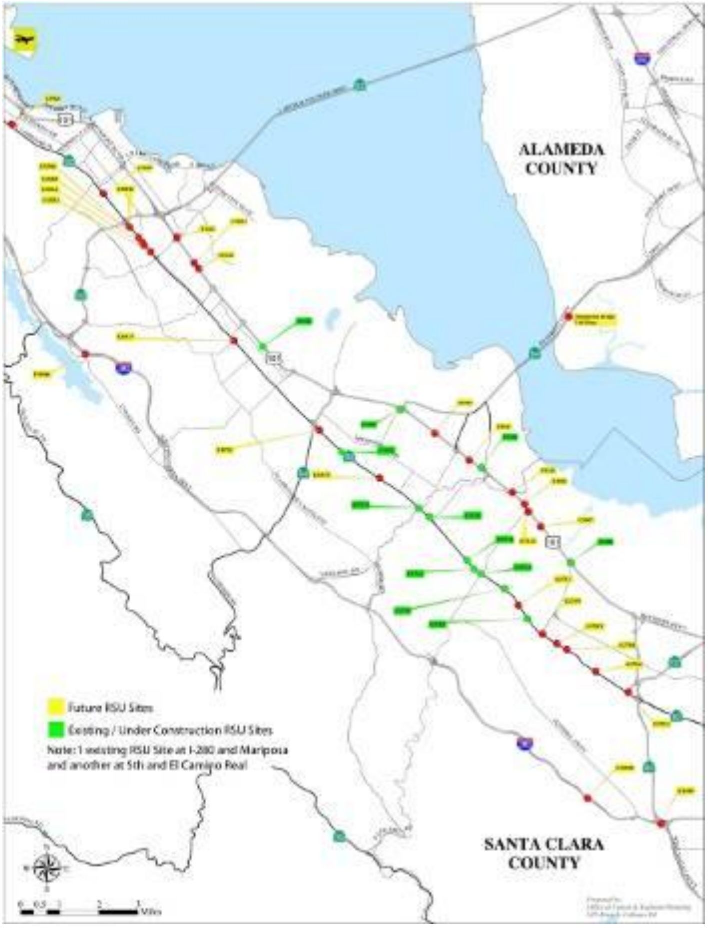


Figure 22: A map of the VII California Testbed (November, 2007).

Installed testbed in green; planned expansion in red.

Overall, the Caltrans and MTC aim in VII California is to:

1. Evaluate exemplar public use cases from which we can generalize VII feasibility;
2. Evaluate institutional, policy and public benefit issues;
3. Explore wireless communication deployment issues and options;
4. Resolve key technical issues involving implementation and operation;
5. Assess implementations of the VII infrastructure, architecture and operations; and
6. Support private sector evaluation interests.

The basis and requirements for the testbed are the VII use cases and in particular the public sector use cases. This list was developed to corroborate with distinct Caltrans and MTC state and regional interests, which in turn address the specific San Francisco Bay Area; moreover, private use cases (item 6) rounds out the set of applications:

1. Traveler Information
2. Ramp
3. Electronic Payment (Tolling)
4. Intersection Safety
5. Curve Overspeed Warning
6. OEM-specific Applications

The VII California test bed, described below, was essentially the on-the-road, large scale laboratory built expressly to address these goals and applications.

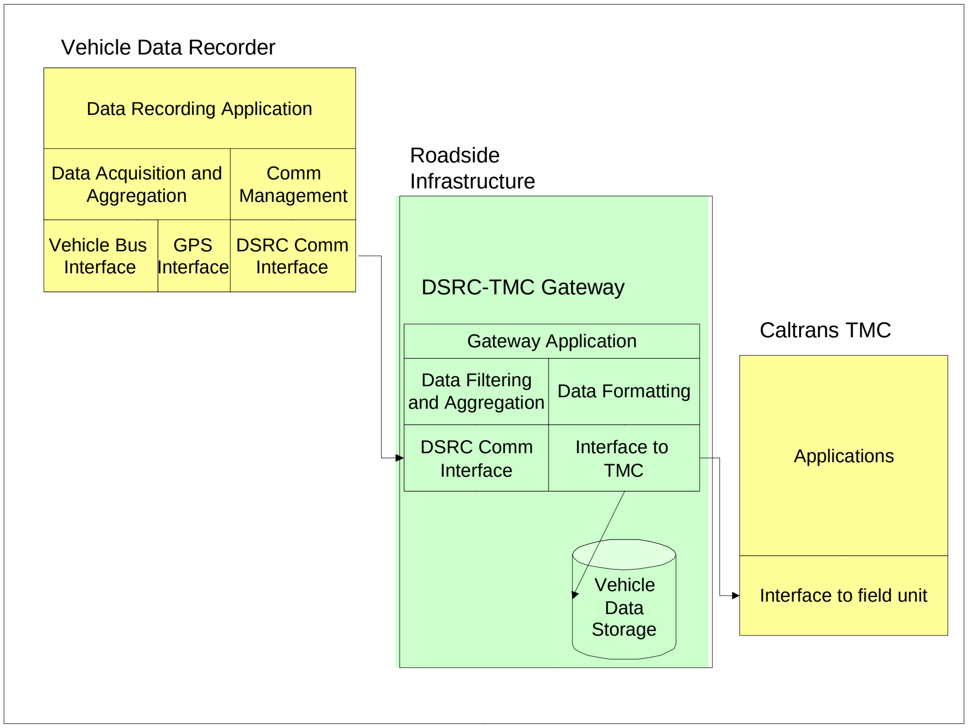


Figure 23: Roadside and Backhaul Communications Architecture. This allows data to move from the vehicle, through the roadside infrastructure and to the VII California network.

3.1.3.1 Elemental Building Block within Network: Roadside Equipment

The hardware experience accrued in developing the VII California test bed focuses on the RSE and its connection to the existing Caltrans roadside appurtenances and their function. The RSE is the basic infrastructure building block for VII. Each RSE serves as an in-the-field gateway between locally transmitted vehicle data and the roadside communications infrastructure. At top level, an RSE is a computer with a radio transceiver and an antenna. The computer must have sufficient processing and storage capability to run a gateway application between its two network interfaces, DSRC and back-haul (to the Traffic Management Center and other servers), and to run additional local safety processor software, with data filtering, buffering, aggregation, and formatting, as needed, and illustrated in Figure 23.

The RSE is therefore between the vehicle and the roadside backhaul network (which might already exist), providing the necessary interface. Physically, it could sit in a Type 332 cabinet, and it would consist of a wireless transceiver (with antenna) atop the cabinet and a computer within the cabinet, with connections.

The initial VII California computer was designed to explore a variety of applications and therefore consists of a PC-104 stack with processor and a PCMCIA card with connection to the WAVE radio and antenna. To fit within the Type 332 cabinet, form factor is low: approximately 6” x 6” x 12”. Power is standard 120V AC, with low current draw. A schematic of the VII California connected RSE, residing within a traffic controller cabinet, is shown in Figure 24.

The hardware is split into two main clusters. One resides in the roadside cabinet and the second in a separate weatherproof enclosure. This design minimizes the length of the 5.9 GHz antenna cable to maximize signal strength. Some installations require a separation of up to 200 feet between the existing roadside cabinet and the location where the 5.9 GHz antenna needs to be in order to provide coverage of the approaching roadways. Figure 25 illustrates a typical RSE installation.

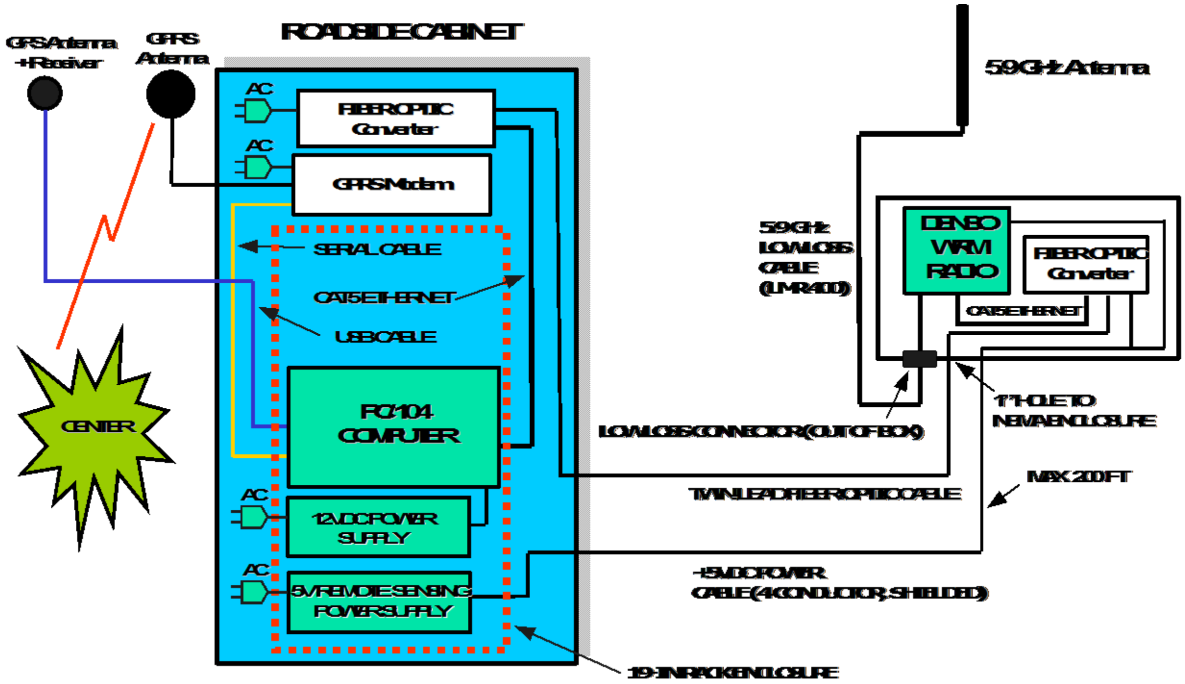


Figure 24: Schematic of VII California RSE Components

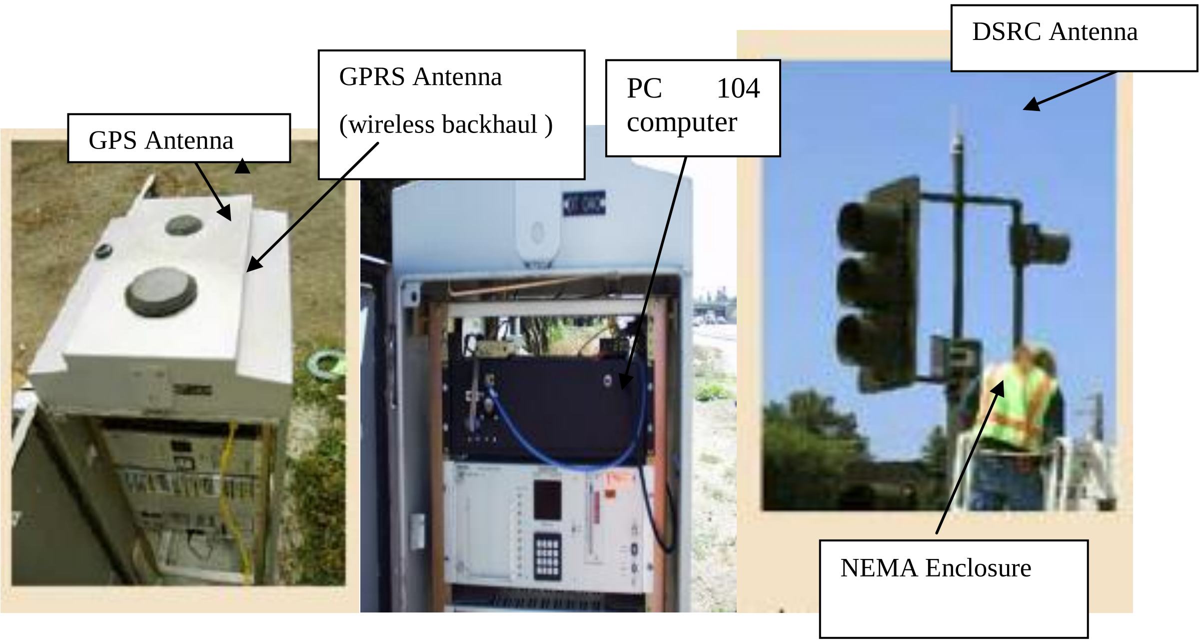


Figure 25: Left and Center: VII California RSE Mounted in Type 332 Cabinet on Caltrans Right of Way; Right: DSRC Radio Enclosure and Antenna Mounted on Ramp Meter Signal Pole at Freeway Onramp.

3.1.3.2The RS-UDP Transport Layer Protocol

While the aforementioned description of the hardware sets the stage, the primary objective of the test bed is to conduct experiments, or in other words, to operate the test bed. The network architecture and software, therefore, is in many senses more interesting – and at the very least, quite important.

A major goal of the VII California testbed is to support an initial set of applications, including probe vehicles, public information providers, and bidirectional non-public services (such as navigation and tolling). The testbed has been used as a development laboratory, with experiments and small-scale demonstrations of these applications conducted with public and vehicle manufacturer partners, starting in 2005. Heavy use of this test bed has exposed a number of issues for future VII implementations and has motivated development of a message transport layer built on top of IP networking, a set of VII application servers, in-vehicle libraries, and administration tools.

The characteristics of this software are best examined against the background of the constraints, many of which exist with any transportation and many wireless network implementations and therefore important to note from a ‘lessons learned’ perspective:

1. The compressed development schedule has required the use of prototype-quality hardware. The Denso DSRC Wireless Access for Vehicular Environment (WAVE) Radio Modules used initially in the RSE is particularly limited: they cannot transmit packets to more than four hosts on their wired side and they cannot assign dynamic

IP addresses to vehicles. Firmware for several components (including DSRC radios and cellular modems) evolved to new generations during the project.

2. The backhaul network is heterogeneous, ranging from cellular modem to dedicated T1 landline. Hence, not all sites can support all services. Furthermore, this diversity requires built-in limits on roadside-to-server communication, such as buffering, prioritizing, and possibly probe data aggregation.
3. The inherent unreliability of mobile wireless networks requires a degree of robustness. Packet loss is likely in an environment with nodes traveling at high speeds with limited range, line-of-sight occlusions, and RF interference. No application can expect to have long-lasting, consistently available connections.
4. Application messages can be long. Probe messages can be up to 64 KB with multiple snapshots.
5. The transport layer should present VII California application code with an interface for communication between vehicles and servers that is message oriented (like UDP, User Datagram Protocol) but has inherent quality of service controls (to some extent like TCP, Transmission Control Protocol). It must be somewhat reliable, but not at the cost of excessive use of the channel. We call this new protocol RS-UDP.
6. Information from the vehicle must be kept as private as possible.

Within these constraints, the VII California transport layer (RS-UDP) succeeds in several ways:

1. The first packet from the vehicle to the server is a data packet; there is no delay for dynamic IP address assignment (DHCP) association, internet transmission control protocol (TCP) session initialization, or other handshaking. The reduction in delay increases the chance that a return message (if any) will be received before the vehicle goes out of range.
2. Message reception probability is robust in the face of short-term failures. The transport layer can detect the loss of a fraction of the packets in a message and retransmit the missing fragments. If packet loss is not extensive, this will quickly and efficiently complete the message transmission. Unlike TCP, if no fragments arrive, no bandwidth is wasted resending them, and no bandwidth is wasted on acknowledgment packets.
3. The suite includes a proxy which runs on the vehicle side to insulate vehicle code from the complexity of the wireless user datagram protocol (UDP protocol) and provide it with a TCP socket interface for sending and receiving messages.
4. On the server side, similarly, the interface to the transport layer is a TCP socket, with multiple vehicle sessions multiplexed in one TCP session using transaction IDs.
5. Message addressing is encapsulated across the wireless link to overcome the Denso limitations.
6. No identifying information from the vehicle (outside of the application payload) propagates farther than the roadside or is stored anywhere.

Certain aspects of a complete VII architecture are not fully addressed by this prototype software, including security, scalability, and conformance to emerging national VII standards.

Part of the material in Section 3.1 can be found in (Dickey/Misener/VanderWerf/Sengupta 2009).

3.2 DSRC Testing Procedures and Results

3.2.1 Introduction

The adoption of the IEEE 1609 Dedicated Short Range Communication (DSRC) / Wireless Access in a Vehicular Environment (WAVE) family of standards for trial use in 2006 (U.S. Department of Transportation, 2006) has given the public sector and the auto industry a well-worked-out framework for conducting proof of concept testing. However, there are many performance issues that require further research to ensure a safe and robust highway communication system. Simulation work such as that in (J. Yin et.al., 2004) and radio prototype and application feasibility development, as has been done by the Vehicle Safety Communications Consortium (Krishnan, 2006) and by exhibitors at the Innovative Mobility Showcase at the 2005 ITS America World Congress, among others, provides a solid basis for continued development, but changes from technology specifications in the current trial use standards may be required before full deployments (Misener and Shladover, 2006; Larsen and McKeever, 2006; ITS America Library Resources, 2005.)

Performance under congested traffic conditions remains an open issue. The density of vehicle communications on crowded freeways and busy intersections is high compared to the typical office WIFI hotspot, and furthermore highway communications are expected to include an unusually large number of broadcasts. Analysis and simulations cannot accommodate the full complexity of practical systems with large numbers of vehicles in close proximity. Overall performance depends not only on physical layer channel effects and on the performance of backoff at the 802.11 MAC layer, but on operating system and application structuring and scheduling of messages. Some standard 802.11 techniques for congestion mitigation, such as the Point Coordination Function, are not possible with vehicular systems because the set-up time is too long to be effective in a situation where many transmitters and receivers are entering and leaving the network in a short period of time. More research is needed to characterize the magnitude of congestion problems and the total amount of communication possible using real hardware in the field and to investigate methods of congestion mitigation.

In addition to the problem with the density of communications, safety applications have critical latency requirements. Communication measurement tools are often only concerned with the aggregate data transfer rates and error percentages, and do not measure the latency of individual messages. However, in DSRC systems the latency may be the limiting parameter on the data transfer rate of the system, since the system load cannot be allowed to rise to a rate that will delay crucial safety communications.

The work described in this report represents first steps in using inexpensive computer hardware with prototype radios to explore performance issues for multiple On-Board Units (OBUs, radios in the vehicles) approaching a Road Side Unit (RSU). A major motivation for this research is the scenario described in the proceedings of the December 2004 DSRC workshop (Broady Cash, 2004) in which many vehicles come in range of a transaction service advertised by a Road Side Unit simultaneously and immediately switch to a service channel and begin broadcasting.

3.2.2 Computer and Radio Equipment

The equipment used for our tests takes advantage of the availability of inexpensive miniature microprocessor portable assemblies. Four assemblies were constructed, each containing three 400 MHz gumstix expansion boards with two Ethernet ports (Gumstix, 2006) (see Figure 26). Funding for the equipment was provided by ARINC Corporation, as part of their work on DSRC for USDOT. ARINC also supplied 12 Mobile Mark magnetic mount antennas specially constructed for the 5.9 GHz frequency. Each of the 12 individual computers runs an embedded Linux system and has two Ethernet interfaces. On one Ethernet interface it is paired with its own Denso WAVE Radio Module (WRM) and rooftop antenna; on the other it can be connected to a host computer for data storage.

