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特集 "Wireless Communications for Vehicle Safety: Radio Link Performance & Wireless Connectivity Methods"*

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Many accidents occur today when distant objects or roadway impediments are not quickly detected. To help avoid these accidents, longer-range safety systems are needed with real-time detection capability and without requiring a line-of-sight (LOS) view by the driver or sensor. Early detection at intersections is required for obstacle location around blind corners and dynamic awareness of approaching vehicles on intersecting roadways.

Many of today's vehicular safety systems require short LOS distances to be effective. Such systems include forward collision warning, adaptive cruise control, and lane keeping assistance. To operate over longer LOS distances and in Non-LOS (NLOS) conditions, cooperative wireless communications systems are being considered. This paper describes field results for LOS and NLOS radio links for one candidate wireless system: 5.9GHz Dedicated Short Range Communications (DSRC).

In implementing vehicle safety systems with multiple channels and using vehicles with a single transceiver, consideration must be given to how a group of vehicles in a localized area becomes aware in real-time of potentially dangerous situations. Given that wireless vehicle safety systems may use multiple links, channels, and message priorities, one might ask how these resources could be used in an organized fashion to optimize the efficiency of a wireless system. This paper discusses a method called Multi-channel Management, which enables vehicles to use DSRC resources to synchronize with each other, receive high-priority safety messages with low transmission latency, accommodate any range of safety message traffic, and participate in non-safety services by sharing capacity on other channels. Given that the DSRC system requires that safety-of-life messages have the highest priority, the described method essentially achieves "continuous wireless connectivity" for high-priority safety messages transmitted and received within a localized group of vehicles.

With prolific worldwide growth in the use of wireless local area network (WLAN) adapters to obtain broadband Internet access at WLAN hotspots, automotive OEMs are considering in-vehicle WLAN radio installation. Further, the wireless industry is investigating how handoffs between WLAN and cellular networks could provide connectivity to vehicles when they are out-of-range of hotspots. With this motivation, this paper discusses an approach for providing continuous vehicular links to the Internet using cellular-WLAN roaming.

Key words: Wireless communications, Vehicle safety, Radio link performance, Wireless connectivity methods, LOS, DSRC, WLAN

1．INTRODUCTION

1.1　Vehicle safety using short range coverage

Emerging systems for active vehicle safety use short-range sensors with LOS links, usually to detect vehicles or lane boundaries immediately adjacent to the host vehicle. Typical applications include forward collision warning, adaptive cruise control, and lane keeping.

Table 1 shows the range of typical sensors, which are typically 100 to 200m, with cameras that work to 500m.[1] These LOS sensors provide coverage for their intended safety system. However, how can we accommodate safety systems that operate over longer range?

1.2　Vehicle safety with longer range coverage

Longer-range vehicle safety systems are needed to help reduce accidents originating from more distant emergency events, roadway impediments, blind corners, and cross traffic. To detect these remote events, such systems may require up to 1000 meters of LOS coverage, and NLOS coverage to detect dangerous events ahead, but out of view.

In many cases, the ability to detect an emergency event occurring at some distance ahead is limited by the inability of drivers to see past the vehicle in front of them. The inability of drivers to react in time to emergency situations often creates a potential for chain collisions, in which an initial collision between two vehicles is followed by a series of collisions involving the following vehicles.[2] The traffic and accident views in **Fig. 1** emphasize the need for driver awareness beyond obstructions.

So, how can we provide real-time alerts to drivers who cannot see remote or oncoming safety hazards?

Table 1　Emerging systems for vehicle safety focus on short-range LOS applications

Vehicle safety system	Max sensor range	Sensor type
Forward collision warning	150m	Radar
	60m	Vision
Lane keeping	200m	Laser
	12m	24GHz radar
Parking assistance	2m	Sonar
	5m	Laser
Night vision	150m	24GHz radar
	500m	Infrared camera
High-speed advanced cruise control	60m	Vision
	100m	Lidar
	150m	Radar

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Fig. 1 Safety systems should enable drivers to "see" conditions beyond their restricted view of traffic.

2．COOPERATIVE WIRELESS SYSTEMS

One way to provide drivers in a local traffic area with advance warning of dangerous situations is to use wireless communication technology.

To date, the majority of development efforts in support of communication capabilities within the ITS architecture have been directed at fixed-point to fixed-point communication and ITS solutions taking advantage of wide area communication networks.[2]

More recently, the combined availability of the Global Positioning System (GPS) and deployment of cellular-based communication systems has further fueled the development of vehicle tracking systems and systems providing information to travelers in vehicles through wireless means.[2]

Interest in roadside-to-vehicle (R2V) and vehicle-to-vehicle (V2V) communication capabilities has only recently gained momentum, as such capabilities were in the past either not technically feasible or too costly to implement and operate. **Table 2** shows selected attributes of a few candidate wireless systems. The 5.9GHz DSRC and WiMAX systems are in development. The other systems are in operation.

Although the systems in the table provide specific communications functions for their intended users, the 5.9GHz DSRC system is the only system that:
- Is dedicated to the US Transportation sector (not shared)
- Provides active vehicle safety with LOS & NLOS links
- Provides low latency using direct V2V links
- Provides broadband, real-time, long range, bidirectional communications

Some attributes of the 5.9GHz DSRC system in the table are used in field tests described in this paper. The 5.9GHz DSRC system is described below.

2.1 Vehicle communications using 5.9GHz DSRC

The idea of using broadband wireless communication links to enable active vehicle safety applications is strongly supported by the US Government and transportation industry partners, including the US DOT, FCC, ITS America, automobile manufacturers, and automotive-product suppliers.

Table 2　Candidate wireless systems and attributes

Wireless system	Attributes for vehicle links & safety
Satellite	• Nationwide coverage • Provides vehicle tracking & fleet mgmt • Not designed for low-latency safety links
Cellular	• Near-nationwide coverage • Shared spectrum and channels • No direct V2V links (uncertain latency) • Provides post-accident support (On-Star)
Electronic toll collection	• Medium-speed LOS roadway links • Interference from other in-band users • No direct V2V links
WiFi (Unlicensed 802.11)	• High-speed broadband internet access • Interference from other in-band users • Direct V2V links (low latency)
5.9GHz DSRC	• System dedicated to automotive safety • Dedicated RF spectrum (ITS licensed) • High-speed LOS/NLOS broadband links • Dedicated channels for vehicle safety • Direct V2V links (low latency)
WiMAX	• New point-to-multipoint wireless system • Provides broadband internet access • Shared spectrum and channels • No direct V2V links (uncertain latency)

In October 1999, the FCC allocated the 5.9 GHz band (5.85-5.925GHz) for DSRC-based ITS applications and adopted basic technical rules for DSRC operations.

