Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) Communication in a Heterogeneous Wireless Network - Performance Evaluation

Kakan Chandra Dey*, Ph.D.
Postdoctoral Fellow, Connected Vehicle Technology
216 Lowry Hall, Clemson University, SC 29634
Email: kkey@clemson.edu
Tel: +1-(313) 523-0865, Fax: +1-(864) 656-2670

Anjan Rayamajhi
PhD Student, Department of Electrical and Computer Engineering
314 EIB, Clemson University, SC 29634
Email: arayama@g.clemson.edu
Tel: +1-(864)-633-8659, Fax: +1-(864)-656-0145

Mashrur Chowdhury, Ph.D., P.E., F.ASCE, Senior Member IEEE
Eugene Douglas Mays Professor of Transportation
Glenn Department of Civil Engineering and Department of Automotive Engineering
216 Lowry Hall, Clemson University, SC 29634
Email: mac@clemson.edu
Tel: +1-(864) 656-3313, Fax: +1-(864) 656-2670

Parth Bhavsar, Ph.D., Member IEEE
Assistant Professor, Civil and Environmental Engineering
327 Rowan Hall, Rowan University, Glassboro, NJ 08028
Email: bhavsar@rowan.edu
Tel: +1-(856) 256-5399, Fax: +1-(856) 256-5242

James Martin, Ph.D.
Associate Professor
School of Computing, Clemson University
211 McAdams Hall, Clemson, SC 29634
Email: jim.martin@cs.clemson.edu
Tel: +1-(864)-656-4529, Fax: +1-(864)-656-0145

*Corresponding author

1. INTRODUCTION

A robust wireless communication network is the foundation for connected transportation systems. Reliable and seamless vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) data communication is the critical component of Connected Vehicle Technology (CVT) applications. Though there are several communication technologies/options available, such as Wi-Fi, WiMAX, LTE, and DSRC, not all can support low latency, accuracy, and the reliability of data transmission required for CVT safety applications (RITA, 2015a). While dedicated short-range communication (DSRC) provides low latency, fast network connectivity, highly secure and high-speed communication for safety applications, reliance on DSRC only may prove detrimental to diverse CVT applications. As a result, research efforts for wireless technologies that can enhance V2V and V2I communications for diverse applications have been undertaken. The wireless communication research community has been exploring combinations of DSRC with Wi-Fi, WiMAX and LTE communication technologies to provide a robust next-generation communication network for connected vehicles (Dar et al., 2010). Moreover, it is expected that DSRC roadside units will be installed at key locations such as intersections and interchanges. Thus, the limited coverage of DSRC (approximately 300 meters) and integration of existing Wi-Fi, WiMAX, and LTE network creates a heterogeneous wireless network (Het-Net) for CVT applications.

For continuous connectivity, the shift from one communication network to another relies on the successful handoffs between the networks that ensure optimal utilization of available communication options (i.e., eliminate the need of using multiple communication options at the same time) and corresponding backhaul communication infrastructure requirements depending on the connected vehicle application requirements. In this study, the authors investigated the potential of a Het-Net to provide connectivity for V2V and V2I communications with optimal network resource allocation based on the connected vehicle application requirements. The objectives of this research were to evaluate the performance of Het-Net for i) V2I communications for collecting traffic data, and ii) V2V communications for a collision warning application. For field experiments, the authors utilized the Clemson University Wi-Fi network, and the National Science Foundation (NSF) sponsored Science Wireless Network (SciWiNet) infrastructure at Clemson, South Carolina that supports WiMAX, 3G and LTE, and DSRC infrastructure installed in test vehicles and roadsides. SciWiNet project supports a mobile virtual network operator (MVNO) for academic research communities (Martin et al., 2015). In addition, an ns-3 simulation experiment was conducted to evaluate Het-Net performance when there are larger numbers of vehicles within close proximity, and validate field test findings.

2. PREVIOUS STUDIES

Various wireless technologies have been used to support the data transfer requirements of diverse intelligent transportation system (ITS) applications (Chowdhury et al., 2009). The selection of wireless communication option relies on the accessibility and feasibility of a wired communication option and wireless communication options (Wi-Fi, WiMAX, LTE), and data transfer requirement of particular applications (Chowdhury et al., 2009; Goodwin, 2003; Dey et al., 2015; Haseman et al., 2010; Zhou et al., 2013). While existing ITS applications are infrastructure-based (i.e., installed at roadside locations), the next major deployment of wireless technologies within the transportation grid is the high speed wireless communication between moving vehicles and transportation infrastructures (V2V and V2I). V2V and V2I communication supported CVT safety applications require fast acquisition, fast message delivery (i.e., low