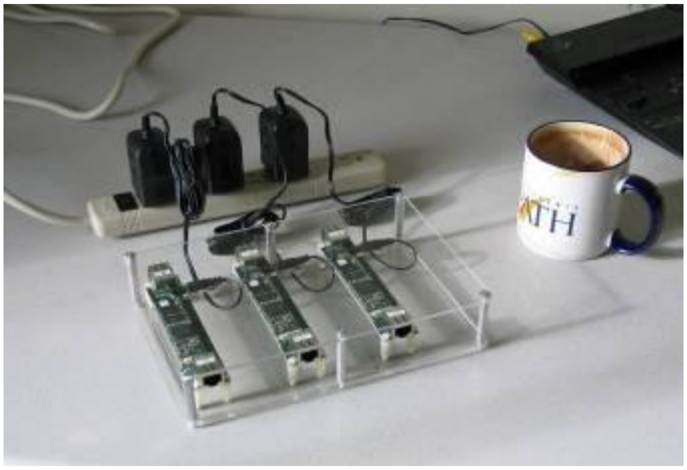


Figure 26: Assembly of three gumstix netduo expansion boards.

The assemblies were designed for flexible configuration. All the assemblies can be connected via a router and deployed in one vehicle for tests to an RSU, or individual assemblies can be placed in different vehicles for vehicle to vehicle research or to test multiple approach paths to an RSU simultaneously. For most of the tests described in this report, the gumstix processors are connected through the router to a laptop, which provides a networked file system where trace data from the test run can be stored. In some tests, the laptop is also connected through a USB port to a GPS unit, so that location can be saved as well. All processors are synchronized through the router.

3.2.3 Data Acquisition Software

There are issues with measuring latency, the delay in receiving a message, as well as overall rate. While many utilities, such as the ubiquitous ping and the widely used iperf, exist to give estimates of the performance of a network link, more thorough tracing is required in the case of DSRC. Because the characteristics of the link change as stations come closer together and move apart, average data transfer and round trip time measurements do not provide enough information to diagnose and elucidate link breakdown conditions. We developed programs for this project that allowed us to trace round-trip time on a message by message basis, accounting for clock skew in the process.

The basic programs developed for this project included a sender, a receiver and a monitor process. The monitor process runs on the same system as the sender and records the round trip information when a return packet is received from a receiver. Two additional convenience programs evaluate the clock skew between a system and its network neighbor, and set the clock based on a message received from the clock skew program. These processes use a library API for communicating with the Denso WRMs that implements the low-level processing of the IP headers and raw IP packets that is required in order to record Received Signal Strength Indication values for each packet.

Figure 27: Antenna placement with 8 active OBUs on one vehicle

The processes can all be configured for different power, channel and rate settings of the Denso WRM. The send process can additionally be configured with the number of bytes per packet, the time interval between sends in milliseconds, and the total number of sends in a run. Data recorded by the monitor process at the originating sender for each round-trip packet were: time that the monitor process recorded the data; destination (RSU) IP; sequence number; number of bytes in packet; time packet was originally sent; time packet was received at remote system ;time return packet was received by monitor program; estimated one-way transmission time; average one-way transmission times over course of run; estimated absolute value of clock skew between OBU and RSU; RSSI at remote host ; RSSI read at sender clocks on hosts and gumstix were synchronized at the start of the experiment, and post processing was used to interpolate GPS data and assign values for UTC time, latitude and longitude to all received packets.

3.2.4 Baseline Testing

As part of our base line testing, we first needed to determine that we were able to measure communication delays, and delays due to interference in communication. There was a question at the start as to whether operating system scheduling delays would make it difficult to measure communications effects. Figure 28 below shows that the basic trip time between two systems in good communication, with no competition from other stations for the airwaves, is typically 2-3 milliseconds.

While the actual time transferring the symbols on the radio medium is much less than this, this includes the time buffering and copying the message on transmission and reception, and scheduling the application processes that are the source and destination of the message. Figure 29 shows the situation when two different stations are sending messages pairwise at a moderate rate. Competition for the airwaves between the two pairwise streams causes the round trip time to rise to between 3-5 milliseconds. Figure 30 shows how a high rate of transfer between two computers can cause greatly increased delay on a pairwise stream between two other computer communicating at a more moderate rate. Note that the trip time scale on this graph is in seconds, not in milliseconds as for the previous trip time graphs. See on the lower graph in Figure 30 that on the higher rate stream packets were actually dropped, due to exceeding the retry limit, between sequence numbers 1454 and 1746.

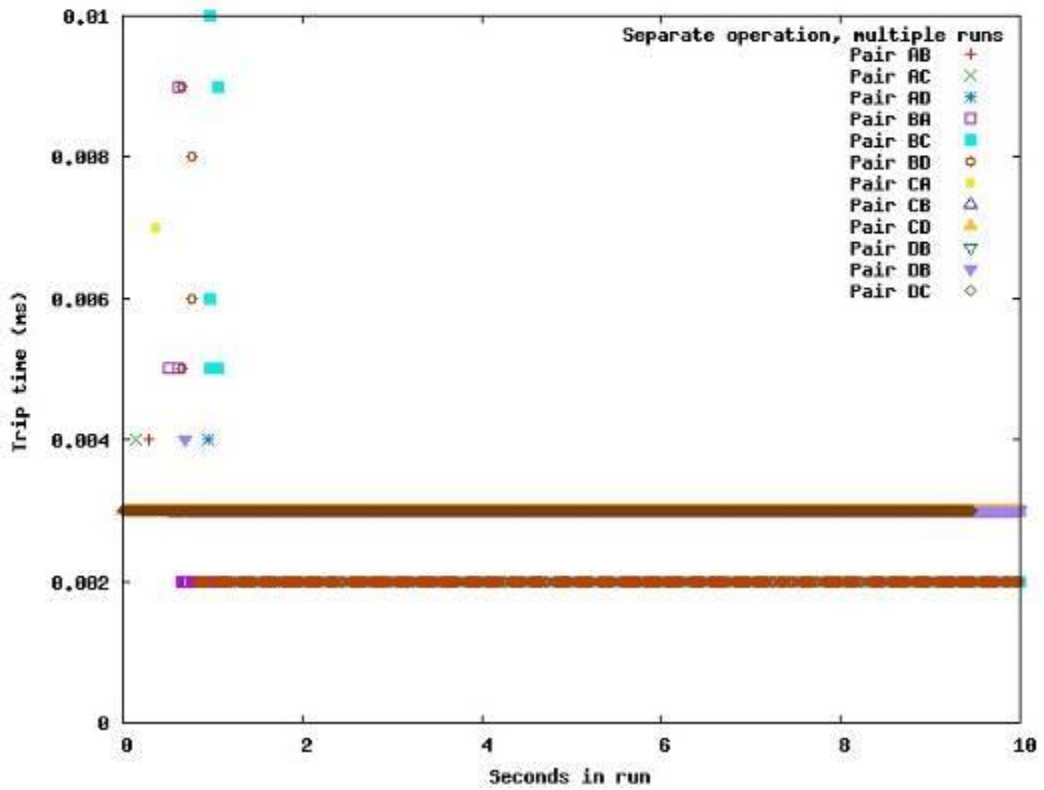
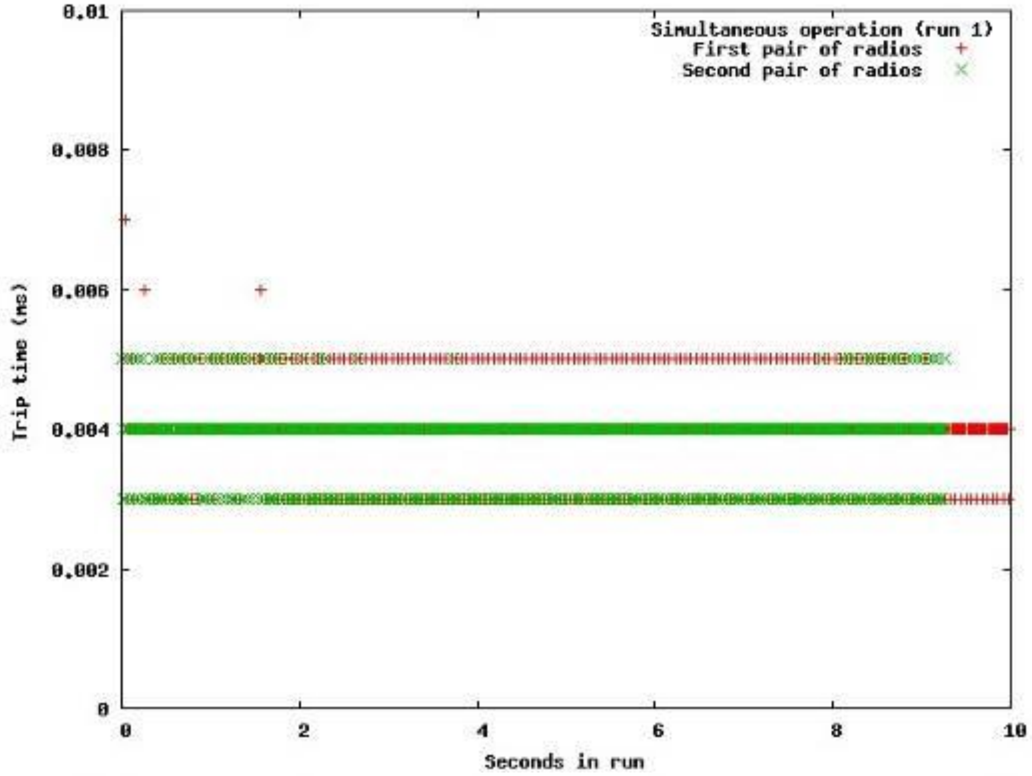


Figure 28: Baseline operation, 1480 byte data per packet, 10 millisecond interval between sends, different pairwise runs of the four stations used for desk checking



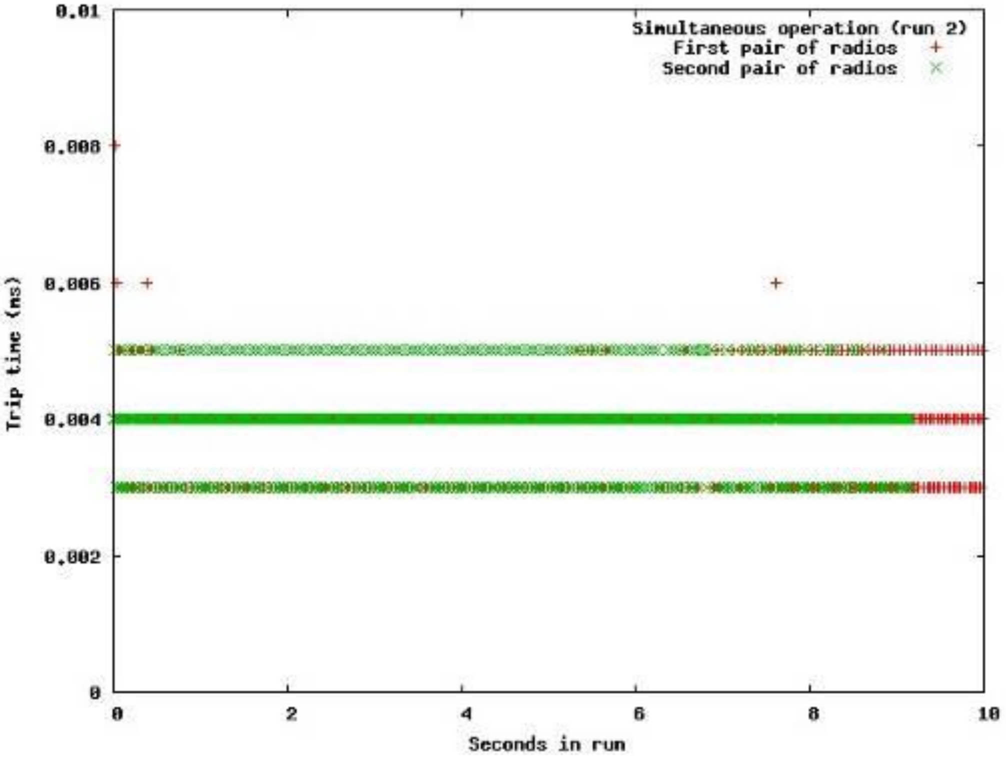


Figure 29: Two runs showing interference between two pairwise communication streams causing slightly increased trip time (1480 byte data per packet, 10 millisecond interval between sends on both streams)

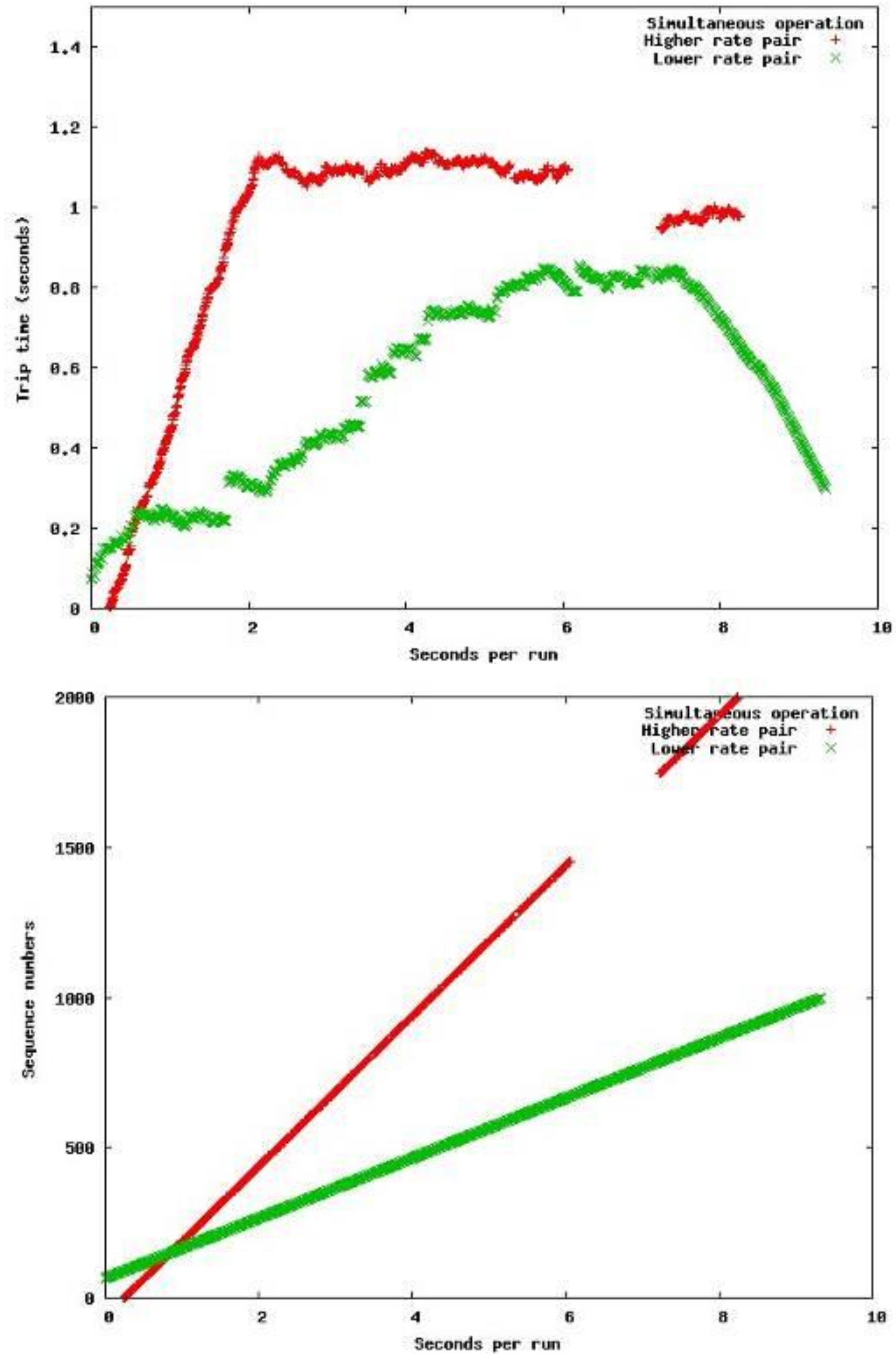


Figure 30: Large increase in trip time due to interference between a higher rate pairwise communications stream (1480 byte packets at 4 ms interval between sends) and a lower rate stream (1480 bye packets at 10 ms interval between sends). Note that the scale for trip time is in seconds; the lower graph shows sequence numbers.

3.2.5 Effects of Channel Switching

The prototype Denso WAVE Radio Modules that we were using for this preliminary testing were not designed to switch channels fast enough in order to allow a 50 ms control channel period and a 50 ms service channel period, as specified in the IEEE 1609.4 standard. However, we were interested in seeing how well communication could be maintained across channel switches even under adverse circumstances. We also wanted to test how well the gumstix processors were synchronized across the router. We found that, while for infrequent channel switching it was possible to continue communications with only a small percentage of lost packets, when channel switching was more frequent it was impossible with our current equipment to maintain synchronization well enough to avoid significant losses.

We began by performing a set of tests, with stationary equipment in close range. Five gumstixs acted as "vehicles" sending to a sixth used as the "road side unit" or receiver. Channels were switched between 172 and 178 by a background process running on the host laptop that sends a message through the router telling each gumstix processor when it is time to switch channels. The gumstix processor writes a record to the shared file system of the time of the switch. Clocks on all gumstix processors are synchronized before the start of testing.

Testname	Switch interval (between channel changes)	Packet Interval (between sends)	Packet size (data bytes)	Load at Receiver (bytes/sec from all senders)
sw0	No change	100ms	200	10K
sw1	5 sec	100ms	200	10K
sw2	5 sec	200ms	200	5K
sw3	5 sec	50ms	200	20K
sw4	100ms	25ms	200	40K
sw5	100ms	10ms	200	100K

Table 7: Parameters used for tests of frequent and infrequent channel switching.

Figure 31 below shows the baseline case with no channel switching. Note that in these graphs the sequence numbers for the different processors have had a constant added so that they appear in different Y ranges; in fact the sequence numbers begin at 1 for every invocation of the program. Figure 32, with case sw1 indicates that infrequent channel switching causes little or no degradation in performance. Figure 33 shows that for this run the channel changes on the different gumstix processors are clustered within about 10-15 ms of each other, with delays through the router from the host laptop where the channel switch directive is initiated and scheduling delay on the individual processors adding up to this amount.

Figures 34 and 35, cases sw2 and sw3, show no appreciable difference from case sw1. However, for case sw4, as shown in Figure 36 the increased overall load and increased channel switching. have caused some dropped packets (evidenced by missing sequence numbers) and some round trip times over 5ms. Notice in the close-ups in Figure 37 how for some processors, the time they are on a channel is skewed enough away from the time of the receiver that they may successfully send only one or two messages while they are connected on the same channel. Figures 38 and 39 show that these effects are more pronounced with the larger load. Overall system load on the router may also be contributing to the greater skew on channel switch times, when sw5 is compared to sw4.

