Cellular Network Reliability During a Crisis in Rural Areas

Requested by
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The Caltrans Division of Research, Innovation and System Information (DRISI) receives and evaluates numerous research problem statements for funding every year. DRISI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing credible work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research. The views and conclusions in cited works, while generally peer reviewed or published by authoritative sources, may not be accepted without qualification by all experts in the field. The contents of this document reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the California Department of Transportation, the State of California, or the Federal Highway Administration. This document does not constitute a standard, specification, or regulation. No part of this publication should be construed as an endorsement for a commercial product, manufacturer, contractor, or consultant. Any trade names or photos of commercial products appearing in this publication are for clarity only.

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Executive Summary

Background

Caltrans relies on intelligent transportation system (ITS) field element devices that use cellular networks and other technologies to relay data between these devices and transportation management center facilities, and to communicate to the public via field element devices. Caltrans lacks direct evidence that 4G/LTE technology functions well during crises, especially in rural areas. Events like the Oroville Dam incident, solar eclipse and wildfires in northern and southern counties suggest, anecdotally, that in 2017 the cellular network was not reliable in rural areas during crises, due both to cellular infrastructure failures and network congestion.

Caltrans is seeking industry and academic evidence of cellular network reliability in rural areas during a crisis or event, with a focus on machine-to-machine data sharing rather than on voice communications or consumer-level cellular uses. Also of interest are technologies and platforms that may offer an alternative to cellular-based communications.

To assist with this effort, CTC & Associates examined published and in-progress research and other relevant publications to gather information about third-party analyses of cellular network reliability in rural areas during crises or events. This literature search also gathered a sampling of publications that address cellular network alternatives.

Summary of Findings

While we found no published research that examined cellular network reliability associated specifically with the use of ITS field element devices in rural areas during a crisis or event, we located publications that consider more generally cellular network reliability and cellular network alternatives. We also identified collaborative research efforts that include in their charges the review of communication-related technologies.

Below is a summary of the resources we identified in three topic areas:

- Cellular network reliability in crises or events.
- Cellular network alternatives.
- Technologies evaluated by pooled fund studies.

Cellular Network Reliability in Crises or Events

Our research uncovered only one research-oriented publication that described a methodology for assessing the performance of a cellular network during and immediately after a crisis (the journal article does not address cellular network reliability in rural areas). The authors of this April 2010 journal article noted that “adding redundancy, particularly through a mesh topology or through the addition of an optical fiber ring around the perimeter of the system can be an effective way to significantly increase the reliability of some cellular systems during hurricanes.” Supplementing this publication are three articles that consider more generally the reliability of a cellular communications infrastructure during a crisis or event, with a focus on consumer uses.

Cellular Network Alternatives

Dedicated Short Range Communications

Dedicated short range communications (DSRC) is a linchpin technology for communication strategies used with various ITS applications. We cite a small sampling of the research conducted in this topic area, including an April 2017 Federal Highway Administration publication providing DSRC specifications for roadside units, a May 2016 National Highway Traffic Safety Administration report that recommends measures to assess DSRC on-board equipment performance and an April 2012 journal article that examines DSRC performance.

Microwave and Other Wireless Communication Methods

Worldwide Interoperability for Microwave Access (WiMAX) has been described as an alternative to cable and digital subscriber line (DSL) platforms that can provide data over long distances. In this section, we highlight selected publications that describe WiMAX and other wireless communication alternatives such as wireless fidelity (Wi-Fi), including:

Cognitive radio network and vehicular ad hoc network (VANET). A June 2016 journal article describes these emerging concepts in wireless networking: “Cognitive radio network obtains knowledge of its operational geographical environment to manage sharing of spectrum between primary and secondary users, while VANET shares emergency safety messages among vehicles to ensure safety of users on the road.”

Mobile ad hoc network (MANET). A 2015 journal article analyzes four successful ad hoc networking paradigms—mesh networks, opportunistic networks, vehicular networks and sensor networks—which the authors noted “emerged from the MANET world.”