In July 2003, the ASTM and IEEE adopted the 5.9GHz DSRC standard (ASTM E2213-03).[3] The basic purpose of this standard is to provide wireless communications for vehicle safety applications generally within a 1000m LOS distance at typical highway speeds. The standard provides seven channels in a 75MHz band for ITS applications, with different channels designated for different applications, including one specifically reserved for vehicle-to-vehicle communications.

Example ITS applications that could leverage the emerging DSRC standard include V2V collision warning and avoidance systems, emergency braking on the highway, and intersection collision avoidance.

In December 2003, based on the 5.9GHz DSRC standard, the FCC formally adopted licensing and servicing rules in the ITS Radio service band.[4]

Table 3 shows a listing of 5.9GHz DSRC stakeholders and their roles in DSRC development. Completion of the development of the lower layers of the 5.9GHz DSRC standard has been transitioned to the IEEE 802.11p standard. The entire DSRC communications stack is also known as Wireless Access in Vehicular Environments (WAVE). WAVE is the mode of operation used by IEEE 802.11 devices in the band allocated for ITS communications.[5]

It is interesting to note that the 5.9GHz DSRC system uses a similar physical layer format to IEEE 802.11a. Prior to DSRC radio availability, DENSO conducted 802.11a field tests that showed DSRC transmission could be feasible in vehicular environments.[10]

Table 3　5.9GHz DSRC stakeholders

5.9GHz DSRC stakeholder	Role related to 5.9GHz DSRC
FCC	Allocated radio spectrum, and adopted licensing and servicing rules for ITS use
US DOT	Proposed an ITS national architecture enabled by wireless communications
FHWA	Supports development of radio technology
NHTSA	Supports development of safety applications
AASHTO	Non-profit organization of State DOTs for education and outreach
ITS America	Coordinates the development and deployment of ITS in US
Automotive OEMs	Defines reqês for developing technology and applications, perform radio evaluation
Automotive suppliers	Supplies radio hardware and software technology to support 5.9GHz DSRC
IEEE	Develops 802.11p and WAVE series of specifications
SAE	Development of message sets
Universities	Support radio development, and characterize and evaluate link performance

2.1.1　5.9GHz DSRC radio module

In 2004, DENSO developed an early prototype radio that operates in the 5.9GHz DSRC band. The radio prototypes are being evaluated in DSRC field tests and ITS applications by the US transportation sector.[6)-9)] **Figure 2** shows a picture of the DENSO prototype radio connected to two rooftop-mountable 5.9GHz automotive antennas.

Table 4 gives the attributes of the radio. It operates in traditional 802.11a-mode and in DSRC mode. The 802.11a mode allows for network access, popular web browsing and Internet access functions and could be used with slow moving or parked vehicles. It is certified to operate in the US 5.8GHz 802.11a unlicensed band.

In DSRC mode, the radio operates in the 5.9GHz ITS band on DSRC-defined channels and provides roadway coverage to high-speed vehicles.

Fig. 2　DENSO DSRC radio module & antennas

Table 4　DENSO radio attributes

Mode	Transmit band	Links to….	Comments
802.11a	Unlicensed 5.8GHz band	Static vehicles	• "Hotspot" coverage • Little or no mobility • Other RF systems share freq. Band • Single channel
DSRC (E2213-03)	Licensed 5.9GHz ITS-band	High speed vehicles	• Roadway coverage • High speed vehicles • 5.9GHz ITS band • Multi-channel

2.1.2　DSRC specifications applicable to RF link testing

DSRC specifications and ranges of values related to RF link testing are given in **Table 5**. These specifications and values are based on ASTM E2213-03. Column three shows values used in radio links investigated in this paper. Key values include RF link range and packet error rate (PER). Although E2213-03 does not specify the vehicular environment in which the range and PER limits apply, it is assumed in this paper to apply to the LOS environment. Since DSRC specs do not define a NLOS PER, a 25% reference limit will be used. The transmit queue line item identifies four MAC-level message queues based on 802.11e.[12)] MAC is medium access control.

3．FIELD TEST SETUP

A discussion of field test goals, test scope, and DSRC system elements are given in the next three sections.

Table 5　DSRC specifications applicable to link testing

DSRC spec. item	DSRC-defined values	Scope of paper
DSRC channels	172, 174, 176, 178, 180, 182, 184	**Ch. 178,** 172, 184
ITS band	5.85 - 5.925GHz	Selected channels operate in ITS band
RF link range	Up to 1,000 meters	**1,000 meters** for **R2V LOS** links
Average LOS packet error rate	<10%	**<10%**
Ave. NLOS packet error rate	Not defined	**<25%** (DENSO reference)
TX output power class	0, 10, 20, 29dBm (Class A, B, C, & D)	**10dBm, 20dBm** (default), **29dBm**
Packet size	64bytes, 1000 bytes	**64bytes**
Burst rates	3, 4.5, 6, 9, 12, 18, 24, 27Mbps	Usually **6Mbps** (DSRC default)
No. RX antennas	1 (default)	**1** or **2** (antenna diversity)
Transmit Queue	4 transmit priorities (0 to 3)	Priority **2** (similar to 802.11a)

3.1 Field test goals

Table 6 gives the goals for the field tests. Goals are given for LOS and NLOS vehicular environments.

3.1.1 LOS test goals

The goals for LOS tests are to measure max link range and PER for R2V and V2V links, and evaluate whether the link performance meets DSRC range and PER limits.

An additional goal of LOS tests is to determine if two antennas, used at different heights on an on-board unit (OBU), can reduce the PER degradation caused by ground signal cancellation on V2V links. This degradation is worst-case in V2V links with both vehicles moving in the same direction and separated at certain distances that maximize signal cancellation. Use of two receive antennas at different heights is referred to as antenna height diversity in Table 6. In theory, antenna height diversity is more beneficial on mobile V2V links with fixed vehicle separations, where cancellation of the received signal is sustained. Therefore, tests were not performed on R2V links where link distances vary and strong signal cancellation is only occasional.

3.1.2 NLOS test goals

The goals for NLOS links are to measure PER in highway tests and evaluate methods to improve PER performance. These tests use V2V links, rather than R2V links, to measure PER in worst-case conditions. NLOS performance will be compared to a 25% PER max reference limit.

3.2 Test scope

In all field tests, a single unidirectional radio link is evaluated, either between two vehicles or between a roadside unit and vehicle.