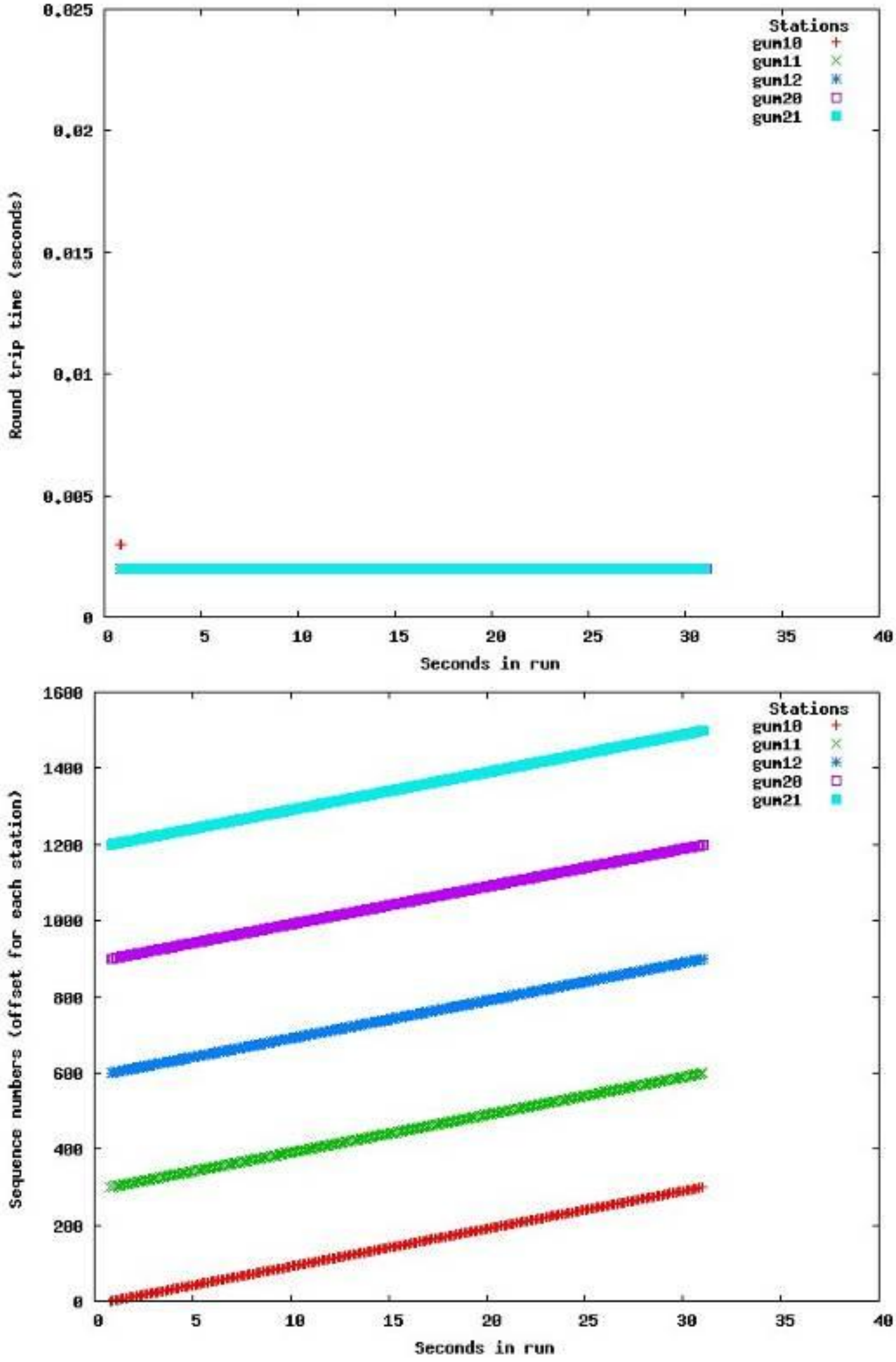


Figure 31: Baseline case: no channel switching, light load.

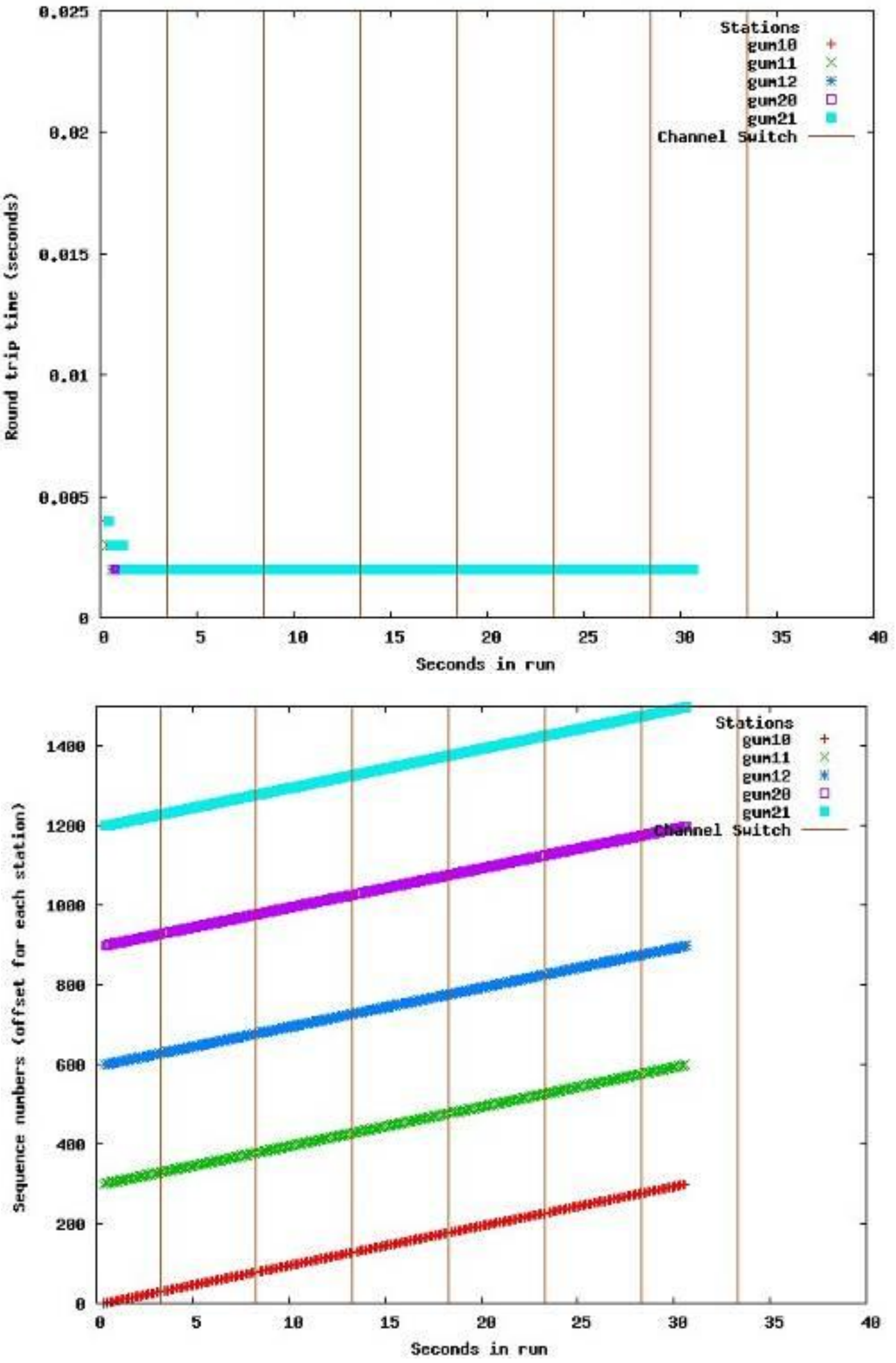


Figure 32: Infrequent channel switching, messages sent at 10 Hz. (t1); each channel switch is indicated by a vertical line, at that point the channel changes

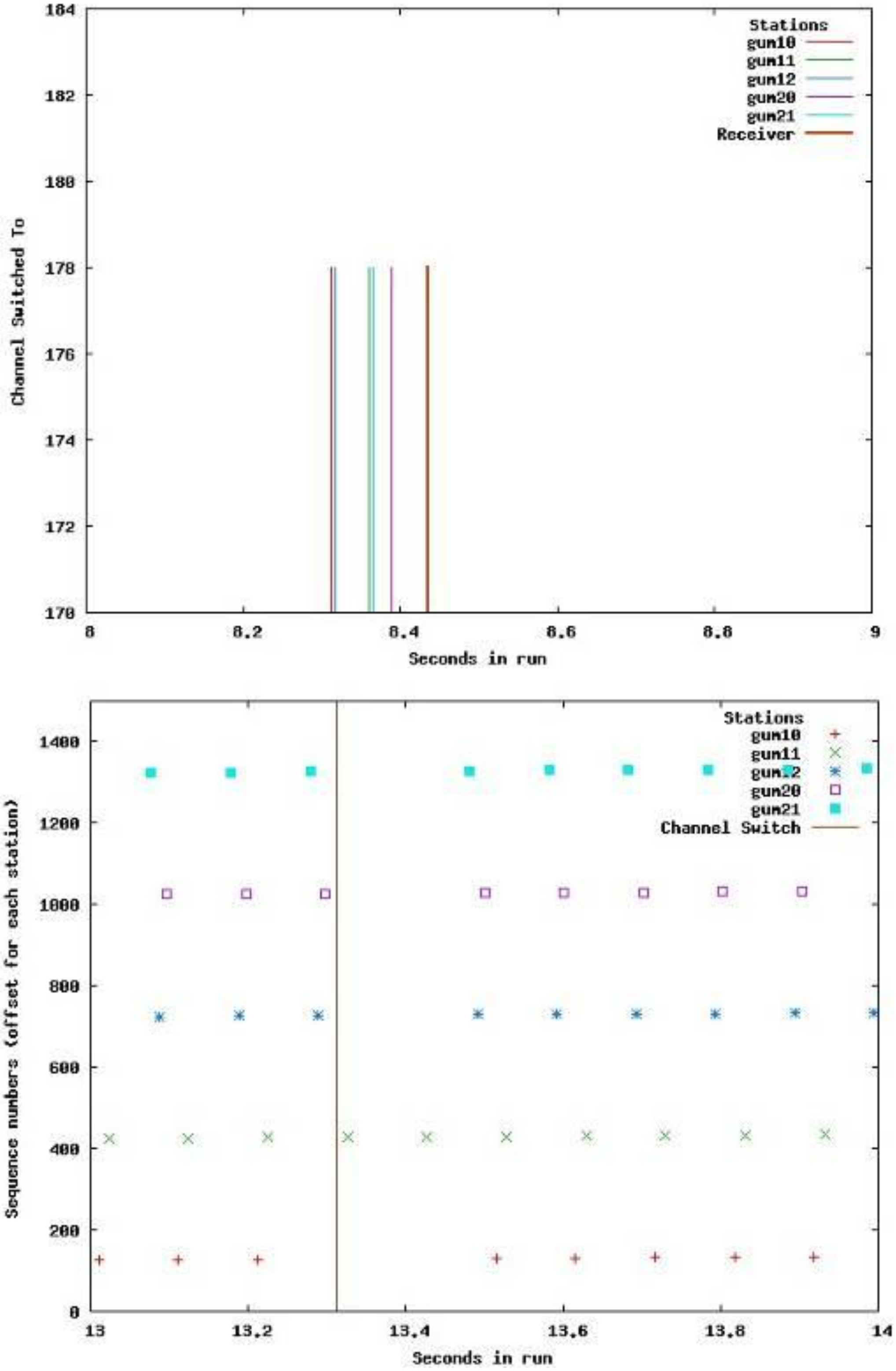


Figure 33: Close-ups, in case of infrequent channel switching (t1).

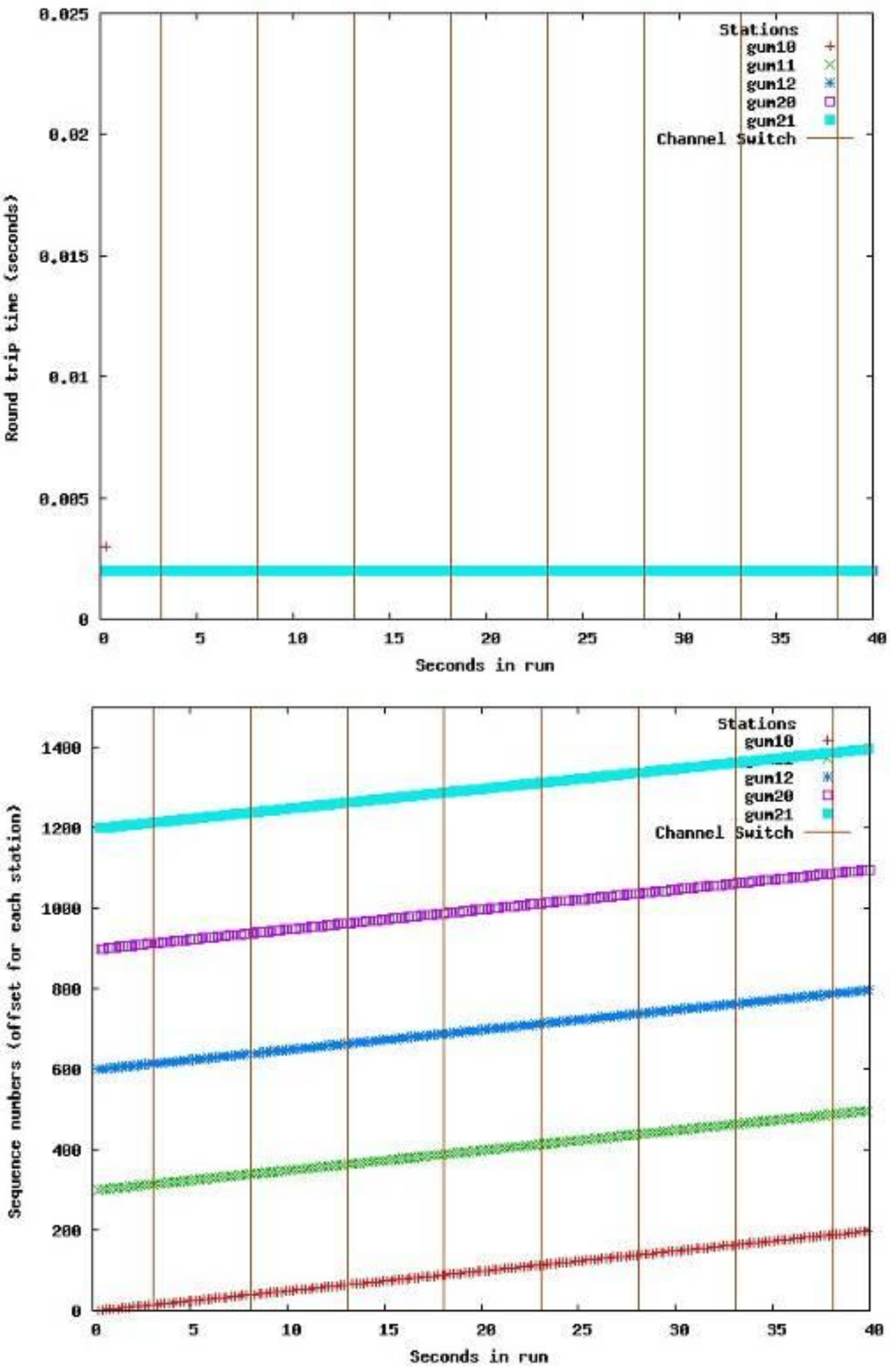


Figure 34: In this case, sw2, the send rate is half that of sw1, and round trip time remains low.

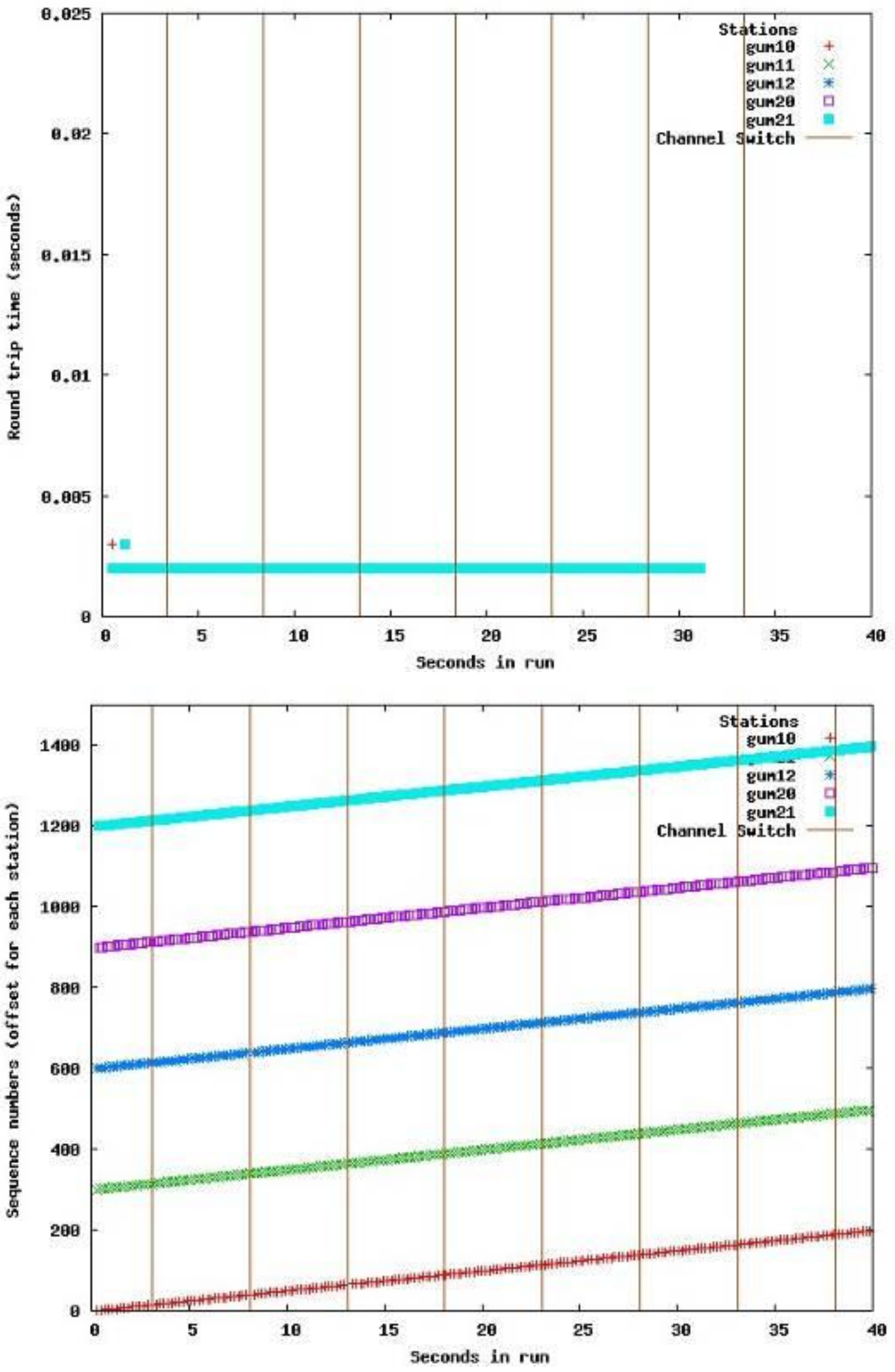


Figure 35: In this case, sw3, the send rate is twice that of sw1, and but the delivery of packets, as shown by sequence numbers remains good and the round trip time remains low.