Short message service (SMS). A December 2015 journal article discusses the use of “the SMS as mechanism for data transfer, especially in scenarios where there is no other network coverage than GSM [Global System for Mobile Communication, a global standard for digital communication], such as in rural areas and developing regions.”

NOMOHi network (Node, Mobil, Hybrid, Intelligent). A 2013 conference presentation describes a network in which the mobile node (in this case, a vehicle) has the capacity “to decide” in what moment it will use one of multiple available technologies and how the transfer of communications is negotiated.

WiMAX. An August 2010 South Carolina Department of Transportation research report describes field tests that evaluated critical parameters of WiMAX and Wi-Fi; a July 2011 journal article discusses the project. A 2010 conference presentation proposed a hybrid system that combines a version of DSRC with WiMAX technology.

Wi-Fi. A 2009 conference paper describes a new networking platform that uses common hardware (bluetooth and Wi-Fi) and open source software. The authors described how the new system “exploits” already-deployed municipal Wi-Fi-based wireless mesh networks (WMNs) to collect and transport ITS data, across the WMN and through the Internet, to a monitoring center.

Wireless mesh networking. WMNs have been described as an alternative to broadband access. Conference presentations from October 2013 and June 2009 address in more detail the use of WMNs in rural and emergency applications.

Technologies Evaluated by Pooled Fund Studies

The activities of two Transportation Pooled Fund Program projects (described below) that are investigating information dissemination and ITS technologies may have some relevance to Caltrans' examination of the reliability of cellular networks:

Aurora Program. This consortium of public road agencies is focused on collaborative research, evaluation and deployment of advanced technologies for detailed road weather monitoring and forecasting.

Evaluating New Technologies for Roads Program Initiatives in Safety and Efficiency—ENTERPRISE (Phase II). This study continues a previous effort to "promote ITS approaches and technologies that are compatible with other national and international ITS initiatives."

Gaps in Findings

We found no publicly available research that specifically addresses the reliability of cellular networks in rural areas during a crisis or event. While our research identified publications describing technologies that may provide an alternative to cellular networks, we did not uncover research that applies those technologies to support the reliable functioning of ITS field element devices in rural areas during a crisis or event.

Next Steps

Moving forward, Caltrans could consider:

- Contacting an author of the April 2010 journal article that describes a methodology for estimating cellular network performance during hurricanes to learn more about those results and the possibility of continued research efforts in this area. (One of the authors, Dr. Seth Guikema, is now affiliated with the University of Michigan's Guikema Research Group (http://ioe-guikema.engin.umich.edu; 734-764-6475, sguikema@umich.edu)).
- Conducting a high-level review of cellular alternatives presented in this Preliminary Investigation to identify technologies warranting a more in-depth analysis.
- Consulting with the lead agency representatives for the Transportation Pooled Fund Program studies cited in this Preliminary Investigation to determine if study activities may have some relevance to Caltrans' interests in cellular network reliability.

Detailed Findings

Cellular Network Reliability in Crises or Events

Our research uncovered only one research-oriented publication that described a methodology for assessing the performance of a cellular network during and immediately after a crisis event (this journal article does not address cellular network reliability in rural areas). Also cited below are three articles that consider more generally the reliability of a cellular communications infrastructure during a crisis event, with a focus on consumer uses.

Related Research

"Estimating Cellular Network Performance During Hurricanes," Graham Booker, Jacob Torres, Seth Guikema, Alex Sprintson and Kelly Brumbelow, *Reliability Engineering and System Safety*, Vol. 95, No. 4, pages 337-344, April 2010.
Citation at http://www.sciencedirect.com/science/article/pii/S0951832009002555
From the abstract: In this paper we develop a new multi-disciplinary approach to efficiently and accurately assess cellular network reliability during hurricanes. We show how the performance of a cellular network during and immediately after future hurricanes can be estimated based on a combination of hurricane wind field models, structural reliability analysis, Monte Carlo simulation, and cellular network models and simulation tools. We then demonstrate the use of this approach for assessing the improvement in system reliability that can be achieved with discrete topological changes in the system. Our results suggest that adding redundancy, particularly through a mesh topology or through the addition of an optical fiber ring around the perimeter of the system can be an effective way to significantly increase the reliability of some cellular systems during hurricanes.