latency) with high reliability, and the highest security and privacy standards (Watfa, 2010). To meet these particular requirements of CVT applications, the Federal Communications Commission (FCC) assigned 75MHz bandwidth between 5.850GHz and 5.925GHz frequency in the US, which is known as Dedicated Short-Range Communication (DSRC). DSRC based V2V communication has been developed, evaluated and demonstrated under the supervision of the USDOT and the auto-manufacturers coalition for multiple safety applications (Lukuc, 2012). However, DSRC is insufficient for supporting the breadth of CVT applications outlined by the current connected vehicle reference implementation architecture (CVRIA) (RITA, 2015b). While DSRC is the primary option for CVT safety applications, other wireless technologies are also accessible for CVT applications. These technologies can supplement availability, coverage, and peak data rate requirements that cannot be supported by DSRC alone (RITA, 2015c). The heterogeneous communication network (Het-Net) can resolve the issues of range and peak data rate.

2.1 Data communication for safety application

Vehicular Ad-hoc Network (VANET) is the most studied data delivery methods in vehicular communication (Yousefi et al., 2006). VANET entails the creation of an ad-hoc based communication mesh network of highly dynamic vehicular nodes. Packets being forwarded in the mesh nodes (i.e., vehicles) need to know the structure of the mesh network, the direction to forward the data traffic based on the vehicle location and route to the destination nodes/vehicles. Multi-hop routing protocols for VANET provide different options that could be used for CVT applications based on their specific latency requirements (Saleet et al., 2011; Al-Rabayah and Malaney, 2012; Tee and Lee, 2010; Jarupan and Ekici, 2010; Sahu et al., 2013; Dey et al., 2015). Also, several studies reviewed the VANET protocols for CVT applications (Darwish and Bakar, 2015; Dey et al., 2015). Table 1 summarizes several potential protocols for CVT applications with low and medium latency characteristics. When there are limited numbers of vehicles in a roadway traffic network, a reliable connectivity through vehicular nodes depend on the availability of backup protocols that could be activated in cases when the multi-hop protocols do not locate a route from a source node to a destination node. Delay tolerant networking protocols were developed to enable data communication between vehicles without steady connection. For example, Vehicular Delay Tolerant Network (VDTN) routing protocols implement “Store and Forward” methods for reliable packet delivery in the case of any lost connection in the connected vehicle network (Little and Agarwal, 2005), but such approaches are not efficient in the case of a time sensitive safety critical warning message delivery scenario for a collision avoidance application. Although VDTN may work for some applications, such as traffic monitoring and traffic data collection, but for latency sensitive applications, such as collision warnings, a communication network with very low latency is always required.

Place Table 1 here

2.2 Data communication for traffic data collection application

Real time traffic data collection is one of the major functions of transportation agencies to inform travelers and provide reliable transportation services. Historically infrastructure based sensors (e.g., inductive loop detector, video cameras, infra-red sensors, blue-tooth) have been extensively used for traffic data collection (Leduc, 2008; Chowdhury and Wang, 2007). The coverage of the infrastructure based traffic data collection system is very limited and resource

intensive to cover all highways. Most transportation agencies deploy roadway sensors to monitor traffic condition on major corridors, however, a growing number of agencies have been using services from private traffic data providers to report real-time traffic speeds and travel times for large transportation network (Herrera et al., 2010). The transportation data service providers aggregate real time traffic data collected from multiple sources, including mobile phones, freight fleets, and GPS devices, that covers a broader highway network in comparison to limited roadway sensor coverage (INRIX-Iowa DOT, 2015). Such as mobile phone MAC address has been used using Wi-Fi, Bluetooth technologies to predict pedestrian and cyclist movement (Abedi et al., 2015). Seo and Kusakabe (2015) proposed a traffic state estimation method, which uses probe vehicle position and spacing data. Roncoli et al. (2015) developed an optimal control problem that could be used to minimize traffic congestion using connected vehicle data. Several vehicle models, with multiple wireless communication functionalities (Wi-Fi, LTE, DSRC), are expected to be introduced in the market over the next few years (GM, 2015), that would provide new set of traffic data through V2I and V2V integration. These new data sources will improve the reliability of traffic operations, such as traffic condition assessment and prediction, and response to traffic incidents based on the assessment, (e.g., routing of vehicles and closing of lanes based on these assessments and predictions) (Ma et al., 2009; Ma et al., 2012), and reduce public transportation agencies reliance on private service providers. VANET based data communication techniques and algorithms that are common in V2V communication could be used for traffic monitoring data collection and incident detection (Baiocchi et al., 2015; Darwish and Bakar, 2015). Argote-Cabañero et al. (2015) proposed a traffic operation measure of effectiveness (MOE) estimation method using limited connected vehicle data. Piccoli et al. (2015) investigated the sampling requirement for first order and higher order traffic parameters. Thus, a motivating argument for CVT for traffic condition assessment applications is that even a small penetration of CVT-enabled vehicles that provide traffic sensing information through V2I and V2V will improve the accuracy and robustness of the traffic management system, with a significantly reduction in real-time traffic management costs (Darwish and Bakar, 2015; Herrera et al., 2010).