The transmitter operates on a single channel (usually channel 17[8]), broadcasting a continuous stream of 64-byte packets at a fixed priority and burst rate, and typically at 20dBm output power (WAVE class C).

To improve PER, some field tests use a higher output power, or two receive antennas (diversity).

3.3 DSRC system elements

The primary DSRC elements are the roadside unit (RSU) and the OBU. Two OBUs are used in a V2V link and an RSU and OBU are used in a R2V link.

Figure 3 shows the OBU elements used in field tests. The upper pictures show an example V2V link graphic and

Table 6 Field test goals

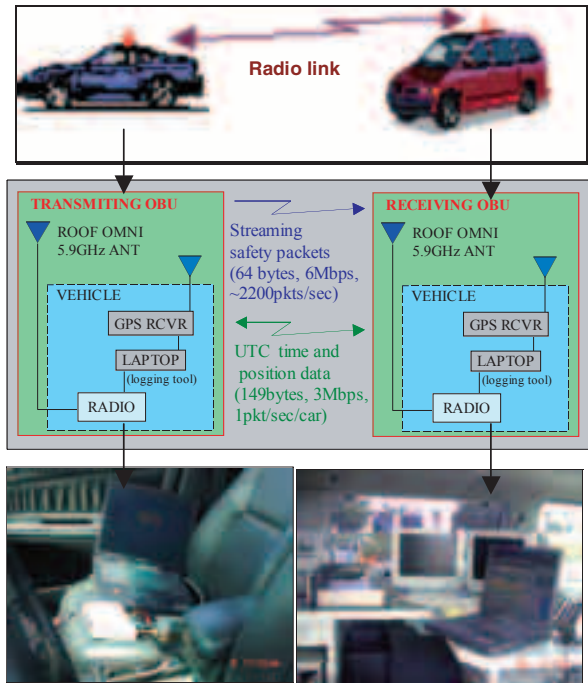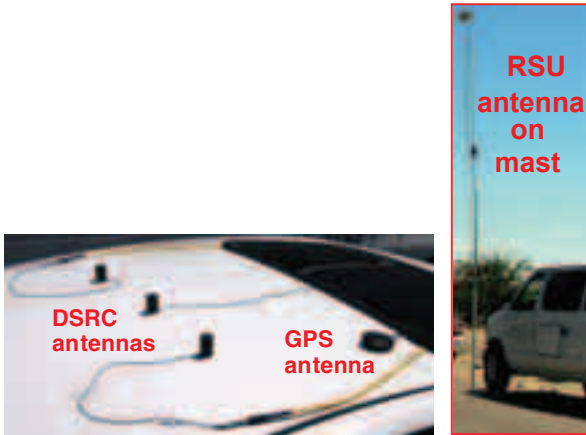| Vehicular environ.	Field test goals
LOS	• Determine max range for R2V & V2V links • Determine highway range for R2V & V2V links • Determine if R2V links meet the max range and PER limits in Table 5 • Determine if antenna height diversity can improve ground cancellation in V2V links
NLOS (Vehicle blockage)	• Determine PER in V2V links with vehicle blockage on the highway • Determine if higher power can improve PER

Fig. 3 OBU elements used in field testing

the elements of the OBU, and the lower picture shows an internal view of the equipment. The RSU is not shown but contains similar equipment to the OBU.

Each OBU comprises a DSRC radio connected to a test laptop via Ethernet; an external 5.9GHz rooftop antenna and RF cable; and a GPS receiver and antenna. The laptop in the transmitting OBU runs a utility to configure the radio and streams test packets to the transmitting radio.

The laptop in the receiving OBU logs the different link metrics, including throughput, PER, and received signal strength (RSS). Both laptops display and log real-time V2V separation distance from UTC time and position data that are output from the GPS receiver.

A transmitting OBU (or RSU) broadcasts a stream of 64 byte packets at 6Mbps rate. This stream is the primary data transmission in a typical field test. However, both OBUs (or an RSU in R2V link) also transmit their position to each other, once per second, by sending 149 byte packets over the air. The position data is used to calculate link separation and to correlate link performance with vehicle distance.

3.3.1 Antennas

Figure 4 shows a picture of several 5.9GHz omni-directional rooftop antennas and a GPS antenna on the OBU, and a high-gain directional antenna mounted on a mast as part of the RSU. The van shown in the figure is co-located with the RSU antenna and contains the equipment shown in **Fig. 3**.

Fig. 4　OBU omnidirectional (roof) antennas and
RSU high-gain antenna on mast

4．FIELD TEST ARCHITECTURE

4.1　LOS max range link architecture

Figures 5-6 show the link architectures for R2V and V2V field tests, respectively. The characteristic of these links is that they are LOS tests and include only two signal paths to the receiver: a direct signal path and a strong reflected signal path.

Figure 5 shows a fixed RSU transmitter and a mobile OBU receiver. **Figure 6** shows a fixed or mobile OBU as transmitter, and a mobile OBU as receiver. Using a fixed OBU transmitter, V2V coverage range is measured. Using a mobile OBU transmitter, worst-case PER is measured at V2V separations with maximum signal cancellation.

These LOS tests are performed on roads with no traffic so that max range measurements can be made. In addition, the same tests are repeated on a four-lane highway as LOS experiments in traffic. See **Fig. 7** for views of these test sites.
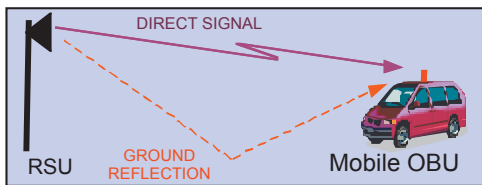

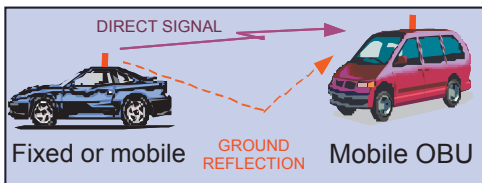
Fig. 5　R2V link with direct & reflected paths

Fig. 6　V2V link with direct & reflected paths

Fig. 7　Site of LOS max range & highway tests

4.2　NLOS vehicle blockage architecture

Figure 8 shows the link architecture for a highway V2V link with vehicle blockage between the OBUs. The characteristic of this link is that it is NLOS and that it includes a diffracted signal path to the receiver. V2V links are selected for worst-case performance.

4.3　Option: Urban canyon architecture

Although not tested for this paper, an urban canyon test architecture is briefly described for completeness. **Figure 8A** shows the link architecture for an urban V2V link. Tests are conducted on city streets in traffic. The characteristic of the link is that it is NLOS (or LOS, if no blockers exist in the link) and that it includes multiple signal paths reflected from city buildings.