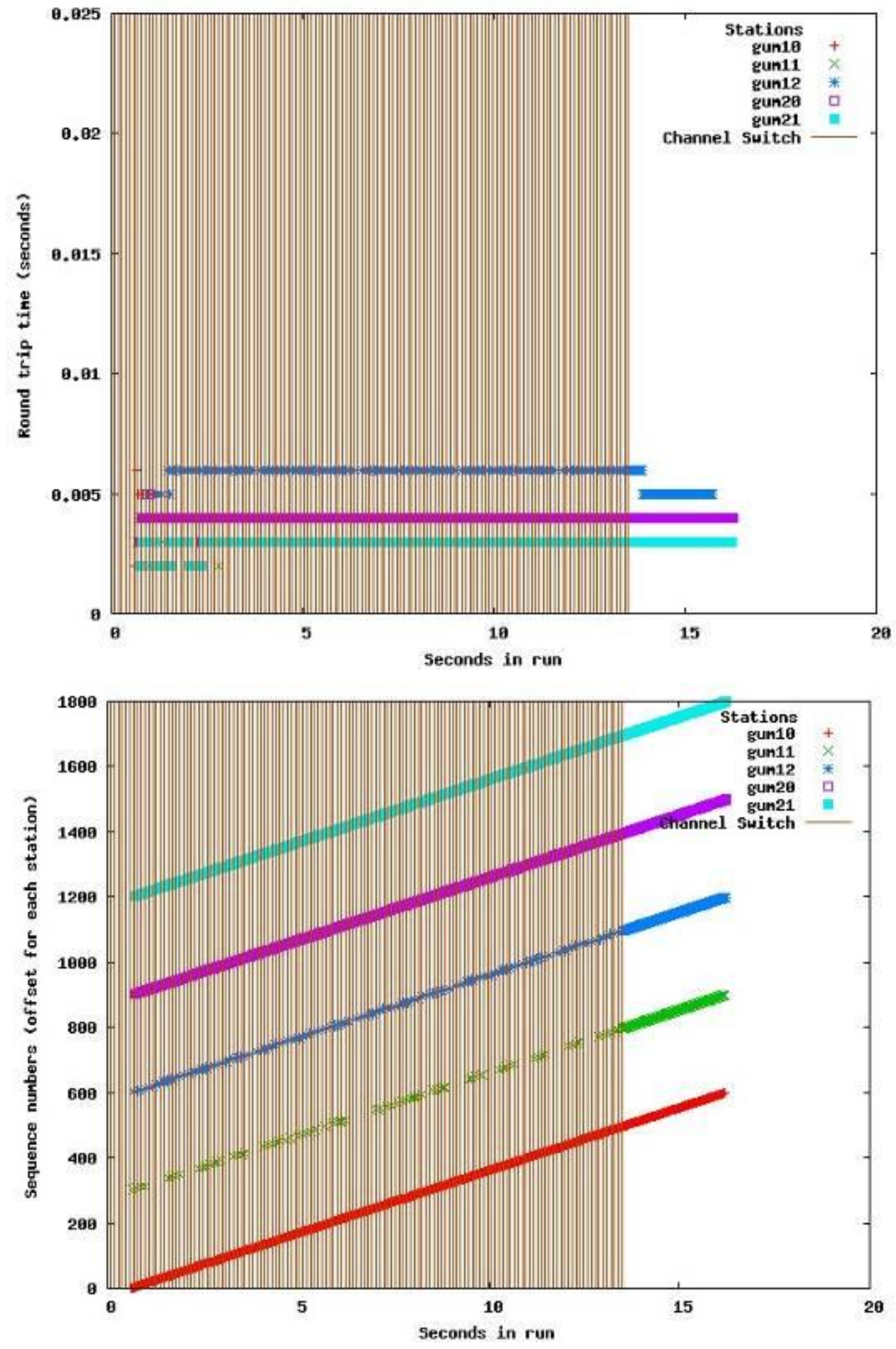


Figure 36: Case sw4, with increased overall load and increased channel switching.

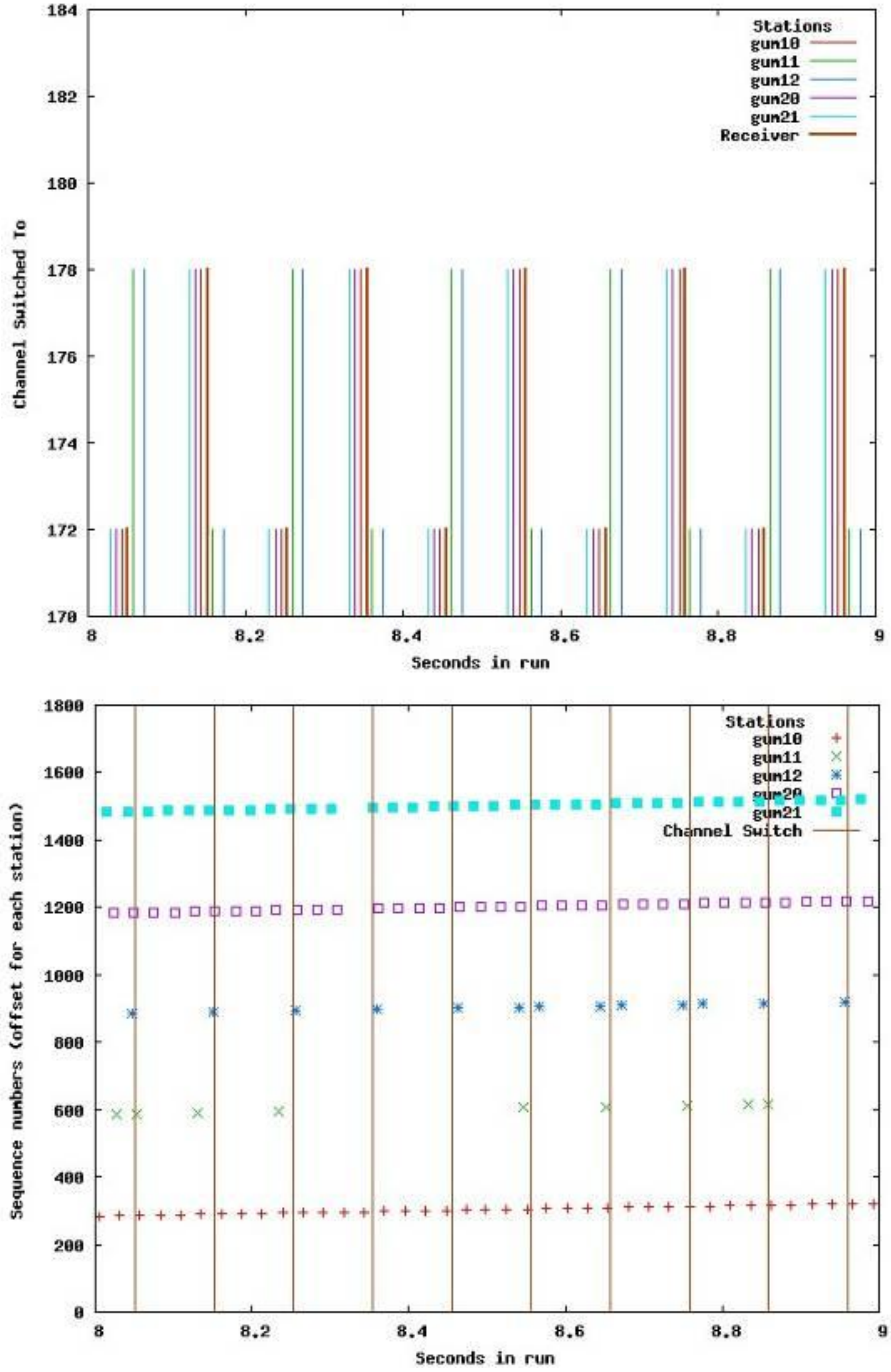


Figure 37: Close up of switching and sequence number loss for case sw4.

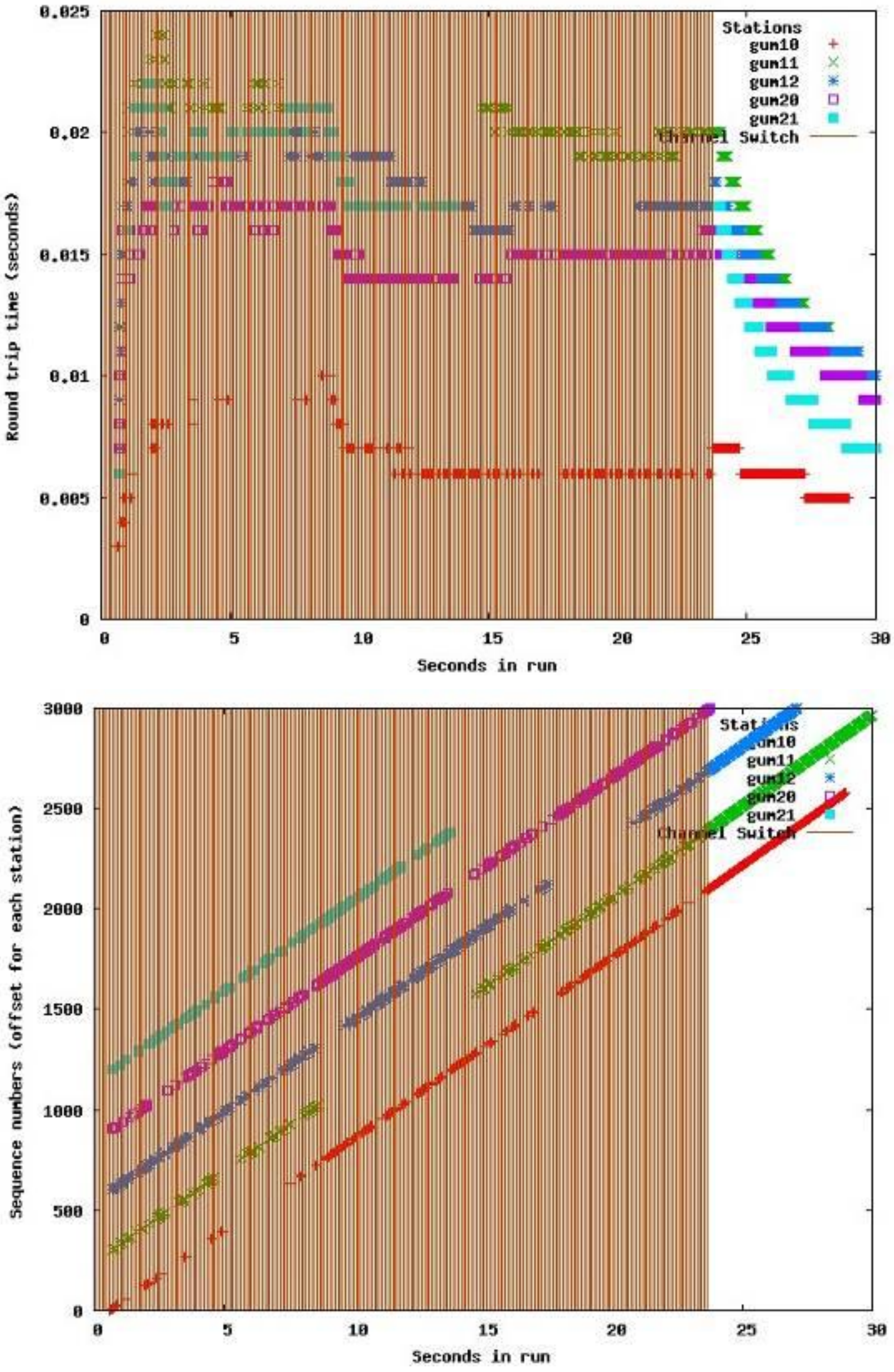


Figure 38: Case sw5 has increased loading and likewise increased latency and packet loss compared to case sw4.

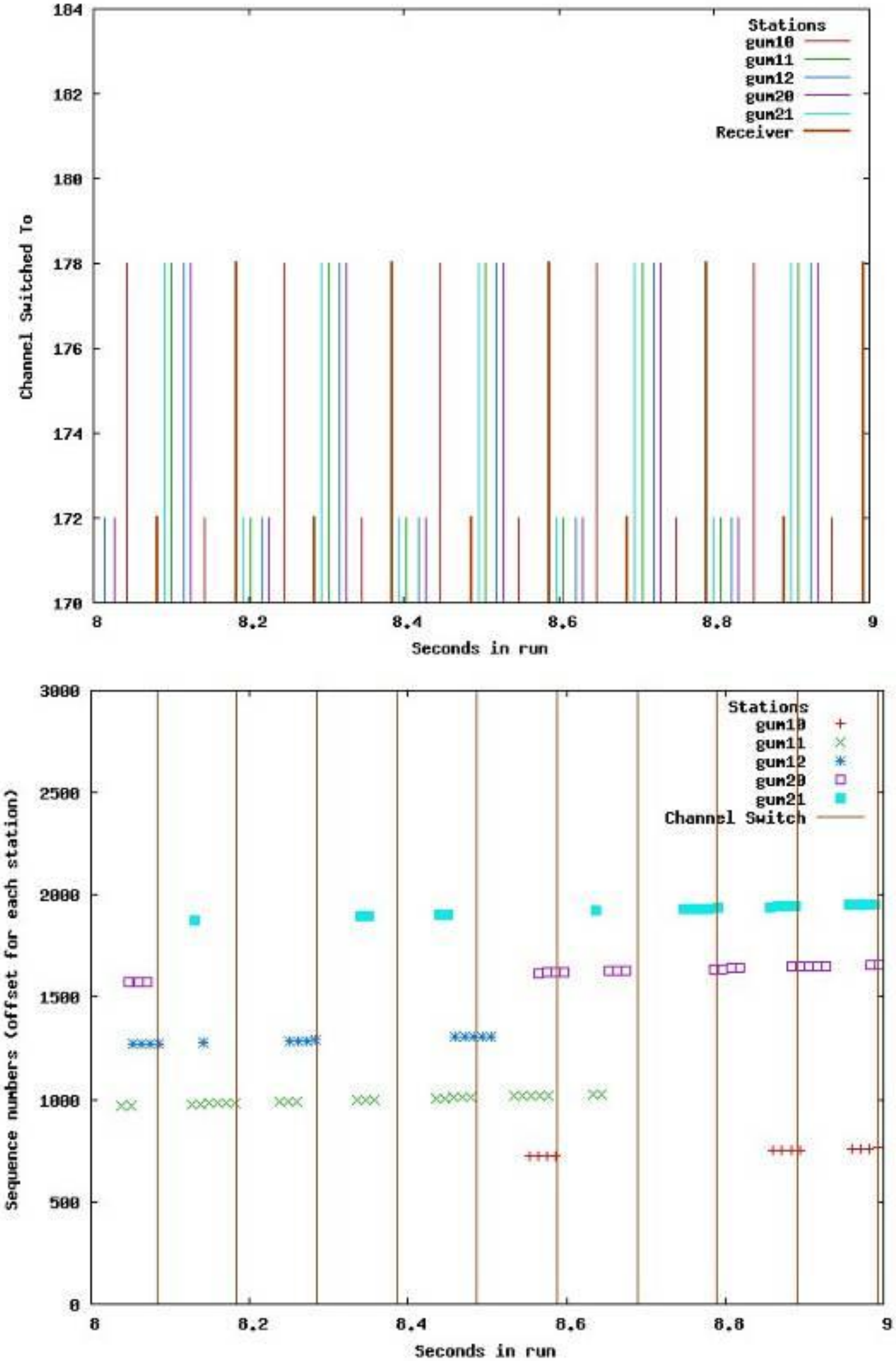


Figure 39: Close-up of case sw5 shows that the switching times for the different processors have spread still more, and the latency has increased to almost 25 ms.

3.2.6 Mobile Radios

As further validation of the test set-up, we carried out experiments with 8 radios on a single van at Richmond Field Station. We ran a variety of different loads and packet sizes, in a stable scenario where the van was parked at about 100 feet from the RSU, and in a moving scenario in which it drove a short distance along the test track. More of that data will be presented in a separate report, but as an example we show in Figures 40 and 41 two runs under the same conditions, except that one was moving and the other parked. In both cases the background channel switching is causing some disturbance. In the case of the moving vehicle the round trip time is higher almost from the start, and gets higher still as the vehicle moves out of range. Note for comparison with the next section that the overall load on the receiver is 160Kbytes/second.

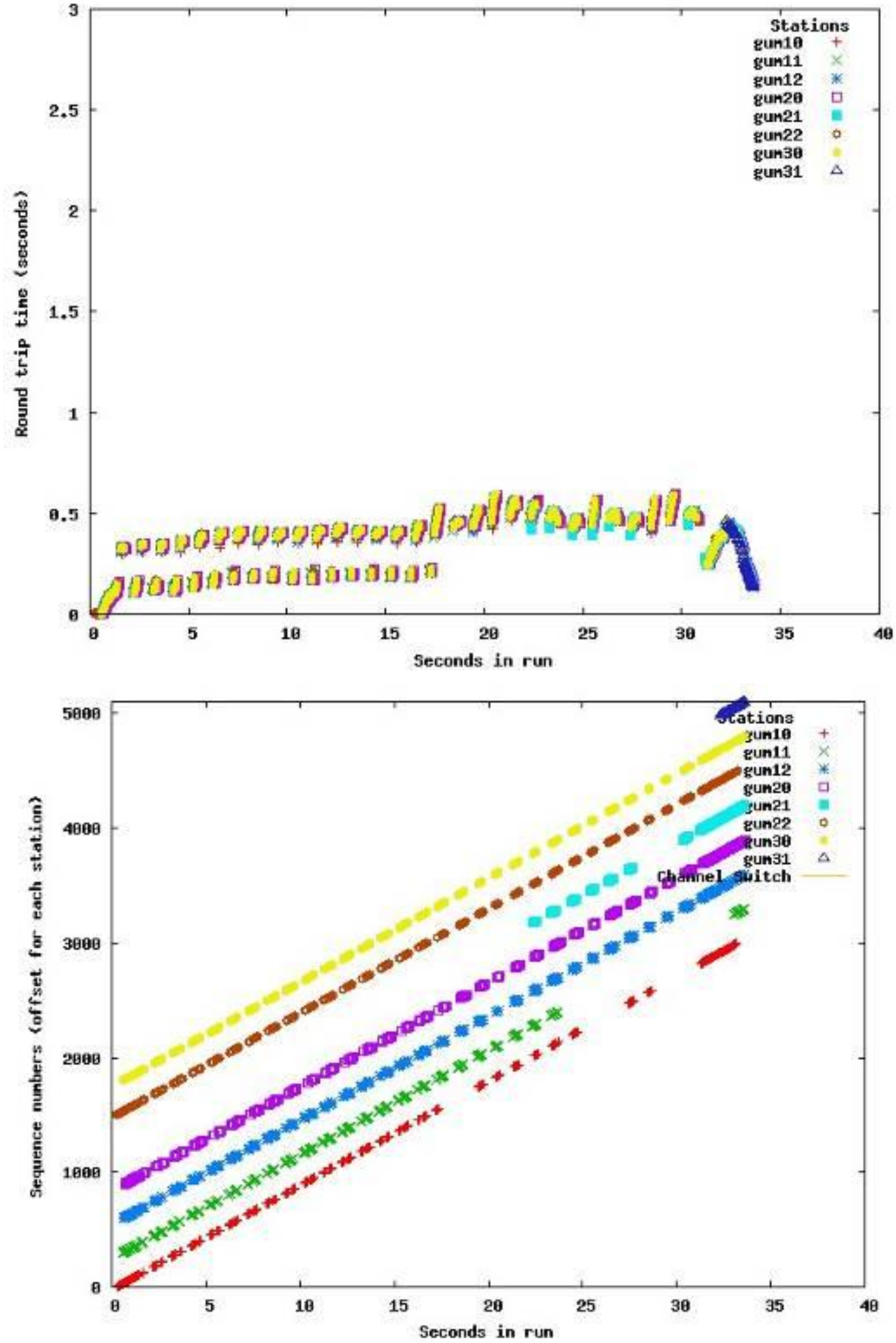


Figure 40: Eight radios, each sending 200 byte packets at 10 ms intervals, with background channel switching twice a second, from van parked within range of Richmond Field Station RSU.