2.3 Data communication in Het-Net for handoff between communication options

The differences in the characteristics of various wireless communication technologies, such as data rates, coverage radius, and security requirements do not prevent their access via mobile nodes for continuous connectivity (Magagula and Chan, 2008). The routing of data traffic during the movement of mobile nodes is a major concern, however, because of the widespread adoption of mobile devices such as laptop computers and smart phones (Giovanardi and Mazzini, 1997). One of the big drawbacks in the use of Het-Nets is the handoff duration, which requires the devices to switch between networks. The time necessary for the handoff between networks in turn hinders the reliability and speed of the Het-Net (Magagula and Chan, 2008). The mobile IP (MIPv6) idea is one concept for managing this handoff, in which a mobile user associated with a home agent uses the home agent to re-route the data connection. A modified version of the MIPv6 handoff protocol, known as the PMIPv6, uses a handoff scheme that communicates with the next wireless access point by measuring the mobile node's signal strength (Giovanardi and Mazzini, 1997). Several handoff methodologies have been developed, which are characterized by modifications to the existing firmware structure (Kong et al., 2008; Kim et al., 2010; Ning et al., 2014; Bargh et al., 2008; Baojiang, 2011; Huang et al., 2013). For example, in the creation of a software defined network based implementation of the Link layer handoff scheme, Izard et al. (2014) developed a smoother transition from one network to another in a Het-Net scenario.

However, the use of the application layer handoff scheme (Leiner et al., 1985) to improve Het-Net performance in CVT applications has yet to be explored. The switching from one network technology to other is decided by the application (discussed more in Section 3). Due to the distinctly separate WAVE stack and IP stack, application layer handoff deemed to be the most effective solution for Het-Net scenarios considered in this study as also concluded in Uzcategui and Acosta-Marum (2009). A National Highway Traffic Safety Administration (NHTSA) study suggests that DSRC will be inadequate for supporting the safety applications for traffic corridors with high traffic density (i.e., dense roadway infrastructure such as interchanges) (Harding et al., 2014). Thus, a Het-Net including DSRC is particularly important as it will expand the application horizon of connected vehicles by allowing seamless V2V and V2I communication (USDOT, 2015; 3GPP, 2015).

3. METHOD

Figure 1 illustrates the research method adopted in this study to determine the efficacy of Het-Net in supporting CVT applications. Field tests and simulation experiments using ns-3 were conducted to answer the research questions and learn about integration challenges of Het-Net for CVT applications that ensures the optimal utilization of available communication options (i.e., eliminate the need of using multiple communication options at the same time) and corresponding backhaul communication infrastructure depending on the application requirements. To evaluate the performance of a Het-Net, case study 1 was conducted for a CVT supported traffic data collection application. To evaluate the performance of Het-Net for a CVT safety application, a forward collision warning application for V2V was conducted in the second case study. Based on field tests and simulation findings, the usability of Het-Net for CVT applications was determined using multiple performance measures. The field tests were conducted with an application layer handoff process developed in this study to test seamless communication between vehicles in a Het-Net system subjected to a hard handoff (Figure 2). For the purposes of this study, the data flow between roadside unit (RSU)-on board unit (OBU), and OBU-OBU do not require an uninterrupted connection simply because of the dynamic nature of vehicular networks. Therefore, applications use burst of packet exchanges through DSRC and through LTE or Wi-Fi, and the term “handoff” is used to define the process of switching from one network technology to another. This application layer handoff is effective as it does not require modification to existing hardware and firmware of connected vehicle equipment, such as OBU and RSU. The technique was designed to detect hard handoff controlled by underlying Link and IP layers. The handoff was controlled by giving priority to DSRC or Wi-Fi over LTE in a Het-Net environment. The application recorded information about the handoff, such as the interface used before and after the handoff, packet loss during handoff, and the time necessary to complete the handoff. A comprehensive description of case studies are presented in the sub-sections 3.1.1 and 3.1.2 respectively.

Place Figure 1 here

Place Figure 2 here

3.1 Case study 1: Traffic data collection using Vehicle-to-Infrastructure (V2I) communication

In order to strategically understand and test the idea of supplementing DSRC with Het-Net for a traffic data collection application, tests were performed in two Het-Net scenarios as described below.