Other Resources

Note: Though the article cited below does not solely examine cellular networks, the author's advice on preventative measures may be relevant to Caltrans' examination of the reliability of cellular networks.

"When Communications Infrastructure Fails During a Disaster," Christina Richards, *Disaster Recovery Journal*, November 2015.
https://www.drj.com/articles/online-exclusive/when-communications-infrastructure-fails-during-a-disaster.html
This online journal article addresses how communication infrastructure fails during a disaster and preventive measures to keep networks intact. *From the article:*

> **Preventative Measures to Keep Networks Intact**
>
> *Network Path Diversity*
>
> Network path diversity is one of the most effective tactics to reduce the risk of communications failure during a disaster. This is accomplished by establishing two or more network connections that use either a different type of technology or follow a different physical path, minimizing the chance that both connections will be knocked out at the same time. These pathways must also be secure and completely redundant in the data they process, so that in the event one path fails, the flow of information is neither interrupted nor reduced.

....

It is often far more effective to use one or more wireless links to complement existing fiber-optic cable connections, as the technologies for millimeter wave and other wireless transmissions utilize entirely separate network pathways. At the same time, however, it is also important that operators use a wireless solution that can meet the reliability and capacity requirements of the network, otherwise a loss of the primary connection may result in severely limited communications, regardless of the back-up connection.

Ad-Hoc Networks

Because network connections cannot always be preserved in a disaster scenario, another effective method for maintaining and/or restoring communications in the hours immediately following the event is to establish one or more ad-hoc network links. Ad-hoc networks allow for the rapid deployment of fiber-like connectivity in situations where capacity is needed on an expedited basis, and they allow both victims and emergency workers to communicate when it is most important.

"Why Your Phone Doesn't Work During Disasters—And How to Fix It," Neal Ungerleider, *Fast Company*, April 2013.
https://www.fastcompany.com/3008458/why-your-phone-doesnt-work-during-disasters-and-how-fix-it
From the article: In the fog of [the 2013 Boston Marathon] disaster, hundreds of thousands of people worldwide tried calling their loved ones in the Boston area. The Boston metropolitan area's robust mobile networks simply clogged up as Verizon, AT&T, Sprint, T-Mobile, and other providers coped with a massive and unexpected surge. … With that in mind, a series of new and innovative methods have been created to temporarily increase bandwidth during times of emergency. These range from mobile emergency wireless trucks to crowdsourced casualty clearing houses to creative bandwidth reallocation.

"Can Mobile Phone Networks be Improved to Better Cope With Emergencies?" Larry Greenemeier, *Scientific American*, August 2011.
https://www.scientificamerican.com/article/smart-phone-emergency/
From the article: Anyone in the eastern portion of the U.S. this week who was forced to evacuate an office, home or school following Tuesday's magnitude 5.8 earthquake soon noticed that cell phone service was spotty or, in many cases, nonexistent. For New Yorkers herded outside of their skyscrapers and into the streets, it was a communication blackout reminiscent of (although of course not the same as) the 9/11 terrorist attacks. In both situations, mobile phone users were unable to connect to the cell network to communicate with loved ones. Whereas the 9/11 cell phone outage was the result of many factors—including the downing of cell phone towers—this week's problems (though brief) were caused purely by volume. Countless cell phone users were fighting for limited access, leaving most without service. With Hurricane Irene bearing down on the East Coast, one is left to question the reliability of mobile phones in the face of serious emergencies. *Scientific American* spoke with Andrea Goldsmith, a Stanford University electrical engineering professor and researcher at the school's Wireless Systems Lab, about why mobile phone users are often unable to connect during emergencies, as well as options for improving cell network performance when it matters most.