5．FIELD TEST RESULTS

5.1　LOS max range (No traffic) results

Figure 9 gives the results of max range tests for R2V and V2V link tests, at various DSRC rates. The V2V ranges were measured at 3 of the 8 rates. For information on how range is determined, see the next section.

At the default rate of 6Mbps, the maximum R2V range is 1676m (5,500') with an average PER of 0.13%, which easily meets the max 1000m and max 10% PER guidelines in the DSRC standard. The RSU tests use the high-gain
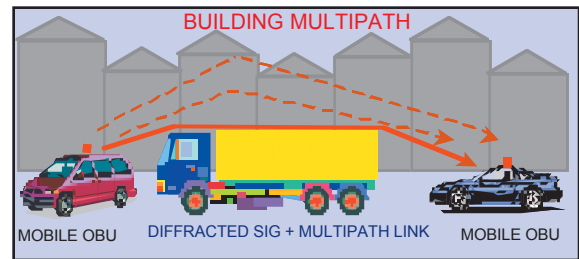

Fig. 8　NLOS V2V link with diffracted path

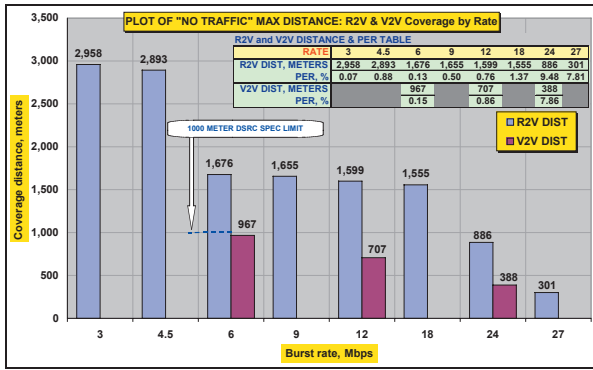
Fig. 8A　NLOS V2V link with building reflections

Fig. 9　Graph of R2V and V2V max range in No traffic conditions

antenna set-up shown in **Fig. 4**.

The maximum V2V range is 967m (3,172') with an average PER of 0.15%, which almost meets the max 1000m guideline. The V2V links give shorter distance coverage than R2V links, due to the use of small rooftop omni antennas versus a high-gain RSU antenna mounted on a mast. It is not clear if the DSRC 1000-meter max range applies to V2V links, but it is used for comparison in this paper.

5.2　How range is determined

The LOS range given in the previous figure is determined from the measured throughput. That is, the max range from the RSU or fixed OBU is the distance for which continuous high throughput is maintained at the mobile OBU. For example, **Figure 10** shows a plot with a region of sustained high throughput (and thus low PER) for which the max V2V distances can be estimated. At a point on the throughput graph near the final roll-off of throughput, an estimate of range and average PER is calculated. Any measured throughput beyond the final roll-off is not included in the distance calculation.
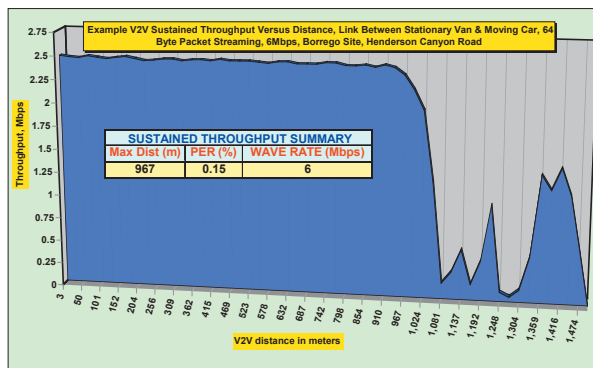

Fig. 10　Example V2V throughput plot used to determine max range

5.3　LOS signal cancellation test results

In LOS V2V links, with both vehicles moving in the same direction, significant PER degradation occurs at specific intermediate distances when link geometries cause maximum cancellation of a direct received signal by a strong ground-reflected signal.

Figure 11 shows an example plot of the effect of distance-sensitive signal cancellation on throughput and RSS. The data set with significant throughput reduction in a range of separation near 107m (350') is from a receiver with one antenna. The second set is from a receiver with antenna diversity (two antennas) and shows no drop-outs over the displayed distance range. Although throughput degradation is shown, the PER (not shown) degrades in a similar manner. This figure, illustrating a mobile OBU receiver moving away from a fixed OBU transmitter, generates a question for a mobile V2V scenario: What is the performance degradation if two OBUs are moving in the same direction, but with a fixed separation where high signal cancellation occurs? This scenario occurs frequently on our roadways, in unidirectional traffic with vehicles traveling at similar speeds. With this motivation, a test was devised to measure the PER degradation at separations that caused cancellation, with antenna diversity considered to overcome the cancellation.

In a two-OBU mobile V2V LOS drive test around a traffic-free 11-mile square roadway, using a single roof antenna on each OBU, the average measured PER was 21% at a 122m (400') V2V separation. Then, in a test using a second antenna on the windshield and activating the receive diversity function in the radio, the average PER was improved to 0.05%. This is a significant improvement. See **Table 7**. This result shows that antenna height diversity can be effective at overcoming the cancellation from a ground reflected signal that occurs at any single antenna.

5.4　Highway LOS experimental results

Figure 12 gives the results of Highway LOS experiments to measure coverage distance and PER for R2V and V2V link tests. The highway tests were performed at all rates. The tests are experiments because highway
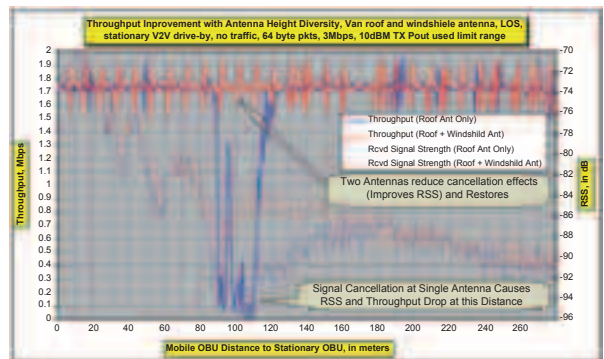

Fig. 11　Signal cancellation using one OBU antenna degrades throughput, but is restored using two antennas (antenna height diversity)