3.1.1 Wi-Fi and LTE Het-Net infrastructure for traffic data collection

To evaluate the efficacy of V2I data communication using Wi-Fi and LTE Het-Net infrastructure for a traffic data collection application, a client-to-server packet transfer scheme was developed, in which the client (i.e., vehicle) sends data containing GPS coordinates, time stamps, and signal strengths of different network interfaces (Wi-Fi or LTE) to a server (i.e., traffic management center, TMC). The test system utilized in this study consists of a RSU with Wi-Fi and LTE support along the test roadway section and in-vehicle OBUs with Wi-Fi and LTE support. The test was conducted on an access route to a parking lot with flat topology and light to medium roadside foliage in Clemson, South Carolina. As shown in Figure 3, the vehicle began from Wi-Fi and LTE availability zone and was connected to the data collection server (i.e., TMC) via Wi-Fi. As the vehicle moved out of Wi-Fi coverage, the connection went through handoff to connect to the server (i.e., TMC) via LTE. In Wi-Fi and LTE enabled Het-Net scenario, Internet protocol (IP) was used to enable vehicle to RSU, and vehicle to TMC data communication (Figure 4). This was a hard-handoff, where the connection was broken before attempting to reconnect. Data was collected during the time between successive packets during the handoff to determine hard handoff duration.

Place Figure 3 here

Place Figure 4 here

3.1.2 DSRC and LTE Het-Net infrastructure for traffic data collection

The authors used a client-to-server packet transfer model to evaluate the applicability of DSRC and LTE Het-Net infrastructure for traffic data collection. The test system is comprised of OBU and a RSU with DSRC enabled radios on a Linux machine. A RSU resides by roadside at a predefined location whereas cars equipped with an OBU are moving up and down along the stretch of roadway and passes the RSU location in each trip. To enable Het-Net functionality, both OBU and RSU are equipped with LTE support, which allows the application layer handoff between the DSRC and LTE network. Tests were conducted on a section of the Perimeter Road in Clemson, South Carolina, which has a flat topology and light roadside foliage. In DSRC and LTE enabled Het-Net, the Wireless Access in Vehicular Environments (WAVE) protocols were used to enable communication between the OBU and the RSU, and the Internet Protocol (IP) was used to enable communication between a remote server/TMC-RSU, and OBU-TMC (Figure 4). Table 2 summarizes the technical specifications of the DSRC RSU and OBU unit used in this study. The parameters in Table 2 were adopted from equipment specifications of OBU and RSU acquired from an USDOT approved DSRC equipment provider. The power level of 23 dBm at 64 QAM is the maximum transmission power and modulation of the equipment used in the field tests. The experimental setup of the application is presented in Figure 5. The Het-Net RSU platform of the traffic data collection application functioned within the laptop connected to a RSU.

Place Table 2 here
Place Figure 5 here

As shown in Figure 5, a vehicle with the capability to use either DSRC or LTE network for V2I communication could receive beacon-like messages from a nearby RSU as soon as it reaches the RSU's DSRC coverage area. Upon receiving a beacon from the RSU, the application would then initiate a handoff to DSRC from LTE and use a backhaul network to store the data in a remote server/TMC. The backhaul of collected data from the RSU to TMC can be transferred either through wireless or wired connection depending upon the availability. The results from the tests of Het-Net handoff behavior and the performance in terms of message delivery latency for the traffic data collection application are presented in section 4.

3.2 Case study 2: Forward collision warning application support using DSRC and LTE within Vehicle-to-vehicle (V2V) communication

The crash avoidance/safety applications supported by V2V connectivity exchange critical safety information (e.g., vehicle speed, vehicle location and the direction of movement) to assess the crash risk based on the proximity of other connected vehicles around the subject vehicle. A safety application-forward collision warning was selected for field experiment. This application warns vehicles at risk of rear end collision to take corrective measures due to a suddenly stopped vehicle in a travel lane. The stopped vehicle broadcasts collision warning message to vehicles within or soon to be within the area about potential safety hazards using V2V connectivity. As with early deployment of connectivity in new vehicle models, there will be a very limited number of vehicles with DSRC connectivity; thus the possibility of an intermittent broken link and the lack of DSRC enabled vehicles will not allow continued multi-hop communication. Considering this early deployment scenario, in this study, the authors adopted a single hop message delivery between vehicles (i.e., OBUs). However, in future research, multi-hop communication such as GeoNetworking (ETSI, 2014; Cadzow et al., 2012) for time sensitive safety message delivery could be explored to support potential CVT applications.