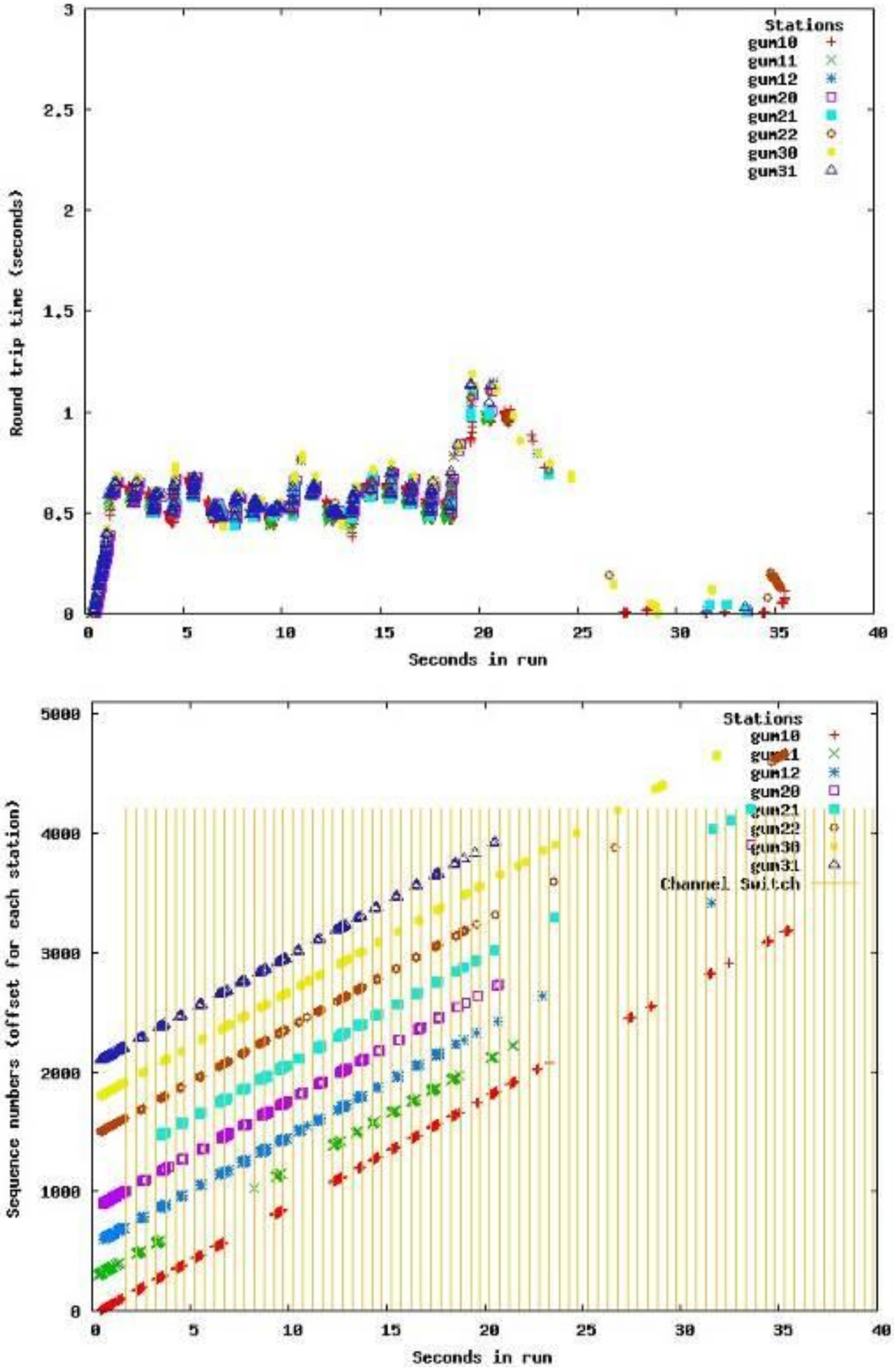


Figure 41: Eight radios, each sending 200 byte packets at 10 ms intervals, with background channel switching twice a second, during a short ride on a test track at Richmond Field Station.

3.2.7 Urban Intersection Testing

3.2.7.1 Packet length and inter-arrival time

The data in this section were taken with the RSU that was installed at 6th and Brannan in San Francisco as part of the Innovative Mobility Showcase for the ITSA World Congress in the fall of 2005 (ITS, 2005). The Denso WAVE Radio Modules (WRMs) for these RSUs were mounted on the signal arm, see the location in Figure 42. The wired interface of the WRM was connected by fiber to a PC104 in the traffic signal controller cabinet, running Linux. The software in the PC104 during this test was source identical with the data acquisition software running on the gumstix computers in the vehicle. These tests were conducted on September 24, 2006.

Figure 42: Location of RSU at 6th and Brannan in San Francisco.

For all runs, data gathering started at the intersection with 5th and Brannan and continued for two minutes, while driving straight along Brannan to 7th street, turning right, coming back along Bryant, and then turning right at 5th. See illustration with dotted line in Figure 42 of active part of the run.

There were three types of run, with low, medium and high overall load. For each set, the intervals between message sends were adjusted to maintain a constant load of messages at the RSU. In the first case the load was 40K bytes per second, in the second it was 100K, in the third 200K. For all runs on this day of testing the data rate setting in the Denso WRMs was set at

6Mbs.

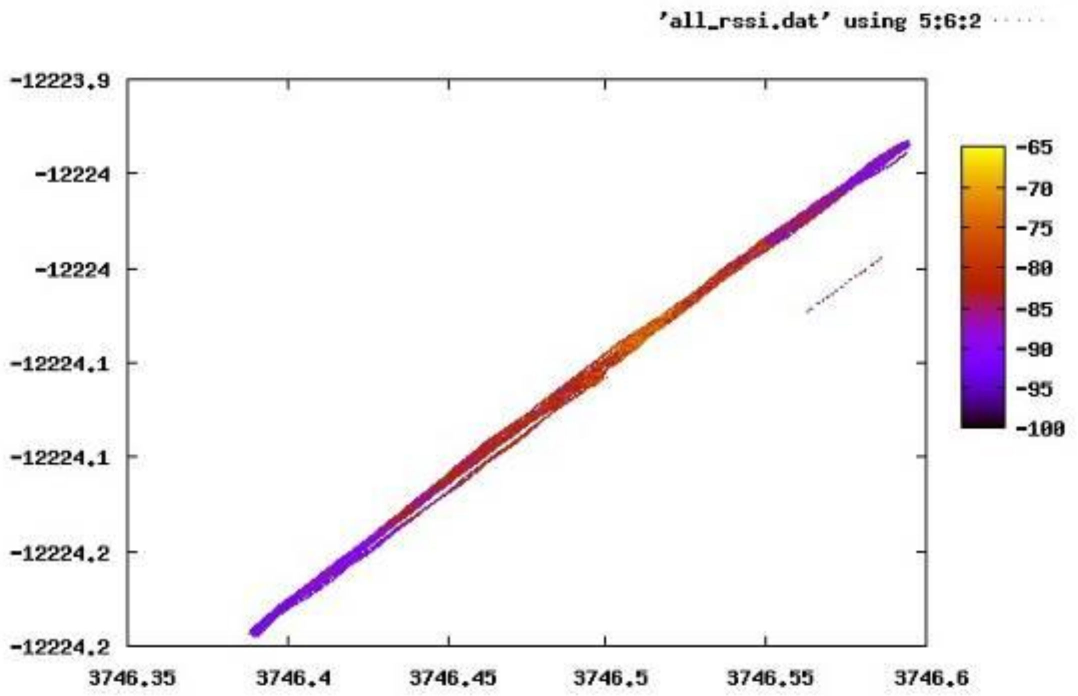


Figure 43: Plot of average of remote and local RSSI by GPS location for all received packets in runs at 6th and Brannan.

This data included two fields for local and remote RSSI, measured in dBm. RSSI values for all the runs are plotted together in against latitude and longitude in Figure 43. Variable parameters for each run were: Denso WAVE Radio Module rate setting, in Mbits/second; number of senders in run; packet size in bytes for this run; number of milliseconds in interval between packets; number of sends in the test (in some cases continuous and halted by user when out of range).

To approximate a model of transaction processing in which the traffic is predominantly generated on a service channel in response to short broadcasts on a control channel received, post-processing created the following summary data for each run: run type identifier string ; B total load for run (in kilobytes); R rate setting of Denso WRM in Mbps; S number of senders; M bytes per packet; I time interval between packet sends; N number of sends in test; successful sends in test; average RSSI (over round trip); start time (time of first reception);message time (time of reception for 8000 bytes -- line 8000/P);end time (time of last reception); message period (message time - start time); connected period (end time - start time); minimum distance from RSE; maximum distance from RSE; average distance from RSE; success rate (line count / possible transmissions; between start time and end time, i.e. while in range); gumstix processor ID number.

In our figures we have graphed two measures of communications performance with respect to interval between sends. In Figure 44 the success rates for each run are used as a measure of probabilities of successful round trip transmissions. In Figure 45, the time required for successful reception of 8000 bytes is used as a measure of transaction time. Reading the graphs, for each line with a fixed packet size, the values on the left represent higher overall loads than the ones at the right. Due to testing time limitations, the set of run types with the highest load was completed only for 2 nodes and 8 nodes.

Looking at the highest load values for 2 nodes and 8 nodes, in these tests, for the same overall load, the 400 and 800 byte packet size tests (with smaller send intervals) have better performance in terms of success rate of packet transmission than the 200 byte packet size. While this is interesting, clearly much more testing is required to characterize the regions of operation for this effect. Note that even with 8 nodes, although the probability of individual packet success is low for smaller sending intervals, because of collisions, at the overall loading used in these tests the time until an 8000 byte transaction is completed, from the time of first connection, stays under 2.5 seconds.

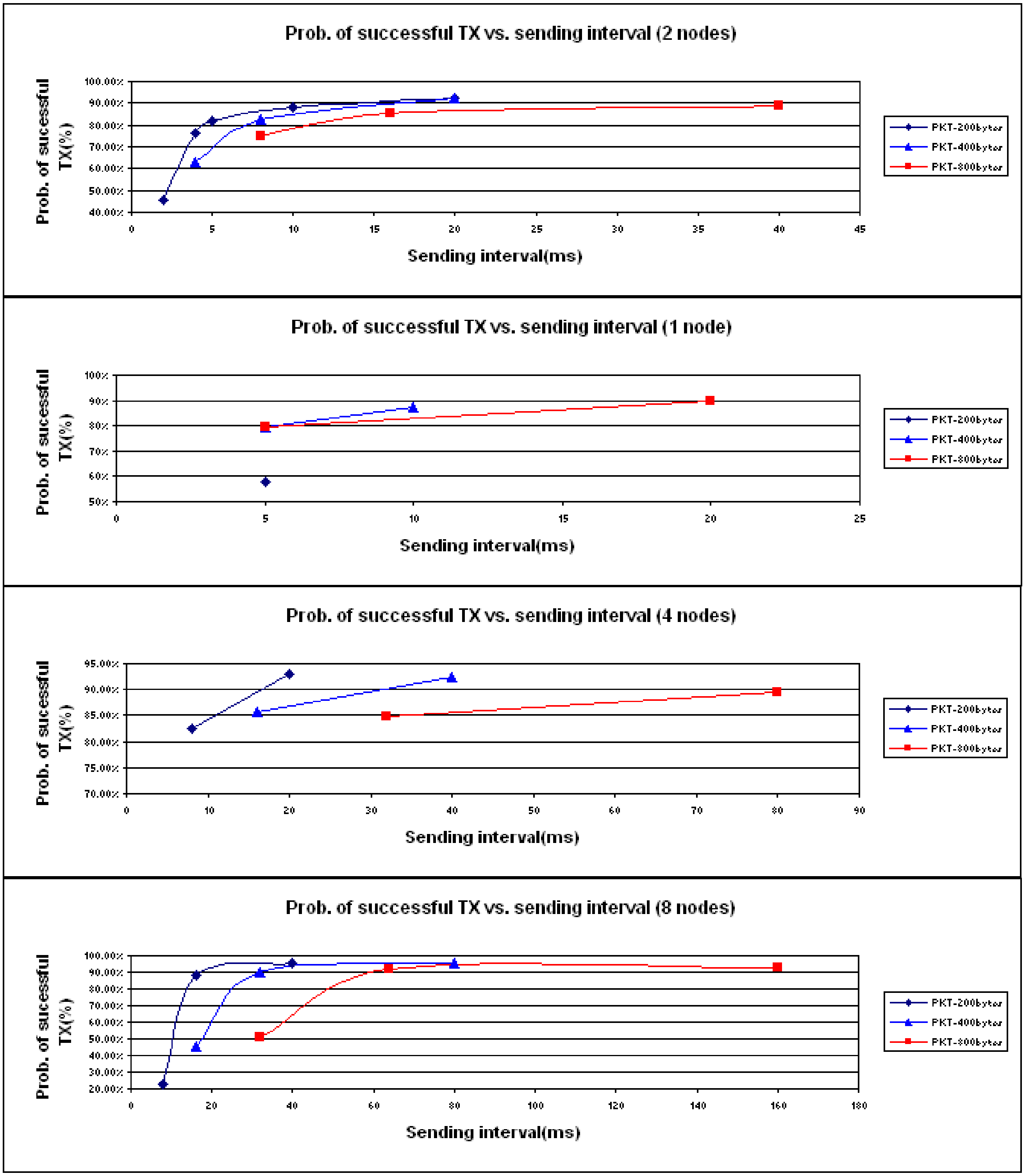


Figure 44: Probability of successful round trip transmission, as a function of the interval between packet sends, for 1, 2, 4 and nodes, with varying packet sizes of 200, 400 and 800.

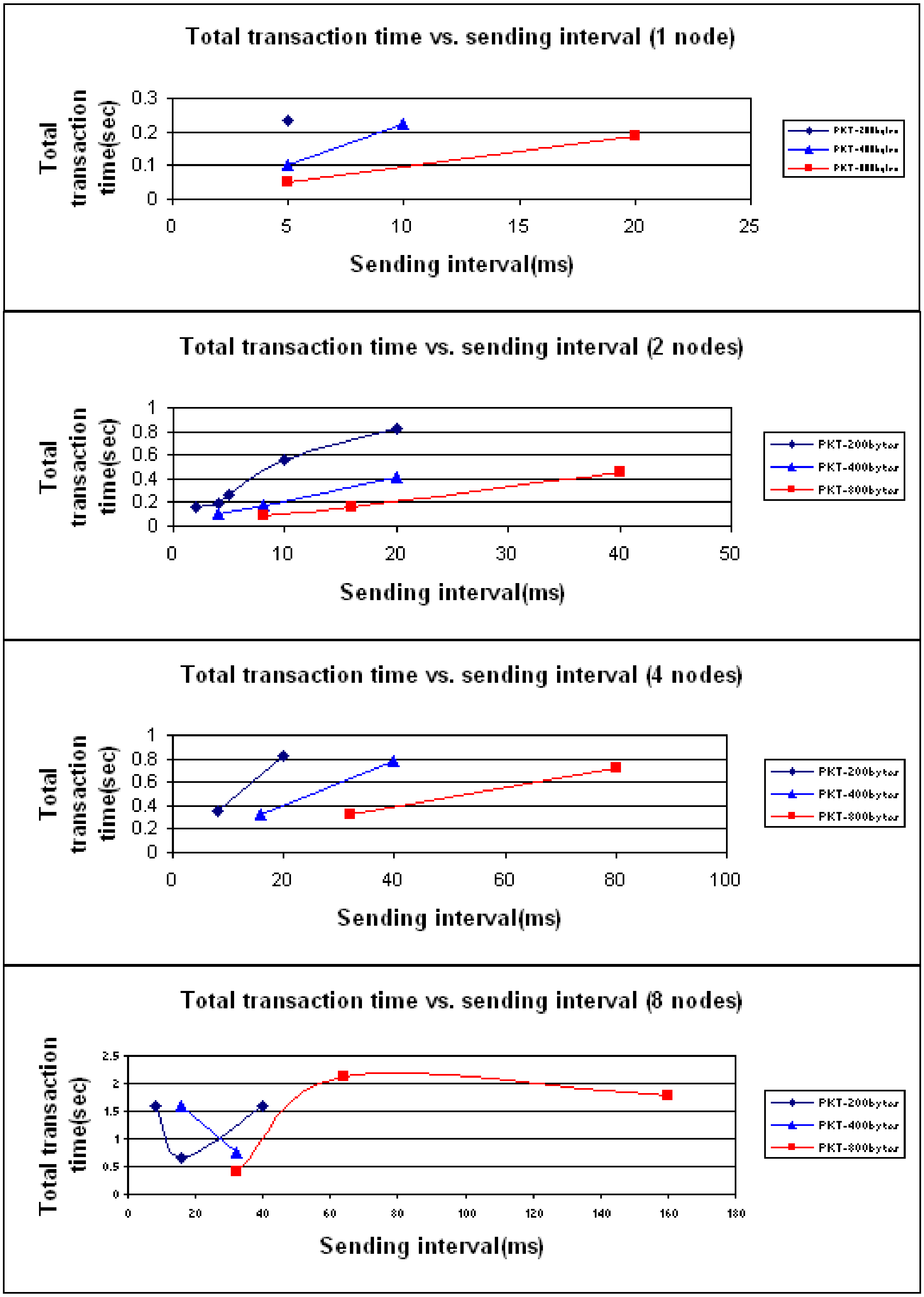


Figure 45: Time (in seconds) until the first 8000 bytes has been transmitted, as a function of the interval between packet sends, for 1, 2, 4 and nodes, with varying packet sizes of 200, 400 and 800 for tests at 6th and Brannan.