Table 7　LOS signal cancellation results

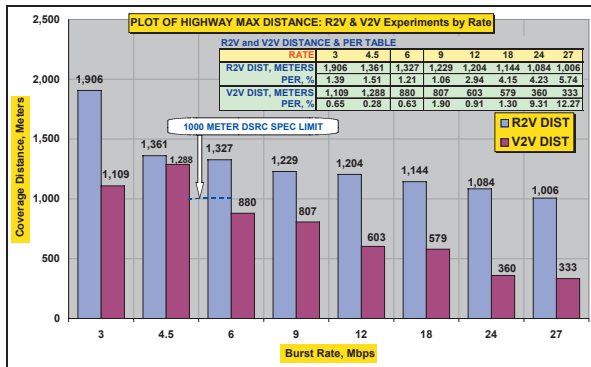| LOS signal cancellation goals & conditions	LOS signal cancellation PER improvement result
Antenna diversity: Yes Link type: Mobile V2V Max PER: 10% TX output: 10dBm Default rate: 6Mbps	V2V distance for worst signal cancellation: **122m** Single antenna PER: **21%** Diversity ant. PER: **0.05%** PER % improvement: **20.95%**

Fig. 12　Graph of R2V & V2V LOS highway link range

traffic is not controlled.

At the 6Mbps rate, the maximum highway R2V range is 1327m (4,353') with an average PER of 1.21%, which meets the max 1000m and easily meets the max 10% PER guidelines. The RSU highway tests used the antenna set-up shown in **Fig. 4**.

At the 6Mbps rate, the maximum highway V2V range is 880m (2,886') with an average PER of 0.63%, which does not meet the 1000m guideline.

In reviewing **Figs. 9 -12**, the highway LOS range for R2V and V2V links is slightly worse than max range in no traffic conditions. We speculate that the shorter range is due to occasional link blockage by other vehicles on the highway, which degrades signal reception. **Table 8** summarizes R2V and V2V LOS range results.

Table 8　LOS range results

LOS test goals/conditions	LOS range
R2V Range: **1,000m** Max PER: **10%** Default rate: 6Mbps	R2V max range: **1,676m** R2V PER: **0.13%** R2V highway range: **1,327m** R2V highway PER: **1.21%**
V2V Range: **1,000m** Max PER: **10%** Default rate: 6Mbps	V2V max range: **967m** V2V PER: **0.15%** V2V highway range: **880m** V2V highway PER: **0.63%**

5.5　NLOS V2V highway blockage experimental results

Table 9 gives the PER results from ten NLOS Highway experiments that measured PER for V2V links with 20dBm links (class C) and higher-power 29dBm (class D) links. In the experiments, the 20 and 29dBm links were operated simultaneously. The average PER for the 20dBm links was high: 70.5%. This demonstrates the severity of the Highway NLOS environment. The table includes truck blockage type, V2V separation, and average speed.

The PER for the 29dBm links was 17.8%. This 52.7% improvement vs. 20dBm link PER shows that higher-power 29dBm links can be very useful in V2V NLOS highway links. **Table 10** gives the NLOS PER summary.

5.6　Field test conclusions

Maximum LOS range and Highway LOS and NLOS experiments have been performed using DENSO's DSRC prototype radios and RSU and OBU equipment. **Table 11** gives the field test summary.

From results of the field test data, we state the following observations:

(1) R2V LOS links more than meet the 1000m-range spec and easily meet the PER spec at 20dBm output power. In fact, V2V LOS links nearly met the requirements. However, in applications using short LOS links (<100m), it would be beneficial to use less power. Providing too much power in the link over-extends the coverage range and potentially interferes with other vehicle links near-by.

(2) A significant degradation in PER (21%) occurred in V2V LOS tests at specific intermediate distances when the direct received signal was cancelled by a strong ground-reflected signal at the receive antenna. A second test using two switchable receive antennas (antenna diversity at different heights on the vehicle) reduced the PER to 0.05%, overcoming the signal cancellation that occurs using one antenna.
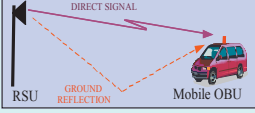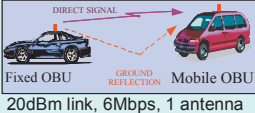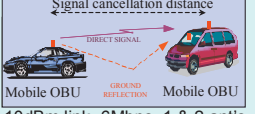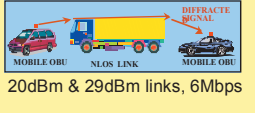
Table 9　PER results from NLOS highway tests

No.	Truck blockage type	Average speed (MPH)	AVERAGE PER, %			V2V distance
			29dBm link	20dBm link	Improvement	Meters
1	Big Rig	11.8	0.03	17.7	17.67	57.9
2	24' Box truck	61.4	11.2	54.1	42.9	91.1
3	24' Box truck	62.4	15.8	30.4	14.6	109.1
4	Big Rig	69.5	25.0	85.5	60.5	120.4
5	24' Box truck	68.6	23.1	78.2	55.1	121.0
6	Big Rig	51.4	12.0	76.2	64.2	136.6
7	Big Rig	60.5	13.5	81.3	67.8	137.2
8	Car Carrier	54.0	30.1	95.6	65.5	217.0
9	Big Rig	59.2	19.4	96.9	77.5	222.5
10	24' Box truck	62.9	27.6	89.3	61.7	229.5
	Averages ->	60.9	**17.8**	**70.5**	**52.7**	144.2

Table 10　NLOS PER summary

NLOS highway test goals & conditions	NLOS highway range (meters) & PER for V2V links
V2V max PER: **25%** Default: **20dBm** links	V2V PER: **70.5%** V2V range: **57.9m to 229.5m**
High power NLOS test V2V max PER: **25%** Link power: **29dBm**	V2V PER: **17.8%** V2V range: **57.9m to 229.5m** PER improvement: **>52.7%**

Table 11 Field test summary

Link type	Range (meters)	Ave. PER (%)	Meets DSRC/ Ref. spec.?
 RSU — Mobile OBU 20dBm link, 6Mbps, 1 antenna	1676m (No traffic)	0.13%	YES (Range, PER)
	1327m (Highway)	1.21%	YES (Range, PER)
 Fixed OBU — Mobile OBU 20dBm link, 6Mbps, 1 antenna	967m (No traffic)	0.15%	YES, NO (PER only)
	880m (Highway)	0.63%	YES, NO (PER only)
 Mobile OBU — Mobile OBU 10dBm link, 6Mbps, 1 & 2 ant's	N/A Improve PER at worst signal cancel distance	21% (One antenna)	NO
		0.05% (Two ant's)	YES (PER)
 20dBm & 29dBm links, 6Mbps	58 - 230m	70.5% (20dBm)	NO
	58 - 230m	17.8% (29dBm)	YES (Ave PER)

(3) NLOS links are significantly more challenging to maintain than LOS links and, even with 29dBm output power, have significantly higher PER than LOS links.