An experimental setup was developed with three vehicles travelling in the same direction and same lane, where two vehicles, one with DSRC support (Vehicle 2) and third with LTE support (Vehicle 3) receive a safety warning message from a downstream vehicle (Vehicle 1) with DSRC and LTE support that had just stopped abruptly due to a road hazard. Vehicle 2 was traveling within DSRC reach of Vehicle 1 while Vehicle 3 was traveling towards Vehicle 1 but away from the DSRC reach of Vehicle 1 and Vehicle 2 (Figure 6). Tests were conducted on a section of Perimeter Road with a flat topology and light roadside foliage in Clemson, South Carolina. The safety warning message packets including GPS location of the stopped vehicle and speed were broadcasted at the rate of 10 messages per second (i.e., at 100 milliseconds interval between consecutive broadcast) by Vehicle 1 upon its abrupt halts at a predefined location on the test route (Figure 6). During each test run, a series of events occurs: ❶- Vehicle 1 stops abruptly, ❷- Vehicle 1 starts sending safety warning message packets, ❸- Vehicle 2 receives the warning message through DSRC, and ❹- Vehicle 3 receives the warning message via LTE. Field tests were conducted to estimate the time required for the warning messages to reach the two following vehicles using the DSRC and LTE networks respectively, where the times were measured between events ❷ and ❸ for Vehicle 2 using DSRC, events ❷ and ❹ for Vehicle 3 using LTE. To observe the influence of vehicle speed on message delivery time, tests were repeated with vehicles travelling at three different speeds- 20 mph, 35 mph and 50 mph.

Place Figure 6 here

To evaluate the message delivery performance when more than two vehicles were traveling toward a stopped vehicle in a given lane, a second set of experiments were conducted with four vehicles (three vehicles with DSRC support and one vehicle with LTE support traveling towards an incident location). In addition, to supplement our field study, which is the primary focus of this paper, simulation experiments in a Network Simulator (Network Simulator Version 3 or ns-3) with more vehicles were conducted. Figure 7 shows the setup of a simulation study conducted to determine the effect of a larger number of connected vehicles than observed/utilized in our field study and their effects on latency of message delivery. Random 2D Walk Mobility Model was used to create the effect of moving vehicles (Network Simulator- 3, 2015). A RSU capable of DSRC communication was placed at (0, 0) coordinate in an 800ft x 800ft simulation area as shown in Figure 7. A LTE transmitter that can reach all vehicles in the simulation area was placed at (400ft, 400ft) coordinate, so that the vehicles moving inside the simulation region have both DSRC and LTE communication capabilities. Propagation loss model based on Benin et al. (2012) was added in ns-3 model. An application for the ns-3 simulation was developed that was able to broadcast messages to vehicles using both DSRC and LTE networks. The simulation tests comprised of up to 40 vehicles that can move within the simulation grid rendering a simplified simulation model for this study. All the simulated vehicles were equipped with DSRC and LTE radios. Table 3 shows the ns-3 simulation parameters used in the simulation. Standard LTE simulation scheme was used that was already available for ns-3 to test LTE throughput and latency.

Place Figure 7 here

Place Table 3 here

4. RESULTS AND DISCUSSION

4.1 Case study 1 test results

4.1.1 Wi-Fi and LTE Het-Net Infrastructure for Traffic Data Collection

Two data transfer protocols-UDP and TCP were used for the V2I based traffic data collection tests. The developed test application was able to detect the breakage of one communication link with one communication network and was designed to restart a new socket as soon as possible with other available network technologies without breaking the connection (Figure 2). The vehicle speed data packet arrival latency during handoff between Wi-Fi and LTE was calculated. The average delay recorded between successive packets arrival at the TMC is used to calculate the handoff time. Table 4 shows the average delay between successive packets arriving at the TMC during handoff. In both TCP and UDP handoff scenarios, the time between arrivals of successive vehicle speed data packets were relatively longer. The longest delay observed was 28 seconds using the TCP mode. The delay includes the time required to activate the 802.11 link and the time required for the vehicle to associate with the RSU (i.e., access point). However, the traffic data collection application does not require vehicle dynamics data as frequently as safety applications (3GPP, 2015). A study found that a data collection frequency with 40 second intervals assessed the average traffic condition with a 95% degree of accuracy (Benin et al., 2012). Thus, transportation agencies can collect traffic data for a larger highway network irrespective of a 25 second handoff delay (UDP connection) and a 28 second handoff delay (TCP connection) observed in the field experiment with sufficient accuracy. Furthermore,

the collection of traffic data at longer time intervals reduce substantial investment required to install data storage and processing infrastructure in comparison to the investment need for traffic data collection at a shorter time interval (Liu et al., 2006).

Place Table 4 here

According to the *Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU)* requirement, state DOTs in the US must provide travel time information along major corridors to travelers with 85% accuracy (FHWA, 2013). Using existing technologies (i.e., loop detectors) to achieve the required level of accuracy is challenging, because of estimation errors, frequent malfunction, and higher maintenance and installation costs of such devices (FHWA, 2006). Several recent vehicle models are already equipped with Wi-Fi and LTE capabilities (Buss, 2014; Uzcategui and Acosta-Marum, 2009). Thus, in the future connected transportation systems, the Het-Net infrastructure can be used to support traffic data collection requirements with a sufficient accuracy.