3.2.7.2 Data rate and queuing

Three different approaches were made to the RSU, from 2nd and Townsend past the RSU at 3rd to 4th and Townsend, from 4th and Townsend past the RSU to 2nd and Townsend, and from 3rd and Berry traveling on 3rd past the RSU. See Figure 46. Additional data was taken while sitting still and with a background process switching channels. The channel switching data is not analyzed in this paper. No RSSI data was taken with this run; the code to record this data had not yet been integrated into the testing code.

For all approaches, packets were sent every 10 milliseconds, with either a short (200 bytes) or a long (1400 bytes) packet length. This gives an overall load, for 9 gumstix senders of 1.44 Mbps for the smaller packet size, and 10.08 Mbps for the larger packet size. In the presence of lost messages due to marginal RSSI or contention, backoff appeared to cause the transmission rate of the receiver to be lowered to the point where queues saturated the receiver, so that delays of several seconds for round trips were observed on some runs. On other runs, some of the senders seemed to either be completely blocked out or have dropped out for some other reason, so for these runs there were fewer than nine vehicles.

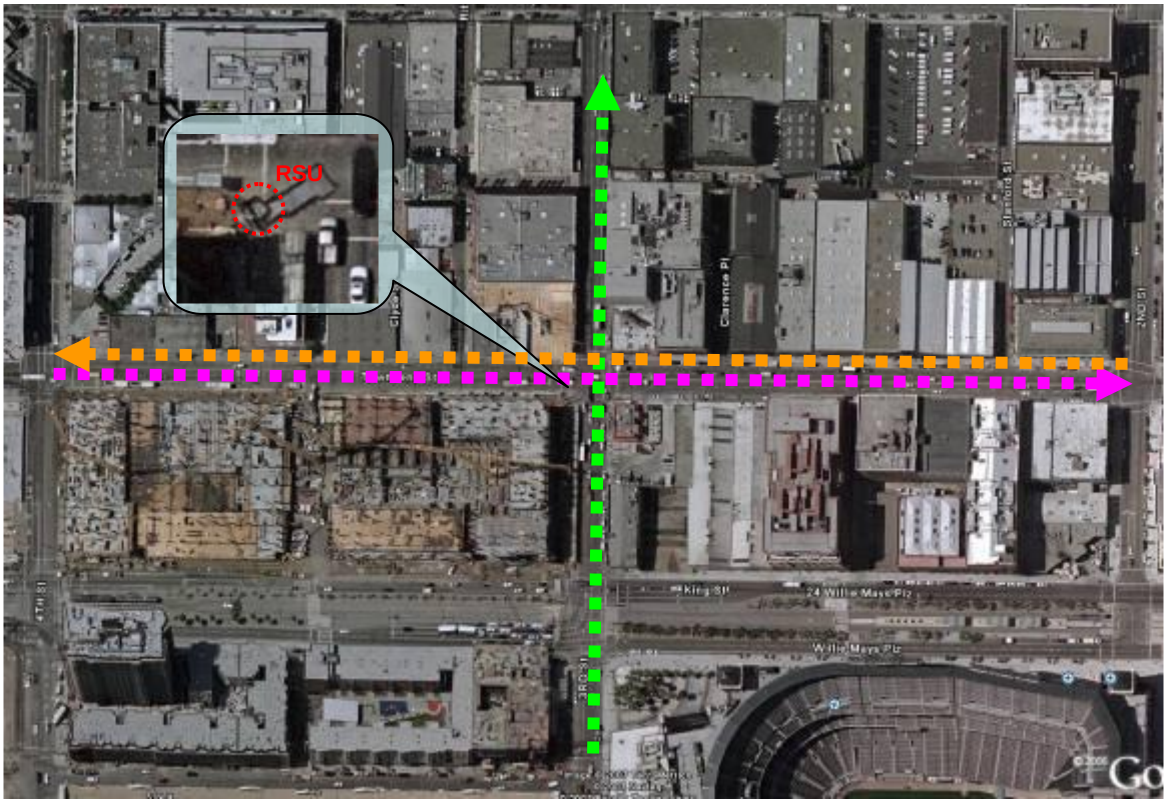


Figure 46: Location of RSU at 3rd and Townsend in San Francisco, and direction of test-runs.

The data described in this section was taken with the 3rd and Townsend RSU in San Francisco, another RSU that had been installed as part of the Innovative Mobility Showcase. Data was taken on June 15, 2006, just before the PC104 computer connected to the Denso WAVE Radio Module was removed because space in the traffic signal control cabinet was required for other uses. Figures 47, 48, 49 and 50 show the transaction delay and the standard deviation of this delay as a function of the data rate setting.

The most striking feature of the data is the high standard deviations and the very poor performance on the run on 3rd Street and the run from Townsend and 2nd to Townsend and 4th compared to the run in the other direction on Townsend and the run that was taken from a car parked in 3rd Street in close range to the RSU. In the presence of lost messages due to marginal RSSI or contention, the transmission rate of the receiver appeared to be lowered to the point where queues saturated at the receiver, so that delays of several seconds for round trips were observed on some runs. On other runs, some of the senders seemed to either be completely blocked out or have dropped out for some other reason, so for these runs there were fewer than nine vehicles.

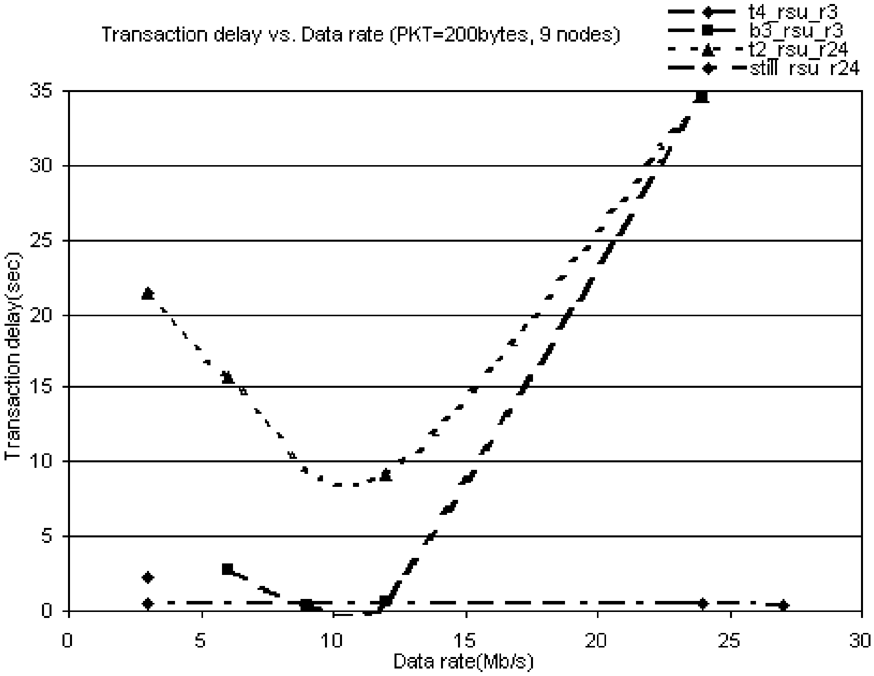


Figure 47: Transaction delay for 8000 byte transaction as a function of data rate, for 9 nodes, packet size 200 bytes, with various testing routes, 10 millisecond interval between packet sends.

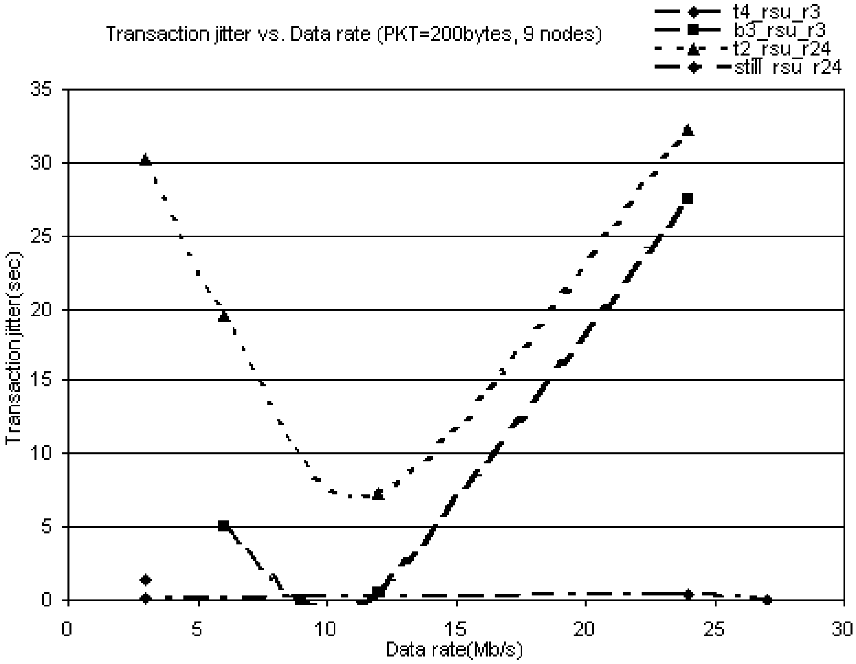


Figure 48: Transaction jitter (standard deviation of delay) as a function of data rate, for 9 nodes, packet size 200 bytes, with various testing routes, 10 millisecond interval between packet sends.

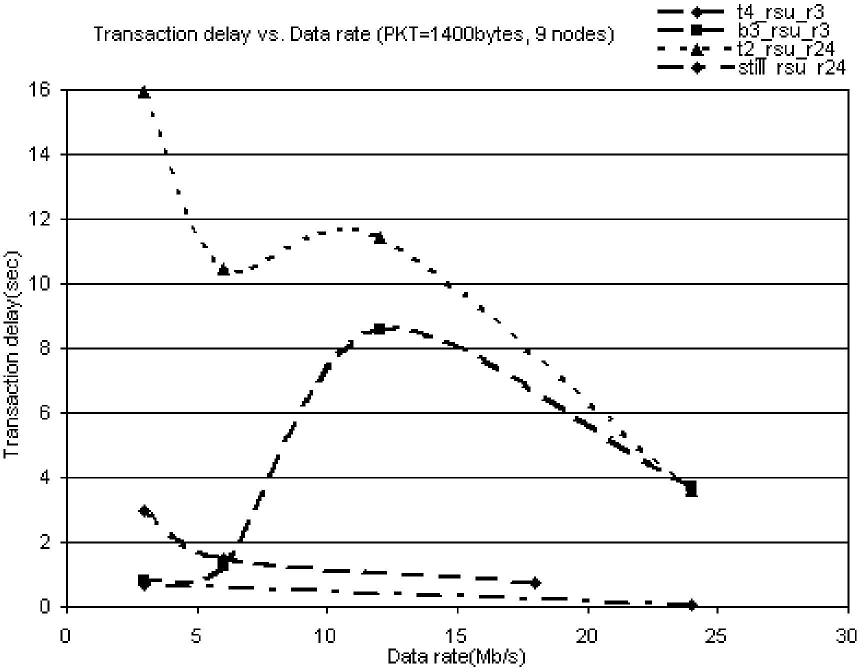


Figure 49: Transaction delay for 8000 byte transaction as a function of data rate, for 9 nodes, packet size 1400 bytes, with various testing routes, 10 millisecond interval between packet sends.

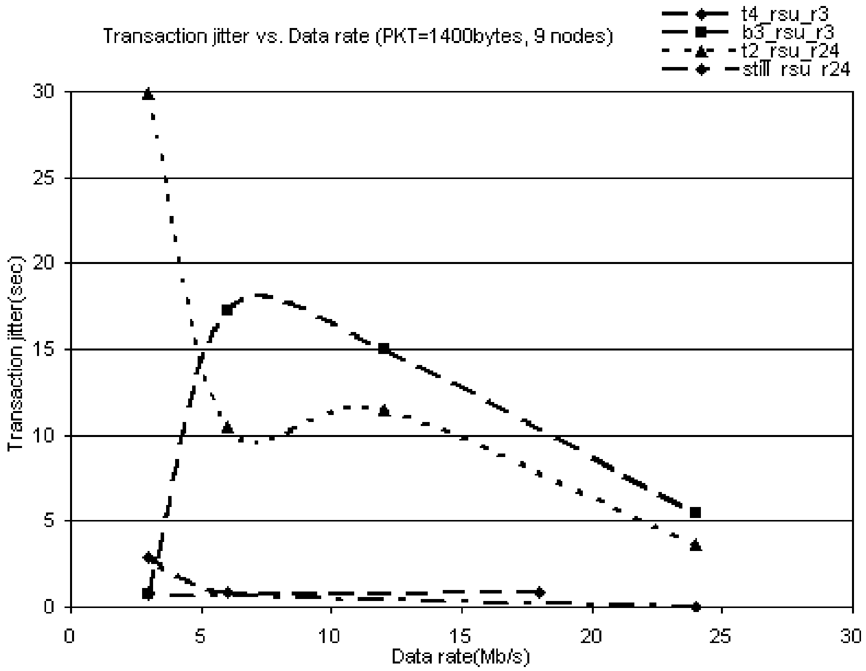


Figure 50: Transaction jitter (standard deviation of delay) as a function of data rate, for 9 nodes, packet size 1400 bytes, with various testing routes, 10 millisecond interval between packet sends.

3.2.8 Summary

The differing performance measurements we have obtained so far indicate the wide variations in performance that can occur with the same installed equipment, depending on variations in sending interval, packet size, and detailed geographical characteristics of the approach. In many of these runs, we see evidence of two regions of performance with respect to the sending interval (see Figure 51 for an illustration for probability of success transmission, and Figure 52 for transaction time). In region R1, the probability of a successful round trip transmission increases as the sending interval increases, because there are fewer collisions. In region R2, the probability of a successful round trip transmission appears to approach a limit. Since the sending interval is already long enough for contention resolution, the performance approaches a bound of *p* which is decided by PHY layer performance. With respect to transaction times, too low a probability of success will cause delays if the sending interval is too short, but over the optimal sending interval the transaction time will increase because of wasted time between packets. The points of optimality in Figures 51 and 52 need not be the same, and a great deal of testing, load characterization and site characterization will be required to determine these intervals in practice. It is necessary to be able to integrate data acquired at all layers of the network stack for complete understanding. We hope to use this data acquisition software and equipment to carry out further vehicle to roadside and vehicle to vehicle tests at VII California RSUs, in conjunction with more physical layer testing, and to development a methodology for site characterization that will allows us to predict the performance of communication with RSUs.

Part of the material in Section 3.2 was presented in the 1st IEEE International Symposium on Wireless Vehicular Communications (Dickey/Huang/Guan 2007).

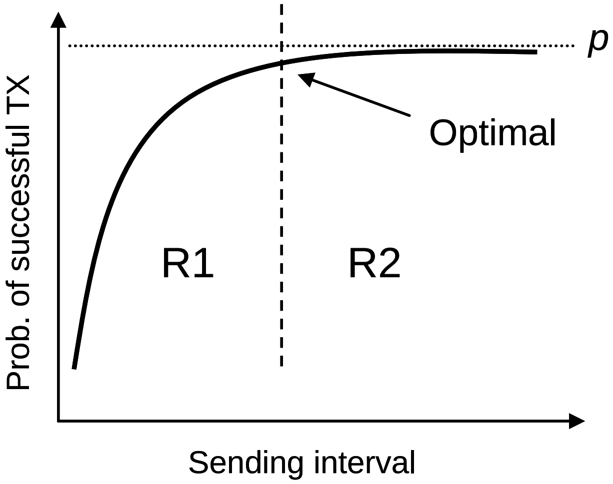


Figure 51: Illustration of regions of performance for successful transmission.

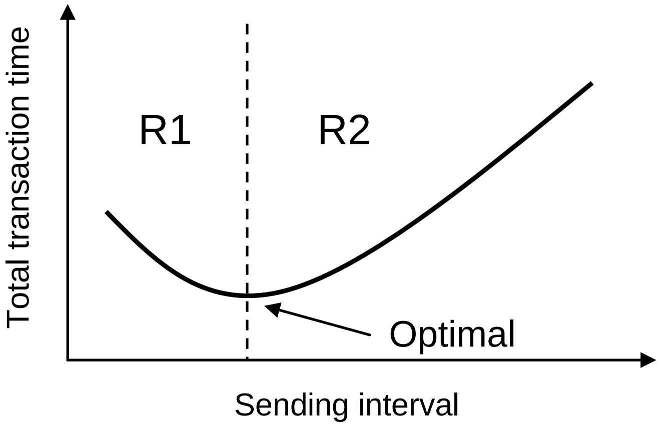


Figure 52: Illustration of regions of performance for transaction times.

3.3 DSRC Testbed of Safe Intersections

3.3.1 Concept of wireless communications to enable Intersection safety

3.3.1.1 The Intersection Crash Problem

Intersection crashes are a tremendous safety and social problem. Consider that in 2004, 40% – or 2.5 million – of all police-reported crashes in the United States either occurred at intersections or were intersection-related (NHTSA, 2006). Of the intersection crashes, 8,619 were fatal and 848,000 resulted in injury. Translated into percentage of all police-reported crashes in the United States, 22.5% of all fatal crashes and 46 percent of all injury crashes occurred at intersections. A very serious and considerably-studied intersection crash is the "red light running", or signal violation (Ragland, 2003; Bonneson, 2001; Brittany, 2004). Approximately 20% of all intersection crashes occur due to signal violation crashes (Brittany, 2004), resulting in an estimated $13 billion a year in a monetization of fatalities plus lost wages, medical costs, property damage and insurance (Chang, 2007).

Signal violation crashes may be divided into three types: (i) a dilemma zone crash, where the driver tries to "beat the light" at the green-amber-red transition; (ii) a willful violation crash, where the driver deliberately violates the red light signal, and (iii) an unintentional violation crash, caused by a distracted or otherwise unaware driver. To quantify the magnitude of each element of this taxonomy, Chovan (Chovan, 1994) has found that drivers who attempt to beat the amber phase caused 16% of the crashes, and drivers who were unaware of the signal presence and its status caused 41% of reported crashes. It follows that the balance of 43% are willful violators. Each of these categories of red-light running may have different safety implications and certainly spawn a host of different potential countermeasures.

3.3.1.2 Dynamic Red Light Running Countermeasures

In recent years, a host of researchers have considered 'dynamic' countermeasures, the basic idea being countermeasures that adapt to impending conflicts depending on knowledge and reaction to vehicle kinematic and impending signal phase and timing. For example, in the case of high speed interurban signalized intersection conflicts, Bonneson et al (Bonneson, 2001) have focused on extending the length of the amber cycle, generally aiming for compliance with the ITE recommendations on amber cycle length. They found that extending the amber by 0.5 to 1.5 seconds reduced red-light violations by more than half. Newton et al (Newton, 1997) have measured the impact of a countermeasure for an all red extension on the "uncertainty zone", i.e. the region surrounding the 50% probability of stopping. If a countermeasure increases the size of this zone, then a negative impact of the countermeasure in terms of an increase in rear end collision can be expected.