(4) The LOS and NLOS conditions generate conflicting goals: The need to restrict output power to avoid over-extending a LOS coverage range versus the need to provide high power to maintain a reasonable PER for NLOS links.

(5) Large blocking vehicles, causing severe PER degradation in these tests, could become a big benefit for vehicle safety if deployment of DSRC is universal. Large trucks, if outfitted with DSRC antennas mounted high on the vehicle, could act as moving "relay towers" to retransmit safety packets to trailing vehicles that have much smaller profiles. Trucks could relay the transmitted packets rather than block them.

6．ACHIEVING WIRELESS CONNECTIVITY: MULTI-CHANNEL MANAGEMENT

In previous sections, field tests were discussed which used DSRC wireless communications on a single link between two vehicles, on a single radio channel, using a single burst rate and transmit priority. In addition, the transmitting radio broadcasted a continuous stream of packets, effectively using the entire capacity of the channel.

6.1 DSRC system resources

DSRC is a wireless system for vehicle communications. Its resources include a licensed frequency band, multiple radio channels and a capability to share them, and multiple transmit queues for prioritizing messages before delivery.

6.2 Using DSRC for vehicle safety

Questions arise for deploying such a safety system. If safety applications have priority, then how are non-safety applications also accommodated? How can system resources be scaled during times when safety message traffic is high and when it is low? How are multiple channels supported when using a single radio? A candidate method is described to address these questions.

6.3 Multi-channel management

This section introduces a method called Multi-channel Management (MCM). The context for MCM in this paper is to describe a method whereby vehicles in a localized area become aware in real-time of potentially dangerous situations. It uses DSRC system resources to perform vehicle safety and non-safety communications. Two elements of the method are discussed: Partitioning of safety and non-safety messages by channel and time, and a simplified description of synchronization and adaptation. The text and figures in this section are simplified descriptions of original concepts from Jason Hunzinger that are published in a DENSO internal document.[11]

6.3.1 Partitioning of safety and non-safety messages

Using the Multi-channel Management method, safety-of-life messages have the highest priority and are transmitted on a dedicated safety channel. This important partitioning of safety and non-safety messages is performed by a channel management entity and is shown diagrammatically in **Fig. 13**. Awareness and separation of safety and non-safety functions are maintained from the upper layers, through the MAC and PHY layers, and onto dedicated DSRC channels.

The figure shows example mapping to safety and non-safety messages onto DSRC-defined channels. The R2V safety channel (ch. 184) is conceptual and the control channel (ch. 178) is not discussed here. For this section, channel 172 is identified as the dedicated safety channel for V2V communications.

Given that vehicles use one transceiver, how do we manage the vehicles in any localized area to receive safety communications on one channel and participate in non-safety communications on one of several other channels?

One idea is to time-partition the transceiver's operation into repeating intervals including a safety period and non-safety period, as shown in **Fig. 14**. At the beginning of the (repeating) interval, in the safety period, all high priority (HP) and some low priority (LP) safety messages are transmitted. During the non-safety period, LP safety and non-safety (NS) messages can be transmitted. From **Fig. 13**, the V2V HP safety transmissions occur on channel 172 to ensure that all vehicles in a local area will receive them, and the NS transmissions occur on one of a number of other channels. LP safety transmissions can occur on safety and non-safety channels.
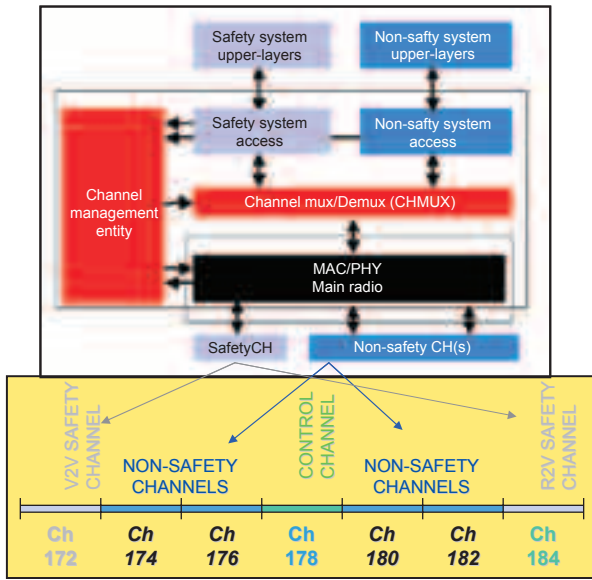
Fig. 13　Partitioning of safety and non-safety transmissions by DSRC channel using a channel management entity
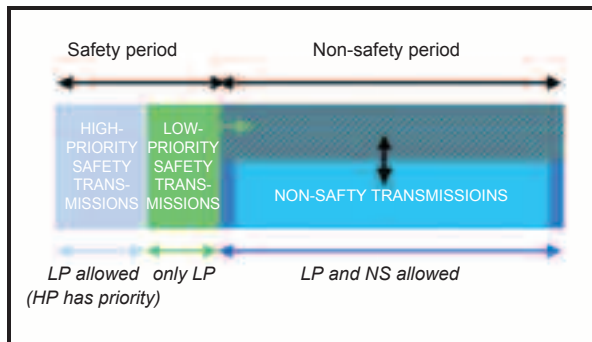

Fig. 14　Partitioning of safety and non-safety transmissions by time periods. One cycle of safety and non-safety periods shows allowed transmissions in each period.

6.3.2 Simplified description of synchronization and adaptation

How can we ensure all vehicles in a local area are on the V2V safety channel to receive HP safety messages? One approach, shown in **Fig. 15**, is to use timers. Individual vehicles transmit short HP safety messages (striped bars in figure) during the safety period. When no HP safety message is received for a period of TIDLE, the vehicles may stay on the safety channel and transmit and/or receive LP safety messages (checkered bars), or may switch to a non-safety channel to transmit or receive NS messages (solid bars).