4.1.2 DSRC and LTE Het-Net Infrastructure for Traffic Data Collection

This phase of the research entailed the use of DSRC and LTE in Het-Net for the purpose of collecting and transferring vehicle speed and location data to a TMC. It was determined that when the vehicles moved into RSU's DSRC coverage areas, handoff occurs from LTE to DSRC, and the vehicle speed data was transmitted to TMC through DSRC. The coverage of speed data collected by vehicles with only DSRC support is shown in Figure 8(a), the coverage of speed data collected by DSRC and LTE support together is shown in Figure 8(b), and the speed profile indicating the collected speeds of the study corridor using both DSRC and LTE is shown in Figure 8(c). It is evident that DSRC support alone (without the use of LTE) was insufficient for obtaining a complete speed profile of the study corridor.

Place Figure 8 here

In terms of average vehicle speed data packet delivery, the observed latency in the field tests during DSRC and LTE handoff was 5.75 seconds, which was much smaller than the Wi-Fi and LTE handoff time. Thus, a Het-Net of DSRC and LTE is more reliable for the traffic data collection application compared to the Wi-Fi and LTE Het-Net. It can be concluded that two Het-Net options considered in this study can be implemented for traffic data collection satisfying the SAFETEA-LU requirement with sufficient reliability.

4.2 Case study 2 test results: Forward collision warning application support using DSRC and LTE within Vehicle-to-vehicle (V2V) communication

The time required for delivering emergency safety message from an abruptly stopped vehicle (Vehicle 1) to two following vehicles, one with DSRC support (Vehicle 2) and the other with LTE support (Vehicle 3) was calculated from field tests. As discussed earlier (shown in Figure 3), the message delivery time of the vehicle using the DSRC fell between events ② and ③, and the message delivery time of the vehicle using LTE fell between events ② and ④. The first few safety warning messages received by Vehicle 2 after Vehicle 1 began broadcasting warning messages under repeated tests at different speeds are shown in Figure 9. The small circles marked with ① in Figure 9 are the first safety message packets received by Vehicle 2 in different test runs. The distance from Vehicle 1, where Vehicle 2 received the first warning message

packets through DSRC are shown in Table 5, Column 2. Also shown is how far Vehicle 2 would travel applying the brake after receiving the warning message (Table 5, Column 3) with the comfortable deceleration rate of 11.2 ft/sec^2 (AASHTO, 2011). As can be seen, Vehicle 2 has a sufficient time/distance to safely stop upon receiving the safety warning message packets from Vehicle 1 using DSRC. The distance at which the vehicles received the first safety message from the stopped vehicle varied due to the dynamic nature of vehicle movements and an increase in packet error rate at high speeds.

Place Figure 9 here

Place Table 5 here

Impact of vehicle speed on message delivery latency: The average time recorded for a warning message to reach Vehicles 2 and 3 (at different vehicle speeds- 20, 35, and 50 mph is illustrated in Figure 10 and 11 respectively. The message delivery latency for Vehicle 2 (using DSRC) increased with vehicle speed, with a maximum of 125 milliseconds at 50 mph and a minimum of 88 milliseconds at 20 mph (Figure 10), both of which satisfy the 200 milliseconds latency requirement for CVT safety applications (Xu et al., 2003). The vehicle with LTE supports (Vehicle 3), which was outside of the DSRC range of Vehicle 1, received the warning message with a longer delay compared to the latency requirement for CVT safety applications (Figure 11). However, Vehicle 3 had a greater margin of reaction time to avoid the incident location because it received the warning message further upstream. Similar to DSRC, using the LTE safety warning message packet delivery time increased with the vehicle speed. Additional research to evaluate the suitability of LTE for safety application warning message delivery must be done because of the highly dynamic nature of delays (i.e. congestion and concurrent background flow) tied to LTE networks (Garcia et al., 2014). Complementary communication options using LTE developed from such research will benefit more vehicles upstream by providing advanced warnings when those vehicles are out of the DSRC coverage area.

Place Figure 10 here

Place Figure 11 here

In four vehicles field-test scenario, the different geographic locations indicating where the vehicles received the first safety warning message packets are shown in Figure 12. These test results were similar to tests with two vehicles scenario. Here, all three vehicles with DSRC connectivity received warning message packets within a closer proximity of the stopped vehicle (i.e., within DSRC range) while vehicles with LTE connectivity received the same information much further upstream.