Cellular Network Alternatives

The citations below describe alternatives to the use of cellular networks for communication. These citations are organized into two topic areas:

- Dedicated short range communications.
- Microwave and other wireless communication methods.

Dedicated Short Range Communications

Dedicated short range communications (DSRC) is a linchpin technology for communication strategies used with various intelligent transportation system (ITS) applications. The following citations offer a small sampling of the research conducted in this topic area.

Dedicated Short-Range Communications Roadside Unit Specifications, Frank Perry, Kelli Raboy, Ed Leslie, Zhitong Huang and Drew Van Duren, Federal Highway Administration, April 2017.
https://transops.s3.amazonaws.com/uploaded_files/Dedicated%20Short%20Range%20Communications%20Roadside%20Unit%20Specifications.pdf
From the abstract: The Intelligent Transportation Systems (ITS) Program definition of connected vehicles includes both 5.9 Gigahertz (GHz) Dedicated Short Range Communications (DSRC) and non-DSRC technologies as means of facilitating communication for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) applications. Non-DSRC technologies (e.g. Radio Frequency Identification (RFID), Worldwide Interoperability for Microwave Access (WiMAX), Wi-Fi, Bluetooth, and cellular communication) enable use of existing commercial infrastructure for additional capacity support, but may not meet the low-latency needs of transmitting safety-critical information.

DSRC is a two-way wireless communications protocol suite that integrates the IEEE 802.11, 1609.x standards, SAE J2735, and SAE J2945. The United States Department of Transportation (USDOT) is pursuing DSRC because of its low-latency and high-reliability performance that can be used to reduce fatalities through active safety applications, including collision avoidance, incident reporting and management, emergency response, and pedestrian safety. Furthermore, DSRC supports the close-range communication requirements to distribute Signal Phase and Timing (SPaT) information for intersection-based applications and localized roadway warnings. This document will set the requirements for roadside units (RSU) capable of acting as a network edge device for 5.9GHz DSRC infrastructure.

Development of DSRC Device and Communication System Performance Measures: Recommendations for DSRC OBE [On-Board Equipment] Performance and Security Requirements, National Highway Traffic Safety Administration, May 2016.
https://rosap.ntl.bts.gov/view/dot/31627/dot_31627_DS1.pdf
From the abstract: This report presents recommendations for minimum DSRC device communication performance and security requirements to ensure effective operation of the DSRC system. The team identified recommended DSRC communications requirements aligned to use cases, performance needs, DSRC functions, existing research, testing and simulation findings, and also developed compliance test procedure recommendations. The team also identifies recommended security functional requirements following the Common Criteria methodology which aligns requirements to a Target of Evaluation (TOE), threats, assumptions, security organizational policies, and security objectives. The report also includes discussions

about outstanding decisions that will affect the operations and performance of the DSRC elements in the system. Next steps and additional analyses that could help further define performance and security requirements are also discussed.

"DSRC Performance Comparison With and Without Antenna Diversity Using Different Transmission Power," Sue Bai and Radovan Miucic, *SAE International Journal of Passenger Cars—Electronic and Electrical Systems*, Vol. 5, No. 2, pages 429-439, April 2012.
Citation at https://trid.trb.org/View/1432312
From the abstract: Vehicle-to-Vehicle (V2V) safety application research based on short range real-time communication has been researched for over a decade. Examples of V2V applications include Electronic Emergency Brake Light, Do Not Pass Warning, Lane Departure Warning, and Intersection Movement Assist. It is hoped that these applications, whether present as warning or intervention, will help reduce the incidence of traffic collisions, fatalities, injuries, and property damage. The safety benefits of these applications will likely depend on many factors, such as usability, market penetration, driver acceptance, and reliability. Some applications, such as DNPW and IMA, require a longer communication range to be effective. In addition, Dedicated Short Range Communications (DSRC) may be required to communicate without direct line of sight. The signal needs to overcome shadowing effects of other vehicles and buildings that are in the way. Some remedies may include increasing transmission power, using higher gain antennas, and using multiple antennas with diversity reception. This paper presents experimental results of several field trials using different configurations in transmission power, antenna diversity, and antenna gain of a DSRC receiving system.