Under the auspices of the Intelligent Vehicle Initiative, Neale (Neale, 2007) is developing adaptive countermeasures for signalized violations. This research has recently been extended to include the US DOT's Vehicle-Infrastructure Integration (VII) concept of Dedicated Short Range Communication (DSRC) transceivers located on the roadside and in vehicles to enable high reliability, low latency communication of intersection signal phase and timing. In the United States, this concept of VII has generated interest in establishing DSRC-equipped intersections at 50% of all signalized intersections in 50 major urban areas, as part of an initial deployment of 100, 000 roadside units. The VII initiative has also engendered research – and in particular the research reported in this paper – that ***VII could become the basis for dynamic red light countermeasures.***

As a case in point, in recent years the research reported in (Neale, 2007) has been expanded with the US DOT and consortium of automobile manufacturers into an effort called Cooperative Intersection Collision Avoidance Systems – Violation (CICAS-V) (Chang, 2007; USDOT, 2005). In (Neale, 2007), researchers focused on enhancing the conspicuity of the red signal by providing an additional roadside warning display and with (USDOT, 2005), the focus is on an in-vehicle audible or visual alert. Additionally, research is underway as part of the CICAS program in a concept called Traffic Signal Adaptation (TSA), where the TSA works with the CICAS-V system to additionally provide a dynamic all-red extension with the objective to enact a safe clearance interval (and provide a photo citation to the signal violator) (Misener, 2006).

Certainly, as outlined in (Chang, 2007) there are other intersection crossing path crash types that could be addressed by VII. In the past several months, the left-turn across path CICAS countermeasure effort called Signalized Left Turn Advisory (SLTA) (Misener, 2006; Zennaro, 2003; Chan, 2004; Chan, 2005; Ragland, 2006) has also been transformed into a VII-enabled effort.

Very much like CICAS-V, the intersection phase and timing would be given to the “subject vehicles”. Unlike CICAS-V, the subject vehicles would be left-turning vehicles that are not necessarily violating traffic signals; rather, the CICAS-SLTA vehicles would be given left turn advisory, with additional information given to the SLTA-based or roadside computers that either sense or are communicated via DSRC the trajectories of straight through vehicles which may present a crossing path conflict. A complicating and important factor for CICAS-SLTA would be the presence of other road users, most specifically pedestrians and bicyclists.

3.3.2 VII California Testbed

3.3.2.1 Location

The VII California testbed (Misener, 2006) extends along approximately 60 miles of roadway (the El Camino Real SR-82 arterial and US-101 and I-280 freeways) on the San Francisco Peninsula starting just south of San Francisco International Airport and extending to Silicon Valley. Important to the research described here are the Roadside Equipment (RSE) along SR-82 (El Camino Real). At this writing, there are nine RSE along SR-82, including three with DSRC transceivers connected to the roadside traffic signal control as described in Section 3.

3.3.2.2 Roadside Equipment

The RSE is an important hardware element in an intersection safety application. The initial VII California system was designed to explore a variety of applications and therefore consists of a DSRC Denso Wireless Application for Vehicular Environment (WAVE) Radio Module, mounted on a pole near the antenna, and connected by optical fiber through a conduit, and a PC-104 stack with processor and multiple Ethernet connection to a backhaul modem and to the fiber optic converter. To fit within the Type 332 cabinet, form factor is low: approximately 6” x 6” x 12”. Power is standard 120V AC, with low current draw. A schematic of the VII California connected RSE, residing within a traffic controller cabinet, is shown in Figure 16.

Two of the VII California intersection RSEs, at Page Mill Rd and SR-82 and at California Ave and SR-82, use the radio and processor architecture above, and use a special “sniffer” circuit board as described in section 3, to get signal phase and timing information from a cabinet equipped with a California Type 170 traffic signal controller. A third RSE, which was installed at 5th and SR-82 for use by CICAS-V researchers, uses the TechnoCom Multiband Configurable Networking Unit (MCNU), which includes both a processor and a newer generation DSRC radio. The MCNU, which will be used for future VII California RSEs, is designed to mount on a pole, which allows short cabling to the radio antenna. Caltrans has installed a Type 2070 traffic signal controller in the cabinet at 5th and SR-82 so that the AB3418 serial protocol (described in Section 3) may be used to communicate with the MCNU processor. Serial-to-fiber conversion is done in the cabinet, and the signal phase and timing information is delivered to a network interface on the MCNU through optical fiber in a conduit.

3.3.3 Signal Phase and Timing Acquisition

Traffic signal timing is a mature and sophisticated study in its own right. Many existing traffic controllers already run software that supports communication protocols, such as the National Transportation Communications for ITS Protocol (NTCIP) and California's Assembly Bill 3418 (AB3418) protocol, designed to communicate signal phase and loop detector information to traffic management centers.

However, these protocols were designed for monitoring and control of actuated and coordinated intersection timings, from a central location over a modem, at a time granularity of seconds. They were not designed to notify vehicles of real-time signal phase count-down, needed for the signal violation countermeasures described in Section 1, over a high bandwidth DSRC connection. Traffic signal controller protocol messages also contain information that is difficult to interpret without access to the timing plan for the intersection developed by the state or local maintaining entity and do not contain geographical/mapping information needed by vehicles in order to recognize what part of the signal phase information applies to the vehicle's approach to the intersection. In addition, many intersections contain legacy equipment that do not support external communication.

Nevertheless, in our experiments we have successfully reconstructed sufficient information to broadcast the signal phase count-down needed for prototype vehicle applications. In different installations we have used the NTCIP protocol, the AB3418 protocol and a special "sniffer" circuit that non-invasively detects signal phase without any interaction with the traffic signal controller.

3.3.3.1 NTCIP

Our first implementation of signal phase and timing acquisition used NTCIP data objects supported on the Siemens Eagle software for the Type 2070 controller. The Phase Status Group Management Information Base (MIB) objects defined in (AASHTO, 2005) were supported by the Eagle software, and code was written to access this information. In an experimental intersection at our facility (Richmond Field Station, University of California, Berkeley), we integrated serial communication with the 2070 controller into the computer/sensor system used for the research described in (Misener, 2006; Zennaro, 2003; Chan, 2004; Chan, 2005; Ragland, 2006).

By reading the red, yellow or green phase status from the NTCIP message from the 2070, and keeping a count-down based on the timing plan in for the Richmond Field Station's (non-actuated) test intersection, we were able to display the signal phase in real-time in an in-vehicle diagnostic program, and correlate information taken on driver behavior with the signal timing. In conjunction with an automobile manufacturer, we developed and demonstrated an early traffic signal violation warning in one of their vehicles. At this test intersection we have also been able to conduct experiments evaluating communication latency (described in Section 5) since we were also able to use the AB3418 and "sniffer" methods. However, so far we have not been able to work with an intersection in the field where NTCIP was supported on a traffic signal controller approved for use by the maintaining entity.

3.3.3.2 California AB3418 Protocol

The Traffic Signal Control Program (TSCP) for the Type 2070 traffic signal controller (originally written by the Los Angeles Department of Transportation and further developed by Caltrans) supports signal phase and timing acquisition using the *GetLongStatus8* message of the AB3418 extended (or CTNET) message set in a serial protocol that at the level of packet encoding is similar to NTCIP.

The fields of the single *GetLongStatus8* message make available much of the information that can be accessed through the PhaseStatusGroup and VehicleDetectorGroup MIB objects in NTCIP, albeit with less generality and redundancy. A single byte *active_phase* field can be decoded to get signal phase status for up to 8 phases; additional information from the *interval* field can be used to distinguish the "green" part of "active" from "yellow" and "red clearance." This signal phase status can be used, as for NTCIP, in conjunction with the timing plan, to construct a phase countdown. The *interval* field also includes encoding of additional information about the segment of the phase, such as "Min Green" or "Max Gap", that may be useful in the future for providing more information to vehicle safety applications concerned with signal state. In addition, the loop detector status is available, although so far in our work with reconstructing the signal phase count-down we have not made use of this information.

The AB3418 is also available on some specially configured Type 170 controllers, and thus in California may be the most readily available means to acquire signal phase information at a Caltrans-maintained intersection. However, most Type 170s are not configured for AB3418, and 2070s are also not yet widely available at Caltrans intersections.

3.3.3.3 Non-invasive Current Sniffer

A path of least resistance to deploying the equipment needed to bring dynamic signal state advisories to DSRC radio may be to retrofit existing or legacy controllers in a "clip-on" fashion. Hence, an electronic signal output to indicate the traffic light signal state in a non-contact fashion was developed. It operates at no interference with the normal signal operation by "sniffing" via a commercially-available and highly sensitive current sensing coil clamped around the insulated cladding of active signal circuit wires, "red", "green" or "yellow". There is therefore no need to remove the wire contact from the active circuit in order to thread it through the coil. The selected device is shown in Figure 45 at installation at a VII California intersection (specifically, SR-82 and Page Mill Rd in Palo Alto) and has been shown to work with the very low current draw used by the modern LED traffic signal bulbs.

As shown in Figure 53, the basic sniffer design consists of the clamp-on coils, a full wave bridge rectifier to produce a dc voltage during signal bulb on state, and a comparator circuit. The comparator is a dual 8 pin dip package. This allows for inverting or non-inverting outputs, and the open collector outputs are used to translate the output signal voltage to TTL levels for computer digital inputs or other voltage levels to trigger different devices. The comparator threshold is adjustable to allow for testing flexibility on a variety of intersection types.

The output is converted to digital format, then interfaced to external devices USB port. Depending on how many signal wires are used and on the complexity of the intersection, the information sent may be just "green" information, that will be compared to the intersection's timing plan to determine red and yellow countdown as well, or redundant information for the red and yellow phases may also be sent, which would theoretically allow software reading the information to "learn" the intersection's timing plan.

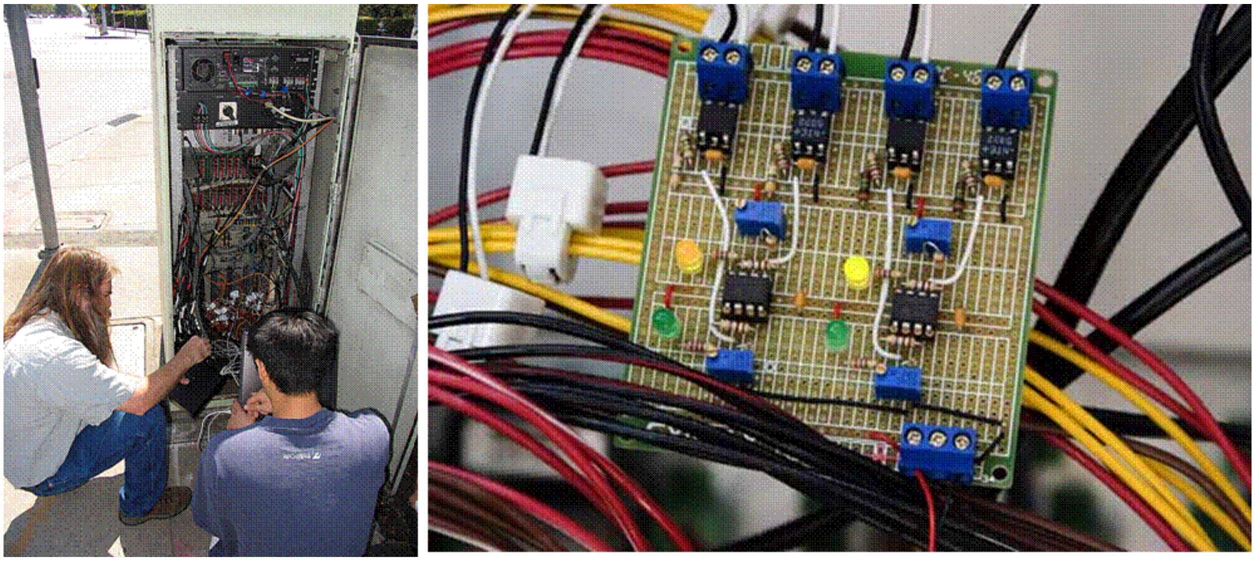


Figure 53: Installation and operation of "clamp-on" signal current sniffer at VII California intersection.

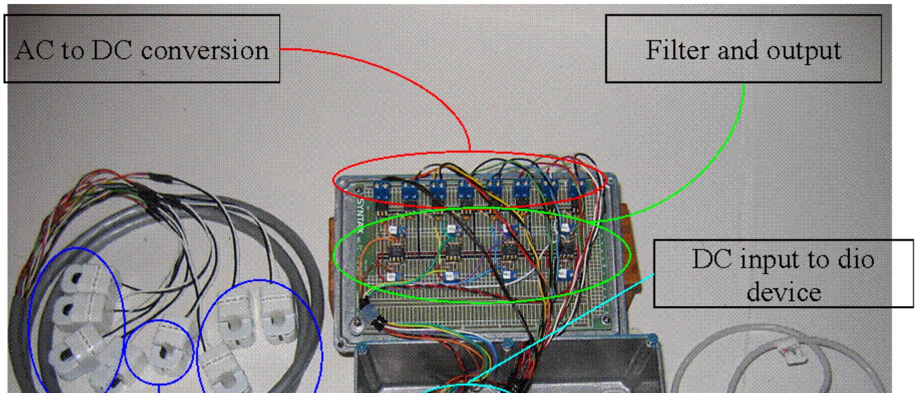
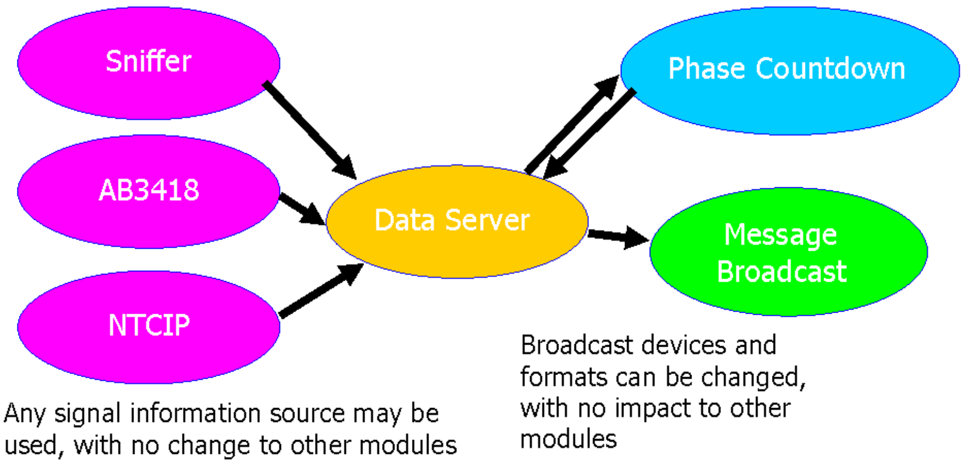


Figure 54: Depiction of “clamp-on” signal sniffer

3.3.4 Interface to Dedicated Short Range Communication

All three methods of acquiring signal phase timing information described in Section 3 have been integrated with the same phase count-down and broadcast software. It is desirable to have well-specified interfaces between the signal phase acquisition, the phase countdown and the broadcast in order to isolate changes required in different installations.



Any signal information source may be used, with no change to other modules

Broadcast devices and formats can be changed, with no impact to other modules

Figure 55: Modular design of signal phase acquisition and broadcast system

The modular system design and logical connections shown in Figure 46 have been used at all three of our VII California testbed intersections, two of which use the sniffer and one of which uses AB3418, as well as at the experimental intersection, where we have tested all three methods. In each case the most complicated part of the software is the phase countdown itself, where we are doing in effect a simplified emulation of the internal logic of the traffic signal controller in order to duplicate the countdown that the traffic signal controller is itself carrying out in order to set the signal phases.

In order to do this, even in simplified form, we require configuration files for each intersection that contain much of the information that has been programmed by the maintaining entity into the traffic signal controller as the intersection's timing plan, as well as a specification of how the signal phase information is being acquired and delivered, and the relationship between the internal phase designations that are meaningful to the traffic signal controller and the geographic description of each approach to the intersection that is meaningful to the approaching vehicle. We currently use three types of configuration files:

- A file that specifies what signal wires the sniffer is connected to, in terms of signal phase, (numbered as in the traffic signal controller logic), and type of light (red, yellow, green). This is not needed with AB3418 or NTCIP.
- A file that specifies the timing plan, giving the interval lengths assigned to each phase, and whether the system is fixed or actuated and/or coordinated.
- A file that gives the correspondence between each approach, defined by geographical information and used as the basic information element in the broadcast message, and the internal traffic signal phase that controls that approach. The geographical information specified in this file becomes part of the broadcast message and is used by the in-vehicle application to determine which signal phase and timing information is relevant.

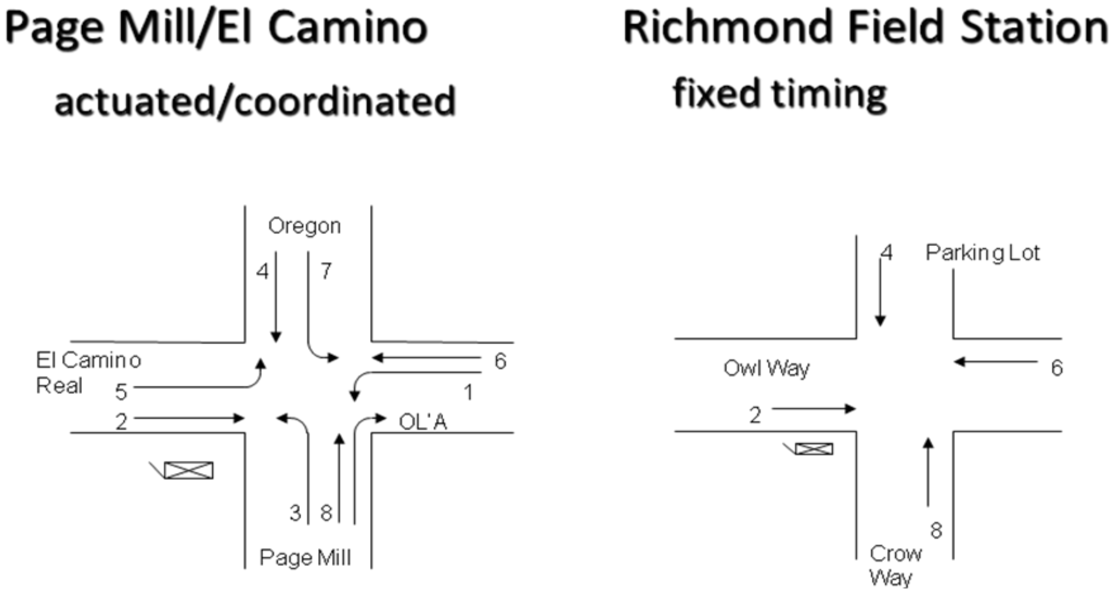


Figure 56: Types of information that must be specified to configure signal phase and timing broadcast.

Figure 48 shows diagrams of the phase plans of two of our intersections as an illustration of the different characteristics that need to be captured in the configuration files. Enough geographical information must be included, in the form of latitude and longitude information describing the lane leading up to a signal, for a vehicle to be able to distinguish what approach it is on to the signal and determine the relevant phase countdown.

3.3.5 Communication Latency for Signal Phase and Timing Information

A serious question about delivering signal phase and timing information to vehicles is whether it can be delivered with low enough latency. Fortunately, our experiments show that it is not difficult to deliver the phase transition information in well less than 100 ms from the time the transition occurred using current technology.