The timer T_{NS} sets the length of each fixed non-safety period. Given the use of timers and each vehicle's safety transmissions for synchronization, how can safety channel capacity be scaled during times when safety message traffic
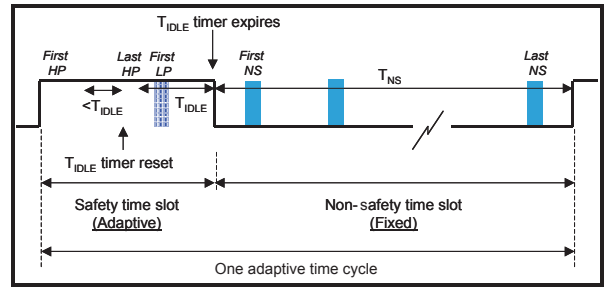

Fig. 15　Timer-based transitions between safety and non-safety periods

is high and when it is low?

6.3.3 Safety period is adaptive

The safety period is adaptive and depends on the amount of safety traffic at a given time. **Figure 16** shows the adaptability in the duration of the safety period to accommodate changes in HP safety packet traffic. The figure shows how transmitted and received safety packets, represented by the striped bars, cause the safety period to adapt automatically. Variation in the number of received packets in each safety period comes from changes in safety traffic. LP safety packets are not shown for clarity.

By using an adaptive safety period and a fixed non-safety period, the average channelization latency is bounded and configurable. In an extreme case where the received HP safety traffic messaging is such that the TIDLE timer never expires, then the full system capacity is allocated to HP safety communications.

6.3.4 Non-safety period is fixed

The non-safety period is a fixed duration and restricted in length to say, $T_{NS} = 50$ms, to ensure that the maximum transmit latency for HP safety messages is 50ms plus the contention latency during the safety period. Because the NS traffic occurs on one of a number of non-safety channels, the traffic is balanced across the available channels.

6.3.5 Multi-channel management discussion summary

MCM is a method that uses DSRC resources in a manner that:

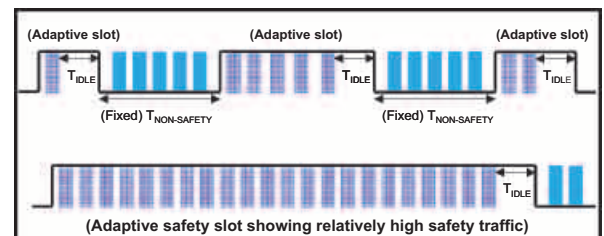(1) Synchronizes transmissions among a localized group of vehicles

Fig. 16　Example time depiction of adaptive safety periods (slots)

(2) Gives highest priority to safety of life messages
(3) Accommodates wide range of safety message traffic using adaptive safety slots

By partitioning safety and non-safety services in all DSRC layers, having transmit priorities appropriate for the safety message importance, synchronizing vehicle safety transmissions and adapting the safety period, the Multi-channel Management method implements the DSRC safety message priority and accommodates non-safety traffic balanced across multiple channels.

7．ACHIEVING WIRELESS CONNECTIVITY: CELLULAR-WLAN SEAMLESS ROAMING

With prolific worldwide growth in the use of wireless local area network (WLAN) radios to obtain broadband Internet access at hotspots, automotive OEMs are considering in-vehicle 802.11 WLAN radio installations.[13] Further, the wireless industry is investigating how handoffs between WLAN and cellular networks could allow cellular links to provide connectivity to vehicles when they are out-of-range of hotspots. Vehicular applications for this nationwide roaming capability could include on-road post-accident reporting and probing for traffic identification and management, vehicle diagnostics, and infotainment links. When roaming on cellular links, connectivity would be maintained but at reduced throughput relative to WLAN links. The infrastructure-side WLAN networks could be located in homes and in business facilities near the roadside.[13]

With this motivation, this section discusses an approach for providing continuous vehicular links to the Internet using cellular-WLAN handoffs. The section includes four parts: Test concept and configuration, vehicle equipment and drive route, mobile router and mobile node, and drive testing.

7.1 Test cncept and cnfiguration

One concept for continuous connectivity to the Internet is to provide micro-mobility coverage on surface streets. Micro-mobility is defined as vehicle movement in small areas and limited to accessing individual, local network segments. In contrast, macro-mobility is defined as vehicle movement through large areas with access to one large monolithic network covering many square miles. In this section, we focus on this micro-mobility environment.

Roadside WLAN coverage areas (hotspots) would be the 1st preference for Internet connectivity because of its higher throughput capability, with handoffs to and from cellular networks to maintain the connection when hot spot coverage is not available. Although the cellular networks have lower throughput than WLAN networks, they have near nationwide coverage. **Figure 17** shows the concept for WLAN areas with a cellular coverage overlay.

With motivation to investigate the concept shown in **Fig. 17**, DENSO CORPORATION conducted experiments in Japan to determine delay time and packet loss for hand-offs between cellular and 802.11 WLAN networks. The results are given here, and provided in a paper presented at a previous ITS-World Congress.[14] **Figure 18** shows the configuration of the test environment. It includes a mobile terminal with WLAN and cellular modules, and
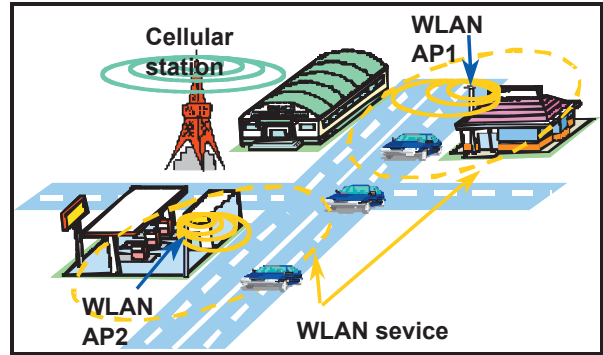

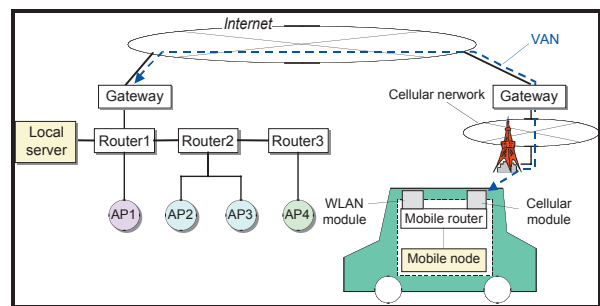Fig. 17 Concept for broadband access using WLAN hotspots & with a cellular network overlay

Fig. 18 Configuration of the test environment

infrastructure equipment including roadside WLAN Access Points (APs), routers, and servers. Gateways connect the WLAN and cellular networks to the Internet. The cellular link is connected to the Gateway via virtual private network (VPN).