Microwave and Other Wireless Communication Methods

Worldwide Interoperability for Microwave Access (WiMAX) has been described as an alternative to cable and digital subscriber line (DSL) platforms that can provide data over long distances. The citations below describe WiMAX and other wireless communication alternatives such as wireless fidelity (Wi-Fi).

"Cognitive Radio Network in Vehicular Ad Hoc Network (VANET): A Survey," Joanne Mun-Yee Lim, Yoong Choon Chang, Mohamad Yusoff Alias and Jonathan Loo, *Cogent Engineering*, Vol. 3, June 2016.
https://www.cogentoa.com/article/10.1080/23311916.2016.1191114
From the abstract: Cognitive radio network and vehicular ad hoc network (VANET) are recent emerging concepts in wireless networking. Cognitive radio network obtains knowledge of its operational geographical environment to manage sharing of spectrum between primary and secondary users, while VANET shares emergency safety messages among vehicles to ensure safety of users on the road. Cognitive radio network is employed in VANET to ensure the efficient use of spectrum, as well as to support VANET's deployment. Random increase and decrease of spectrum users, unpredictable nature of VANET, high mobility, varying interference, security, packet scheduling, and priority assignment are the challenges encountered in a typical cognitive VANET environment. This paper provides survey and critical analysis on different challenges of cognitive radio VANET, with discussion on the open issues, challenges, and performance metrics for different cognitive radio VANET applications.

"From MANET to People-Centric Networking: Milestones and Open Research Challenges," Marco Conti, Chiara Boldrini, Salil S. Kanhere, Enzo Mingozzi, Elena Pagani, Pedro M. Ruiz and Mohamed Younis, *Computer Communications*, Vol. 71, pages 1-21, 2015.
http://www.iit.cnr.it/sites/default/files/Conti,%20Boldrini%20et%20all.pdf
From the abstract: In this paper, we discuss the state of the art of (mobile) multi-hop ad hoc networking with the aim to present the current status of the research activities and identify the consolidated research areas, with limited research opportunities, and the hot and emerging research areas for which further research is required. We start by briefly discussing the MANET [mobile ad hoc network] paradigm, and why the research on MANET protocols is now a cold research topic. Then we analyze the active research areas. Specifically, after discussing the wireless-network technologies, we analyze four successful ad hoc networking paradigms, mesh networks, opportunistic networks, vehicular networks, and sensor networks that emerged from the MANET world. We also present an emerging research direction in the multi-hop ad hoc networking field: people centric networking, triggered by the increasing penetration of the smartphones in everyday life, which is generating a people-centric revolution in computing and communications.

"Secure and Reliable Data Communication in Developing Regions and Rural Areas," Arcangelo Castiglione, Raffaele Pizzolante, Francesco Palmieri, Alfredo De Santis, Bruno Carpentieri and Aniello Catiglione, *Pervasive and Mobile Computing*, Vol. 24, pages 117-128, December 2015.
Citation at http://www.sciencedirect.com/science/article/pii/S1574119215000759
From the abstract: Nowadays, despite the ever increasing need of people for staying "connected" at any time and everywhere, in many areas of the world data connection is extremely expensive or even absent. The Global System for Mobile Communication (GSM) network virtually covers all the populated areas of the world and on average, the entire world population have a handheld device capable of accessing at least the GSM services. Therefore, it makes sense to consider the Short Message Service (SMS) as the most popular wireless data service for such devices. In this work, we exploit the SMS as mechanism for data transfer, especially in scenarios where there is no other network coverage than GSM, such as in rural areas and developing regions. In particular, we propose a framework, based on the SMS as transport facility, which enables secure end-to-end data communication in a ubiquitous and pervasive manner. Moreover, we investigated how, by using compression techniques, the overall processing and transmission efforts needed for secure data communication can be effectively reduced, with the obvious consequences also in terms of energy consumption on the involved devices. Finally, we successfully tested the effectiveness of the proposed framework within the context of a proof of concept implementation.