Place Figure 12 here

ns-3 simulation results: Four test runs with different number of connected vehicles (i.e., 10, 20, 30 and 40) in the ns-3 simulation were conducted to determine the impact of number of connected vehicles on message delivery latency for using the DSRC or LTE network. Figure 13 shows the plot of average latency in seconds with a 95% confidence interval (CI) for four simulation scenarios with different number of connected vehicles that use DSRC and LTE networks. An analysis of variance of average latency was conducted to determine the statistical significance of increase in average latency for using the DSRC or LTE due to an increase in

number of connected vehicles. It was found that the latency increase was statistically significant with a greater number of connected vehicles compared to scenarios with less number of connected vehicles as greater number of vehicles increase network congestion and cause higher latency in the DSRC and LTE network. Another four test runs were conducted for four different connected vehicle speeds (i.e., 20, 35, 50 and 70 mph) to determine the impact of vehicle speed on the DSRC and LTE latency. Figure 14 shows average latency in seconds with 95% CI for four different vehicle speed scenarios. An analysis of variance of average latency revealed that the latency increase was statistically significant with a higher vehicle speed compared to scenarios with lower vehicle speed in the DSRC or LTE network. Table 6 compares the packet delivery latency at different speeds between simulation and field tests for both DSRC and LTE networks. It can be concluded that packet delivery latency trend in simulation is similar to what was observed in field tests. The delays in LTE system depend on network congestion level, user demands and environmental parameters, not only on the physical link state at any timestamp. The subscribers' priorities, availability of resource blocks, traffic volume and packet congestion play a major role in the LTE delay. Depending on the number of users within a network at any given time and associated congestion level of the system; network performance varies (Mir and Filali, 2014). In the ns-3 simulation conducted in this research, vehicles equipped with LTE were moving in the simulated network received broadcasted message through LTE networks (as shown Figure 7). The authors evaluated the variation in latency due to a change in vehicle speed, and number of connected vehicles. As shown in Figures 11, 13 and 14, LTE latency is dependent on the speed of the vehicles as well as number of consecutive connections with other vehicular and user applications. The LTE latency observed in ns-3 simulation in this research (Table 6) is similar as reported in a simulation study performed for a city area by Mir and Filali (2014). Moreover, an increase in the number of connected vehicles in an area causes packet error rate to also increase (Figure 15). As more vehicles attempt to transmit messages to the RSU, wireless channel congestion causes large number of packet loss (i.e. higher packet error rate). This illustrates a typical traffic data collection application where large numbers of OBUs attempt to register their data with the RSU. However, due to the lack of proper scheduling of data from different OBUs near a RSU and no requirement of acknowledgements, the packet loss rate was significantly high. A higher packet error rate is a significant concern for safety applications if congestion results into a significant delay in receiving warning messages.

Place Figure 13 here

Place Figure 14 here

Place Table 6 here

Place Figure 15 here

5. CONTRIBUTION OF THIS RESEARCH

To overcome the limited range of DSRC, the authors demonstrated that LTE and Wi-Fi, in combination with DSRC, was an effective solution in the traffic data collection with reliability that ensures the optimal utilization of alternate communication options and corresponding backhaul communication infrastructure. Case studies performed in this research demonstrate the use of Wi-Fi and LTE to widen the range of vehicular communication, which is not possible with DSRC alone. The use of the application handoff technique to maintain seamless connectivity for CVT applications was also evaluated. This study provides a unique perspective on the use of Het-Net for seamless CVT applications. This study demonstrates that, although there is a long handoff time of about 25 seconds using UDP mode between Wi-Fi and LTE, and approximately

six seconds between DSRC and LTE, traffic data collection related applications could be supported by Het-Net with significant accuracy. However, these long handoff times between network options are not suitable for collision warning message delivery for an imminent crash that would require a much lower latency of less than 200 millisecond. In future work, different Het-Net service models that are more appropriate for safety-oriented vehicular applications could be explored.

6. CONCLUSIONS

In this study, the authors demonstrated the potential of V2V and V2I in a Het-Net environment with Wi-Fi, DSRC and LTE that guarantee the optimal utilization of available communication options and minimize the corresponding backhaul communication infrastructure requirements while considering connected vehicle application requirements. Existing CVT architecture, such as CVRIA, suggests that seamless communication for V2V and V2I are required to utilize the full potential of CVT applications. The performance of a CVT application using Het-Net depends on the availability of multiple wireless communication options, acceptable communication latency, data security, and reliability of timely message delivery. For a broad range of CVT applications (i.e., safety, mobility, environmental), a viable communication option should include V2V and V2I capable of utilizing a Het-Net optimally without losing connectivity while moving from one communication network to another. It will require a successful handoff from one wireless network to another in a Het-Net environment. However, these different networks have not been designed for the seamless message transfer from one network to another for moving nodes/vehicles. Consequently these networks must be reconfigurable for developing such a robust synchronized Het-Net. The research detailed here is the first attempt in designing and evaluating such a network for CVT applications.