7.2 Vehicle equipment and drive route

Figure 19 shows a diagram of the Mobile Terminal, which comprises the mobile router and mobile node. It includes a picture of an 802.11b WLAN transceiver and PHS cellular phone attached to a mobile router. The PHS network was used because it is widely accessible in Japan, where the experiments were conducted. The mobile terminal

7.3 Mobile router

The mobile router is based on a PC/AT compatible architecture with a Linux operating system. The mobile router includes roaming manager software. The roaming manager establishes the wireless connection, selecting the WLAN link if the AP is in range, or the cellular link if not in range.
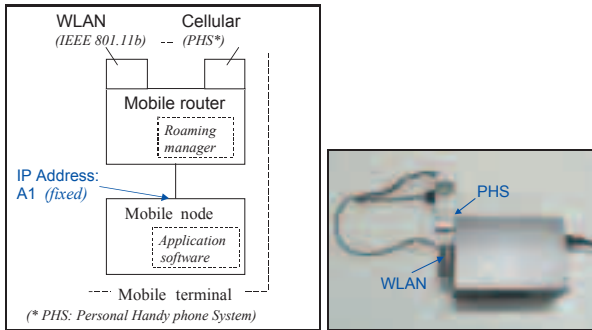
Fig. 19 Diagram of the mobile terminal, including a picture of the WLAN transceiver and PHS cell phone attached to the mobile router (In-vehicle equipment)
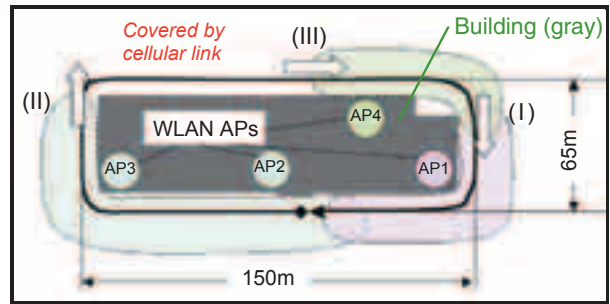

Fig. 20 Circular drive route and AP coverage areas around building

command. And PIT is the interrupted time over which a mobile node can't receive packets.

7.4 Mobile node

The mobile node executes application software and connects to the router via Ethernet. In the mobile node, a variety of network applications are installed, including a web browser and video player. The mobile node has a fixed IP address, designated as A1 in **Fig. 19**, and this address is not changed even if the mobile router performs hand-offs to other WLAN or cellular networks. The premise is that the mobile node and the host continually communicate with each other, using fixed IP addresses, while the node moves. As it moves, the IP address of the WLAN module is changed after entering each new WLAN coverage area. Basically, seamless roaming is realized by coordinating the network routers to update their routing tables with the new IP address. Because of the fixed address, the application software keeps the connection while the vehicle is moving. Details of the procedure for routing updates are included in the source paper.[14]

7.5 Drive testing

In this experiment, APs are placed around the building as shown in **Fig. 20**, and the test vehicle drives around the building. The test area is 150m x 65m. Along the test course, between AP3 and AP4, there is shadow area where the WLAN is out of service. In this area, cellular link will maintain the connection. The figure shows a circular drive route around a building, and the cellular and AP coverage areas for performing roaming experiments (hand-offs). There is no WLAN coverage between AP3 and AP4, so a handoff to a cellular link will be required in this area. As the mobile terminal enters each new coverage area, the mobile router triggers a routing update procedure.

7.6 Measurements

Using the test environment, the routing update and the packet interruption delays were evaluated. From the local server, UDP test packets are sent to the mobile test vehicle. The packet length was 60 bytes and interval was 100ms. By capturing received packets at the mobile terminal, we analyzed routing update time (RUT) and packet interruption time (PIT). Here, RUT is the required time to update the routing table entries after sending the routing update

7.7 Results

Table 12 shows the test results. In this experiment, we used a PHS data module with 64kbit/s throughput. We checked three conditions as shown in **Fig. 20**. (I) Inter-APs roaming: AP4 to AP1; (II) AP to cellular roaming: AP3 to cellular; and (III) cellular to AP roaming: cellular to AP4.

From the table, connection (II) shows the longest RUT and PIT. For this connection, the routing update command is sent by cellular link. This link is narrowband, less than 50kbit/s in operation, and the latency is also long. This is the reason that the routing update is slow, and interruption time is relatively long.

Connection (III) shows the shortest RUT and PIT. These data paths are shorter than inter-APs roaming in connection (I). For connection (III), the routing update is sent via high-speed WLAN link and the mobile router is able to establish the WLAN link just after entering the AP service area. The time to search for AP4 is not included in the PIT because it occurs while the cellular link is still active. In case of connection (I), on the contrary, after moving into the new AP area, the mobile router begins to search for an available channel. After finding the channel, the mobile router can establish the new link. That is our speculation for

Table 12 Experimental result of router update time and packet interrupt time

Connection	RUT (ms)	PIT (ms)
(I) AP4 to AP1	72	350
(II) AP3 to Cellular	111	405
(III) Cellular to AP4	46	247

why connection (I) is slower than connection (III).

7.8 Conclusions

This roaming experiment has shown that, by using the routing update commands, a mobile terminal can communicate with a server without disconnection. This continuous connectivity could be used for applications such as post-accident reporting and traffic management. Using WLAN and PHS cellular handoffs, a packet interruption time less than 0.5 second was achieved. Considering the results described above, using a more broadband cellular link will reduce RUT and PIT.

Note that this seamless roaming system uses a conventional IP network, using only roaming manager software in the mobile router. No special software is used with the network routers. Because the control is performed over network layer, any IP-based wireless communication system can be used with our system.

8. FOLLOW-ON WORK

DENSO will continue to investigate how DSRC resources could be used to improve the efficiency and reliability of vehicle safety communications. This effort will extend into DENSO's development of a next-generation 5.9GHz automotive radio.

DENSO will continue to investigate radio link impairments and develop countermeasures to improve communications in vehicular environments.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AP: Access Point
RF: Radio Frequency
LOS: Line Of Sight
NLOS: Non-Line Of Sight
DSRC: Dedicated Short-Range Communications
WAVE: Wireless Access in Vehicular Environments
ITS: Intelligent Transportation Systems
ITS America: Intelligent Transportation Society of America
TX: Transmitter
RX: Receiver
OBU: On-board Unit
WLAN: Wireless Local Area network
RSU: Roadside Unit
Mbps: Megabits per second
GHz: Gigahertz
PER: Packet Error Rate
R2V: Roadside-to-Vehicle
V2V: Vehicle-to-Vehicle
PHS: Personal Handy Phone System

NS: Non-Safety
MAC: Medium Access Control
UTC: Coordinated Universal Time
GPS: Global Positioning System
RSS: Received Signal Strength

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