"Hybrid Wireless NOMOHi Networks, IEEE 802.11 and Ultra Wideband IEEE 802.15.3 Working Together to Support Emergency Inter-Vehicle Communications," Juan José Martínez Castillo, Karina Avilés Rodríguez and Ivan José Salazar, *20th ITS World Congress*, 2013.
Citation at http://trid.trb.org/view/1320647
From the abstract: A vehicle could establish Emergency communications at short distance with other vehicles and stations bases with IEEE 802.15.3; and when going away, in order not to lose covering, it will communicate via WIFI or 802.11h, depending on the standards approved in the region where the vehicle is. In a NOMOHi Network (Node, Mobil, Hybrid, Intelligent), [t]he mobile node (vehicle) it will have the capacity "to decide" in what moment it will use some of the 2 available technologies and the form of negotiating the transfer of those communications. The authors would propose a possible common architecture of collaboration among both, they would

study the problems of interoperability among them and they would compare this architecture with others that are in study or already available in the market.

Evaluation of Communication Alternatives for Intelligent Transportation Systems, Mashrur Chowdhury, K.C. Wang, Ryan Fries, Yan Zhou, Lee Tupper, Jennifer Ogle, Tahera Anjuman, Vikram Bhide and Parth Bhavsar, South Carolina Department of Transportation, August 2010.
https://rosap.ntl.bts.gov/view/dot/25117/dot_25117_DS1.pdf
From the abstract: The primary focus of this study involved developing a process for the evaluation of wireless technologies for intelligent transportation systems, and for conducting experiments of potential wireless technologies and topologies. Two wireless technologies: Wireless Fidelity (Wi-Fi) and Worldwide Interoperability for Microwave Access (WiMAX) were chosen to demonstrate the proposed evaluation process. The authors performed numerous field tests on these technologies to evaluate various critical parameters of wireless communication. The authors also implemented a network design process using Wi-Fi and WiMAX technologies to support a traffic surveillance system in seven metropolitan areas of South Carolina. Additionally, a video surveillance test was conducted to study the transmission of real-time traffic video over a wireless network. Making use of the results from the field study, the authors applied a communication simulator, ns-2, to compare the communication performance of a traffic sensor network under simulated environmental conditions. They also built an integrated simulator using ns-2 and a vehicular traffic simulator, PARAMICS. This integrated simulator was then used to study the communication behavior of the system during traffic incidents. Additionally, the authors conducted a performance-cost analysis for selected wireless technologies.

Related Resource:

> **“Wireless Communication Alternatives for Intelligent Transportation Systems: A Case Study,”** Yan Zhou, Glenn Hamilton Evans Jr., Mashrur Chowdhury, Kuang-Ching Wang and Ryan Fries, *Journal of Intelligent Transportation Systems*, Vol. 15, No. 3, pages 147-160, July 2011.
> Citation at http://www.tandfonline.com/doi/abs/10.1080/15472450.2011.594681.
> *From the abstract:* Performance and reliability are among the most important parameters to be considered when examining wireless communication options for traffic control and management applications. The authors first conducted interviews with selected traffic agencies regarding their experiences with performance of wireless communication infrastructure, as well as their interests and plans on future expansion. Next, they conducted a thorough literature review focusing on various wireless technologies that could be used in an intelligent transportation system environment. Last, the authors conducted a case study in which a section of the South Carolina Department of Transportation traffic camera system was wirelessly connected via either [a] WiFi or WiMAX network architecture. This case study followed the proposed network design process presented in the article using WiFi and WiMAX technologies to support a traffic surveillance system that considered coverage range and two different network topologies: mesh/ad hoc (devices forward data to neighboring devices to reach the destination) and infrastructure (devices send data to an access point directly). The network simulator ns-2 was used to assess the average throughput that each camera can receive in different network topologies. Throughput/cost analysis of WiFi and WiMAX mesh and infrastructure topologies indicated that for [a] given number of devices, a mesh network has better throughput for every dollar spent than infrastructure based topology.