A long handoff time was observed due to the time required to activate the 802.11 link and the time required for the vehicle to associate with the RSU (i.e., access point) in LTE and Wi-Fi Het-Net scenario. Field test results revealed that Het-Nets did not compromise the performance of the traffic data collection application studied in this research. Unlike safety applications, very low latency (200 milliseconds) is not required for traffic data collection. Het-Nets provide additional connectivity beyond DSRC range to collect traffic data for a larger traffic network, which is required for many CVT applications. The handoff between networks (Wi-Fi to LTE, DSRC to LTE and vice-versa) require several seconds to establish a connection and resume the data transfer, which means that Het-Net could not be used to support time sensitive safety applications. Field tests revealed that the message delivery time during the handoff was much higher than the CVT safety application latency requirement of 200 milliseconds. However, Het-Net could provide supplementary connectivity for CVT safety applications to warn vehicles upstream about any safety hazardous conditions downstream, so that they can take proactive actions to avoid the problem locations. ns-3 simulation experiments with a larger number of connected vehicles, compared to the field tests, were conducted for a DSRC and LTE Het-Net scenario to complement and validate the findings from field tests that included a limited number of connected vehicles. Results from these ns-3 simulations were similar to the field experiment results. This study is the first of its kind to evaluate the performance of Het-Net for a seamless V2I and V2V communication for CVT applications. This application layer handoff method for Het-Net communication developed in this study can be adopted in future Het-Net-supported connected vehicle applications. Examinations of the feasibility and performance of Het-Net for a

traffic data collection application and a collision warning application were the focus of this research.

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Table 1: Latency of different VANET protocols

VANET protocols		Network Delay
Intersection-based Geographical Routing Protocol (IGRP) (Saleet et al., 2011)		Low
PROMPT (Jarupan and Ekici, 2010)		
Back-Bone-Assisted Hop Greedy (BAHG) (Sahu et al., 2013)		
Vehicle-Assisted Data Delivery (VADD) (Zhao and Cao, 2008)		
Greedy Perimeter Stateless Routing (GPSR) (Karp and Kung, 2000)		Medium
Hybrid Location based Ad-Hoc Routing (HLAR) (Al-Rabayah and Malaney, 2012)		
Junction-based Adaptive Reactive Routing (JARR) (Tee and Lee, 2010)		
Static Node-assisted Adaptive Data Dissemination Protocol (SADV) (Ding and Xiao, 2010)		

Table 2: Physical Layer Specifications of DSRC Equipment

Properties	RSU Specifications	OBU Specifications
Frequency	5.85 – 5.925 GHz	5.85 – 5.925 GHz
DSRC Radio	23 dBm @ 5.9 GHz standard	24 dBm @ 5.9 GHz standard
Channels	10 MHz	10 MHz
Modulation	BPSK rate 1/2	BPSK rate 1/2

Table 3: ns-3 Simulation parameters

DSRC Simulation Parameters		LTE Simulation Parameters	
Propagation Loss model	Three Log Distance	Propagation Loss model	Friis Spectrum
Fading	Nakagami-m	Mac Scheduler	Proportional fairness MAC
Tx Power Level	23 dBm	UL Bandwidth	25 Mhz
Freq	5.9 Ghz	DL Bandwidth	25 Mhz
Channel BW	10 Mhz	Tx Power (UE)	10 dBm
Packet Size	250 Bytes (both case)	Tx Power (enodeB)	30 dbm

Table 4: Average delay between packets at the TMC during Wi-Fi and LTE handoff

Het-Net Type	Average delay between packets during handoff
Wi-Fi and LTE (TCP connection)	28 seconds
Wi-Fi and LTE (UDP connection)	25 seconds

Table 5: Stoppage distance for Vehicle 2

Vehicle Speed (mph)	Distance from Vehicle 1 when 1st safety warning message packet received (ft)	Distance required to stop at 11.2 ft/sec ² deceleration rate (ft)
20	272 (test run 1)	38
	336 (test run 2)	
	308 (test run 3)	
35	260 (test run 1)	118
	340 (test run 2)	
	237 (test run 3)	
50	355 (test run 1)	240
	304 (test run 2)	
	282 (test run 3)	

Table 6: Comparison of latencies from ns-3 simulation and field tests

Speed (mph)	DSRC latency (milliseconds)		LTE latency (milliseconds)	
	Field test	Simulation	Field Test	Simulation
20	88	89	2555	1305
35	107	94	2851	1320
50	125	96	2977	1375

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