To measure this, since we did not have access to the internal delays and logic of the traffic signal controllers, we first measured the delays on our sniffer circuit with an oscilloscope. These delays are tunable, by changing the triggering points of the comparator circuit, and we adjusted them until the delay for setting the digital output corresponding to the “on” transition of the green signal was reliably under a millisecond. We then measured the sample time of the digital I/O subsystem and found that it was reliably about 2 milliseconds. Since the rise time for the signal driving the light LED was on this order, we then used the transition time for the on signal with the sniffer circuit as our ground truth. Note that this transition time will be later than the time when the activation signal leaves the traffic signal controller to begin to drive the load switches to turn on the light, but within a few milliseconds of the time when the light can be expected to actually change visually in response to the change in the AC signal.

For the AB3418 and NTCIP protocols, which are both query/response protocols, we adjusted the time between queries to be the minimum that the system would tolerate. For AB3418, this was a cycle of 50-60 milliseconds for the entire query response cycle; for NTCIP, this was a cycle of 75 milliseconds required between requests in order to avoid a fault. The results we obtained were somewhat surprising, in that we had expected the AB3418 protocol to typically report a transition time later than the sniffer, but this was not the case, see Figure 49. We conjecture that the internal state machine in the traffic signal controller using AB3418 is setting up the values for the AB3418 message ahead of actually driving the signal, and this allows the AB3418 time to be as early as the sniffer’s on occasion, despite it 50-60 millisecond query/response time.

For the NTCIP implementation we have tested, on the other hand, the delay was much greater, over half a second. We expect that other NTCIP implementations need not have this much latency, since the basic constraints are close to those of AB3418, and conjecture that our NTCIP software was not tuned for real-time performance. We have not yet been able to obtain another implementation of NTCIP to evaluate.

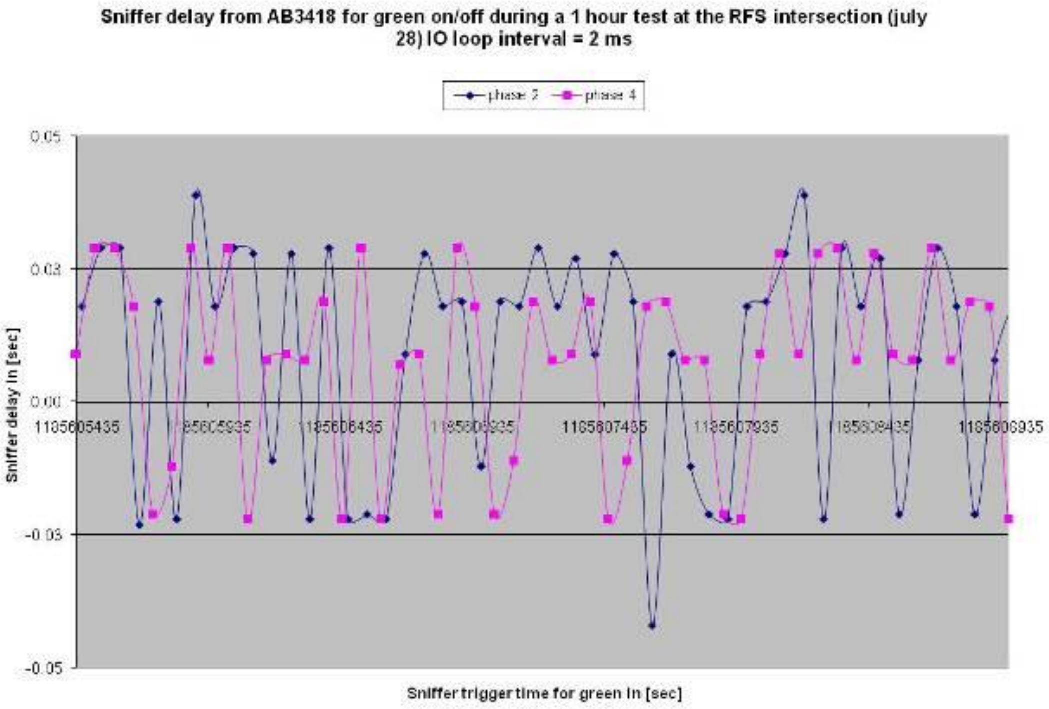


Figure 57: Difference in transition time between AB3418 and sniffer acquisition, run simultaneously

3.3.6 Implementation Status of DSRC Hardware

Several different manufacturers have developed WAVE device prototypes. The Denso Wave Radio Module (WRM) and DSRC Industry Consortium (DIC) Prototype were early prototypes that were used in automobile company demonstrations of a variety of applications, including toll tag reading, map downloads, traffic signal red light warning and collision avoidance, at the ITS World Congress in November 2005. The Caltrans-sponsored VII California testbed in the San Francisco Bay area has 11 existing sites with Denso WRMs, which have been extensively used by car company research labs in the Palo Alto area for developing DSRC-enabled safety applications. These early prototypes, however, do not implement the multi-channel operation of 1609.4.

Commercial systems by Technocom, for Road Side Equipment (RSEs) and by Denso and Parvus for On Board Equipment (OBEs) that implement 1609.3 and 1609.4 are just becoming available now. Under the auspices of the federally funded VII Consortium, Raytheon and Booze Allen Hamilton have been implementing a radio handler that provides a proprietary interface to the 1609.3 and 1609.4 layers on the Technocom RSE, and Cogenia is developing proprietary Java code to interface to these layers on the Wind River Linux Parvus OBE. These proprietary software modules were not operating successfully in any application at last report, and in my opinion the closed nature of their development has violated the spirit of open interoperable standards development.

The Technocom RSE, which uses the Atheros 5006 chipset and a driver based on the open source MAD WIFI driver, is currently under test at PATH. Their licensed 1609 software comes with an open Applications Programming Interface for development, and we plan to use their platform as a basis for developing upper layer and alternative 1609 layers. We also plan to talk with Atheros about the possibility of using the commercially available AR5008 chipset as the basis of a MAD WIFI based DSRC implementation.

Denso has been working closely with the automobile companies in developing a new prototype that implements multichannel operation, but these are currently difficult to obtain. In our conversations with Denso representatives, they indicate manufacture of the device is still at the prototype stage and they are having trouble keeping up with demand. We have been given different information from different sources about whether the Denso 1609 implementation interoperates with the Technocom implementation. They are supposed to interoperate, but it is not clear if they actually do yet or not. We are anxious to obtain units for test.

Cohda Wireless, an Australia-based company, provides low cost, small size, WAVE-DSRC radio for large scale field trials. Their radio is compatible with current 802.11p draft and allows for 1609 stack upgrade. California PATH will be evaluating their hardware (Cohda Wireless MK2 DSRC) and porting implemented software to Cohda platform in early 2010. Table 8 shows the comparison of data throughput using a WiFi chipset and a Cohda DSRC radio. As reported by Cohda Wireless, their radio is more robust to outdoor environments and performs well under the multi-path effect.

Scenario	**Environment**	**Speed (Km/hour)**	**Data Transferred (MBytes)**	
			DSRC using WiFi Chips	**Cohda DSRC**
Road Side Unit	Closed Intersection	60	0.6	13.7
Road Side Unit (OBU is behind a truck)	Closed Intersection	60	0.3	9.5
Road Side Unit	Open Intersection	60	1.2	21.5

Table 8: Performance comparison of WiFi chips and Cohda chips in Field Trial (reported by Cohda: http://www.cohdawireless.com/technology/whitepapers.html)

3.3.7 Summary

In summary, our efforts to obtain and broadcast up-to-date traffic signal phase and timing information using current traffic signal controllers, existing communications standards and moderately priced hardware have been successful. It is not difficult to reformat the information received from either the sniffer or AB3418 into the object structure defined by NTCIP, as we have done, and use that as the basic interface to the signal phase information. In the future it may be desirable to make the phase countdown program more sophisticated and exact for actuated intersections by including loop detector information. This also can be formatted into NTCIP data object definitions before passing on to the phase countdown module.

If exact count-down information is required for all phases, at some point the phase countdown logic would represent a complete duplication of the traffic signal controller logic. It might be better if the information could be sent directly from the controller. Indeed, this has already been done in; signal phase and timing information was sent out as an Ethernet broadcast message and forwarded to the Denso WAVE Radio Module as part the Innovative Mobility Showcase at the 2005 World Congress (Provenzano, 2005). This seems the simplest solution when installing a new intersection, but given the large installed base of existing traffic signal controllers without communication capabilities, add-on devices to do signal phase broadcast and countdown may be the only alternative in many installations for some time. In addition, it may turn out after further experimentation that less detailed information, providing exact countdowns only in certain situations of most importance to vehicle safety applications, may be sufficient.

As another alternative for intersections with legacy equipment, Eberle Design, Inc provided one of their 2010ECL conflict monitors that was configured to send a message over Ethernet with real-time signal status information. Since conflict monitor boards are already standard equipment in traffic control cabinets, this greatly eases the difficulty of qualifying equipment. The signal status message is updated every 60 ms, and can be used with the same software architecture shown in Figure 47, as an additional signal information source.

Implications for the future where the intersection crash problem may be addressed through dynamic red light running countermeasures and other VII-enabled systems that “talk” (in a data sense) between the intersection and car are multi-fold. Clearly, institutional and related capital and operations costs not described in this paper play a part. Additionally, human factors issues ranging from usability to specific design are important and also not described in this paper. However, what is clearly important and covered in this research are the software and hardware implementation and interface issues. Some of those issues – how to adapt to legacy systems, either in an analog fashion (via our “sniffer”) or through software and existing signal controller communications protocols – may actually help circumvent some of the uncovered issues. Our research shows that indeed there can be deployment path to retrofit the heterogeneous and still “ain’t broke” legacy systems and given its reliability, we may be able to deliver to the driver reliable and low latency VII- and DSRC-enabled signal timing information that addresses the purpose of this research, to save lives at intersections.

Part of the above material in Section 3.3 was presented to the Transportation Research Board, January 2008 (Dickey et. al. 2008).

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Appendix A: User's Guide: UCB WAVE Software

This guide has been written to describe the software originally developed as part of Caltrans Task Orders 5214 and 6214, "ITS Band Roadside to Vehicle Communications in a Highway Setting." This software is currently running on the Kapsch/Technocomm Multiband Configurable Networking Unit and on the Savari Networks Mobiwave On-board Unit. Development for the Denso Wireless Safety Unit is underway. To obtain this software distribution, contact Dr. Susan Dickey, dickey@path.berkeley.edu.

A1. Design goals for UCB WAVE software

The purpose of this development was to create a standards-based, open source body of code that would make all of the capabilities the IEEE 1609 Wireless Access in Vehicular Environments standards, which provide for interoperable use of the 5.9 GHz Intelligent Transportations Systems (ITS) Dedicated Short Range Communication (DSRC) band, available to the applications programmer. Since the standards were under development during the period of Task Orders 5214 and 6214, and are still being revised for full-use, the software is necessarily a work in progress.

The UCB WAVE software is designed to provide a platform-independent Applications Programming Interface, so that software written for one WAVE-compliant radio platform can easily be ported to another, and so that proprietary details of the hardware are hidden from the application writer, and only need to be known by the API implementer. In order to be able to run the software directly on the embedded processor used for the hardware vendor's radio service routines, the C language was used for efficiency and portability. Rather than providing a limited set of capabilities through an integrated graphical user interface, this software is organized as library functions that may be called from other languages, and as sample test programs which illustrate the use of the functions, so that the platform-independent API can be used by programmers when developing a variety of applications.

The radio hardware typically includes a processor powerful enough for many applications, but may not include a disk drive for permanent storage, so programs must be careful not to write logs or trace data to the file system. Inter-process communications must likewise be carried out in- memory; for this purpose we investigated the use of lightweight databases and data servers. The radio hardware typically does include other networking (wired and ordinary Wi-Fi access as well as DSRC), so sample programs for forwarding information from WAVE Short Messages to UDP ports are included among the test programs.

Capabilities required to test performance of on-site installation of Road Side Equipment (RSE) are provided. These include:

- The capability to send and receive a basic safety message including GPS location and timestamp information
- The capability to access and report signal strength information as provided by the radio vendor's service routines
- Examples of how to use probe vehicles and correlate timestamped data collected from vehicles and RSE in order to evaluate radio performance at an installation site.

The software package also includes code that was written to receive Signal Phase and Timing (SPAT) information from real intersections in New York City during Intellidrive demonstrations at the 2008 ITSA World Congress, as an example of how to use the API.

A2. Software structure

A2.1. Overall Structure

The software is not tied to a particular process or development environment, and is designed to compile on a variety of systems that have the standard Unix-based tool sets. The `make` utility is used with a system-specific include file that can be used to tailor the software build tree to either a cross-compile or native compile environment as required.

Device-independent files and directories are open source, and include the API description, utilities for using GPS, timestamp utilities, an in-memory data server with example client software, and examples for lightweight database access. Proprietary device-dependent files for the different DSRC radio vendors are distributed only to those who have purchased hardware from the vendors and associated software licenses.

A2.2. WAVE API

The WAVE API implementation consists of a directory `vii_wave_api` containing an open source header file, `vii_wave_api.h` and a library, `libvii_wave_utils.a` that implements the following functions for the desired DSRC platform:

```
vii_wave_handle_t * vii_wave_alloc_handle ()

void vii_wave_free_handle (vii_wave_handle_t *phandle)

int vii_wave_register_provider (vii_wave_handle_t **pphandle,
int psid, unsigned char *psc_bytes, unsigned char psc_length,
char *dev, struct in6_addr *paddr, int port, int flags)

int vii_wave_unregister_provider (vii_wave_handle_t **pphandle)

int vii_wave_register_user (vii_wave_handle_t **phandle, int
psid, unsigned char *psc_bytes, unsigned char psc_length, char
*dev, int flags)

int vii_wave_unregister_user (vii_wave_handle_t **pphandle)

int vii_wave_activate_service (vii_wave_handle_t *phandle, int
repeats, unsigned char ch_num, unsigned char wme_set_channel)

int vii_wave_inactivate_service (vii_wave_handle_t *phandle)

int vii_wave_wait_event (vii_wave_handle_t *phandle)

int vii_wave_event_to_confirm (vii_wave_handle_t *phandle)

int vii_wave_event_service_terminated (vii_wave_handle_t
*phandle)

int vii_wave_event_service_active (vii_wave_handle_t *phandle)

void vii_wave_close_api ()
```

```
int vii_wave_create_wsmp_socket (vii_wave_handle_t *phandle, int
use_sch)
```

```
int vii_wave_send_wsmp (vii_wave_handle_t *phandle, char *buf,
int size, unsigned char *dest_mac, int use_sch)
```

```
int vii_wave_rcv_wsmp (vii_wave_handle_t *phandle, char *buf,
int buffer_size, int millisec)
```

The library is built in device-dependent directories particular to the DSRC radio vendor. The "handle" shown in the above function calls is a structure with no visible fields that hides the details of the particular WAVE implementation from the applications programmer. In the functions above, providers and users are implemented according to the trial-use IEEE 1609.3 standard, and "wsmp" refers to the WAVE Short Message Protocol and the operations necessary to send WAVE Short Messages.

In addition to the libraries, there is a `test_suite` directory that contains source code to build the following programs that use `libvii_wave_utils.a`:

`wsmp_snd`	Reads standard input and send CCH WAVE Short Messages
`wsmp_rcv`	Receives CCH WAVE Short Messages and writes to standard output
`wsmp_snd_hex`	Reads binary data and sends as CCH WAVE Short Messages
`wsmp_snd_wrfile`	Receives CCH WAVE Short Messages and writes as binary data
`fwd_wsm_udp`	Receives CCH WAVE Short Messages and sends to UDP port.
`fwd_udp_wsm`	Receives on UDP port and sends as CCH WAVE Short Messages.

A2.3. California PATH utilities

The software in the `path` directory is based on code used at California PATH for a variety of projects, includes data server, GPS and timestamp utilities, and consists of the following subdirectories:

`local` This directory contains source for a library with a variety of useful utility functions for timestamps and data logging. (On these embedded systems, using the data logging facilities is best done with an in-memory file system like `tmpfs.)`

`gps` This directory contains a `src` subdirectory to build a library with GPS reading and coordinate transformation functions, as well as an `examples` subdirectory that includes programs that send and receive formatted GPS location and timestamp data to and from UDP ports. These can be used with Unix process pipelining and the `fwd_wsm_udp` and `fwd_udp_wsm` programs from the `test_suite` directory to send basic safety messages.

`db` This directory contains the source code for a lightweight "publish and subscribe" data server, based on Posix inter-process communication primitives, that provides read and write semantics for communicating data between network and other processes.

`clt` This "client" directory includes sample programs for accessing the `db` data server, as well as network utility code, including code for keeping track of round-trip timing for network sends and receives.

A2.4. Signal Phase and Timing Example

The `j2735` subdirectory contains code based on SAE J2735 DSRC Message Set Rev 29 that was used to receive Signal Phase and Timing information and send Transit Signal Priority Requests in exchange with New York City traffic controllers. The bus sending and receiving these messages was using a prototype Savari Mobiwave, the New York city traffic controller installation was using a Kapsch MCNU. The `src` directory contains a “hand-coded” parse table for the preliminary version of SAE J2735 available at the time; now that compilable ASN for the SAE J2735 standard is available, this should be replaced with code automatically generated from the ASM. However, the table-driven approach may still be useful for holding the functions to be executed by an automatic parse.

The `j2735/examples` subdirectory shows how to use the WAVE API in the context of an extended application. In this example, interoperable communications were successful with another WAVE device that was not running the UCB WAVE API, due in part to excellent support from Kapsch and from Peek Traffic, who implemented the RSE side of the demonstration.

A2.1. Probe vehicle analysis

The `plot` subdirectory contains an extended example, using data from several runs at Richmond Field Station, Unix scripts for filtering the data, Javascript code for displaying it using Google Earth, and gnuplot scripts for creating presence/distance graphs, of how to determine the performance of an RSE communicating with probe vehicles.

A3. Getting started

To get started with using the UCB WAVE software, follow the following steps:

1) Install the radio service software from the DSRC radio vendor and make sure you can build and run example programs that they provide. It is assumed that a standard Unix toolset including `make` and `gcc` is available.
2) Unpack `capath_ucb_wave.tar.gz` in a directory of your choice. Change to the `path/build` directory that is part of the distribution, and edit the `capath_[radio vendor designator].mk` file that corresponds to your DSRC radio vendor. This is the file that contains necessary definitions for compilation on your system, and needs to be included by any makefile you use. Change `DISTRIB_DIR` to designate the directory where you unpacked the UCB WAVE distribution, and follow any other directions in the file for setting definitions to the location of the correct compile tool chain for your system.
3) Set up the account that will be building the software to have the environment variable `CAPATH_MK_DEF` set to the full pathname of the `capath_[radio vendor designator].mk` file you are using. Then all of the makefiles provided as part of the UCB WAVE distribution, which contain the line `include $(CAPATH_MK_DEF)` will work correctly.

4) Change directory to the `path` directory and type `make` to set up the rest of the compile environment and build the California PATH utility libraries and sample programs.
5) Change directory to the `itsband` directory and type `make` to build the WAVE API and example programs.

See the shell scripts for examples of how to run the programs described in the Software Structures sections, see the UCB WAVE Reference Manual and comments in the source code for detailed information about the functions and programs. Send email to dickey@path.berkeley.edu with questions and any bug reports.