"Hybrid Telematics System Combining WAVE DSRC with WiMAX," Kang-Chiao Lin and Chun-Huang Lin, *17th ITS World Congress*, 2010.
Citation at http://trid.trb.org/view/1136391
From the abstract: Dedicated Short Range Communication (DSRC) is the latest technology in infrastructure investment of Intelligent Transportation Systems (ITS). Wireless Access in Vehicular Environment (WAVE) is one of the most potential standards that would yield short- and long-term economic benefits. In this paper, the authors propose a hybrid field-trial system combined with WAVE DSRC and WiMAX technology. Two demonstration scenarios are introduced. One is Congestion Avoidance System and the other is Emergency Alert System. This field-trial system is composed of an Onboard unit (OBU) in the vehicle, Roadside unit (RSU), Local Traffic Server (LTS) and Global Traffic Server (GTS). All of the communication messages sent from vehicle to vehicle (V2V) or sent from vehicle to road-side unit (V2R) is in WAVE short message protocol (WSMP) format. Worldwide Interoperability for Microwave Access (WiMAX) connection is used to send global traffic information from vehicle to infrastructure (V2I).

"Wi-Fi Service-Oriented Framework for ITS Infrastructure Communication and Monitoring," Hazem Ahmed, Mohamed EL-Darieby and Baher Abdulhai, *TRB 88th Annual Meeting Compendium of Papers DVD*, Paper #09-3428, 2009.
Citation at http://trid.trb.org/view/882271
From the abstract: In this paper, we introduce and describe a new service-oriented platform for ITS monitoring, communications and wireless applications development. The framework consists of software and networking platforms. The state of the art service oriented software platform can be used by ITS application developers as a modular environment to develop their ITS software applications. Latest trends in software development methodologies such as enterprise service oriented development and design were followed to establish this framework. In addition, the new framework encapsulates a novel and cost effective ITS networking platform that uses traveling cars as probes for monitoring traffic and ITS infrastructure. The networking platform is built using common hardware (bluetooth and Wi-Fi) and open source software. In addition, the networking platform exploits the already-deployed (municipal) wireless mesh networks (e.g., WI-FI-based WMN) to collect and transport ITS data, across the WMN and ultimately through the internet, to a monitoring center. We describe the network and software architecture including the wireless protocols and their interactions that we used to build our platform. The developed platform can be extended to provide many applications and services such as congestion identification and quantification, traveler information systems, and navigation and route guidance services. This paper illustrates how our platform is used to detect and track vehicles and measure their approximate speeds as a proxy for congestion level. The data collected at the hardware level is wrapped and presented as services with standard access interfaces. Our pilot field tests and results in Regina, Canada are encouraging. We plan to incorporate more advanced algorithms to enhance speed calculation accuracy.

Wireless Mesh Networking in Rural and Emergency Applications

A few citations in the previous sections considered the use and efficacy of wireless mesh networks, which have been described as an alternative to broadband access. The citations below address in more detail the use of wireless mesh networks in rural and emergency applications.

"A Survey on Wireless Mesh Network Applications in Rural Areas and Emerging Countries," Christian Kobel, Walter Baluja Garcia and Joachim Habermann, *IEEE Global Humanitarian Technology Conference*, October 2013.
Citation at http://ieeexplore.ieee.org/document/6713717/
From the abstract: Wireless Mesh Networks (WMN) offer a cost-effective possibility to enable wireless access in remote villages or cities. This work is a survey on WMN solutions in rural areas and developing countries. The authors intend to inform potential network planners about the specific advantages of WMN technology and its deployment. Positive effects range from enabling connectivity in remote zones, to a better accessibility to extended public services. Representative, state-of-the-art mesh setups, mostly situated in rural zones have been selected, considering humanitarian aspects. Both community-driven and commercially oriented projects are covered.

"Wireless Mesh Networking: A Key Solution for Emergency and Rural Applications," Abdulrahman Yarali, Babak Ahsant and Saifur Rahman, *Second International Conference on Advances in Mesh Networks*, June 2009.
Citation at http://ieeexplore.ieee.org/document/5222973/
From the abstract: All communities whether they are rural or urban will have to respond to safety, disasters, and emergency situations. These situations place a special burden on communication systems for having a fully operational system. Given the shortcomings of current Public Safety and Disaster Recovery, reliable wireless mobile communications that enable real-time information sharing, constant availability, and interagency interoperability are imperative in emergency situation[s]. Wireless Mesh Networks have been receiving a great deal of attention as a broadband access alternative for a wide range of markets, including those in the metro, emergency, public-safety, carrier-access, and residential sectors. This paper provides a background on technology requirements for emergency and public safety communications systems and addresses some of the technical influences of wireless mesh networks. The article describes the capabilities and architecture of the Man-portable, Interoperable, Tactical Operations Center communication system which was funded by the U.S. Department of Homeland Security. It is a modern mobile communications infrastructure well suited for public safety and disaster recovery applications.

Technologies Evaluated by Pooled Fund Studies

The activities of two Transportation Pooled Fund Program projects that are investigating information dissemination and ITS technologies may have some relevance to Caltrans' examination of the reliability of cellular networks.

Aurora Program, Study Number TPF-5(290), Transportation Pooled Fund Program, estimated completion date: May 2019.
Study description at http://www.pooledfund.org/Details/Study/532
From the study's objectives:

> The Aurora Program is a consortium of public road agencies focused on collaborative research, evaluation, and deployment of advanced technologies for detailed road weather monitoring and forecasting. Members seek to implement advanced road weather information systems (RWIS) that fully integrate state-of-the-art roadway and weather forecasting technologies with coordinated, multi-agency weather monitoring infrastructures. Aurora's research projects are designed to improve the efficiency of highway maintenance operations and distribute effective real-time information to travelers. Its initiatives are expected to result in technological advancement and improvement of existing RWIS, significantly reducing the adverse impacts of inclement weather on mobility.

The pooled fund study's description includes the following areas of interest that guide its research program:

- Decision support systems.
- Meso-scale modeling.
- Standards and architecture.
- Small-scale modeling and analysis.
- Information dissemination technologies.
- Equipment evaluations.
- Road condition monitoring.
- Innovative weather-related data collection and dissemination instrumentation and methodologies.

Contacts: Khyle Clute, Iowa Department of Transportation (lead agency), 515-239-1646, khyle.clute@iowadot.us; Roemer Alfelor, FHWA Technical Liaison, 202-366-9242, roemer.alfelor@fhwa.dot.gov.

Evaluating New Technologies for Roads Program Initiatives in Safety and Efficiency—ENTERPRISE (Phase II), Study Number TPF-5(359), Transportation Pooled Fund Program, estimated completion date: September 2021.
Study description at http://www.pooledfund.org/Details/Study/611
The objectives of this study are to:

- Investigate and promote ITS approaches and technologies that are compatible with other national and international ITS initiatives.
- Support the individual ITS program plans of ENTERPRISE participants.

- Provide a mechanism to support multistate and international project cooperation and technical information interchange.
- Facilitate the formation of public-private partnerships for appropriate program activities.
- Pursue emerging ITS project opportunities in areas of interest to the group.
- Provide test beds in a variety of environments and locations for emerging ITS technologies.
- Identify common needs within the group and proceed with appropriate technical activities.

Contacts: Andre Clover, Michigan Department of Transportation (lead agency), 517-636-6053, clovera@michigan.gov; Jonathan Walker, FHWA Technical Liaison, 202-366-2199, jonathan.b.walker@dot.gov.