Design and Experimental Evaluation of a Database-Assisted V2V Communications System Over TV White Space

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journal or publication title	Journal of Signal Processing Systems
volume	83
number	1
page range	45-55
year	2016-04
URL	http://hdl.handle.net/10228/00006174

doi: info:doi/10.1007/s11265-015-1035-z

The Journal of Signal Processing Systems

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--Manuscript Draft--

Manuscript Number:	VLSI-D-15-00050R1
Full Title:	Design and Experimental Evaluation of a Database-Assisted V2V Communications System over TV White Space
Article Type:	SI: WINNF2014
Keywords:	vehicle-to-vehicle communications; TV white space; dynamic spectrum access; white space database.
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Funding Information:	
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Design and Experimental Evaluation of a Database-Assisted V2V Communications System over TV White Space

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Abstract Automakers are increasingly employing wireless communications technologies into vehicles, which are expected to be one of the primary tools to improve traffic flow and traffic safety. Anticipating a significant increase in the accompanying spectrum and capacity requirements, in this paper, we speculate about using dynamic spectrum access in general, and TV white space in particular for vehicular communications. To this end, we describe the concept, design, general architecture and operation principles of a vehicle-to-vehicle communications system over TV white space. This system makes dual use of a geolocation database and spectrum sensing to understand spectrum vacancies. In this architecture, whenever a database query result is available, that information is prioritized over sensing results and when the database access is disrupted, vehicles rely on the spectrum sensing results. After describing the general concepts, we numerically analyze and evaluate the benefits of using proxy vehicles for geolocation database access. Finally, we present the middleware-centric implementation and field test results of a multi-hop vehicle-to-vehicle communications system over the licensed TV-band. We present results regarding multi-hop throughput, delay, jitter, channel switching and database access latencies. This study complements our previous work which described spectrum sensing based vehicle-to-vehicle communications design and testing.

Keywords *vehicle-to-vehicle communications; TV white space; dynamic spectrum access; white space database.*

1. INTRODUCTION

Vehicles capable of communicating with other vehicles, and “connected vehicle” are not anymore future concepts with the automobile manufacturers increasingly employing wireless communications technologies in new vehicles. Advanced driving support applications which rely on wireless communications among the vehicles, aiming to increase driver awareness and situation perception are being envisioned to help decrease accidents. Similarly, efficiency of traffic flow is expected to improve by using such technologies [1].

The U.S. Federal Communication Commission (FCC) allocated 75 MHz of spectrum in the 5.9 GHz band for dedicated short-range communications (DSRC) to be used by intelligent transportation systems (ITS), in 1999. Ever since then, applications of one-way or two-way vehicle-oriented communications have evolved into various forms. Recently, 10 MHz of spectrum centered at 760 MHz band has been allocated for ITS in Japan. The first generation of vehicles capable of communicating in this band will become available in Japan in 2015. Europe has allocated 50 MHz of spectrum in the 5.8 GHz band for ITS. Furthermore, several standards supporting vehicular communications have already been designed, e.g., ARIB STD-T109 in Japan, ETSI ITS-G5 in Europe, IEEE 1609 and IEEE 802.11p elsewhere.

The number of vehicles which are capable of performing wireless communications is a negligibly small fraction of the total current market, as of today. Furthermore, the spectrum requirements of these vehicles presently are relatively low compared to wireless applications deployed in other sectors. However, not only the communications among vehicles, but also the communications between people, objects and vehicles are expected to become ubiquitous in the future, resulting in a significant increase in the accompanying spectrum and capacity requirements. This requirement of spectrum may further be enhanced by the developments in automated driving systems where autonomous vehicles might need to exchange significant amount of sensor and image data with hard real-time delivery requirements. Eventually, vehicular applications might suffer from spectrum scarcity and overcrowding, as has already been experienced by other mobile wireless communications sectors. For example, one recent study [2] looks into the spectrum requirements of vehicular communications for safety applications in which more than 80 MHz of spectrum is deemed as necessary to be able to keep the packet error ratio under 1%.

Spectrum scarcity and overcrowding might eventually lead to the need to look for spectral resources elsewhere, as in the dynamic spectrum access (DSA) paradigm where unlicensed devices temporarily borrow licensed but spatially and/or temporally unused spectrum. In the rest of this paper, we will first describe our previous work regarding DSA for vehicular communications in general, and V2V communications over TV white space (TVWS) in particular. Following that, we will continue with the description of the database assisted vehicular communications system underlying concepts, and a brief description of the architecture. After describing the general concepts and operation principles, we analyze and numerically evaluate the benefits of using proxy vehicles for geolocation database access. Finally, we will present the middleware-centric implementation and field test results of a multi-hop vehicle-to-vehicle communications setup over the licensed TV band. Results regarding multi-hop throughput, delay, jitter, channel switching and database access latencies will be presented.

2. PREVIOUS WORK ON V2V COMMUNICATIONS OVER TVWS

In the vehicular environment, application of dynamic spectrum access principles can help to satisfy capacity demand for vehicular applications, and to offload time-insensitive applications from the spectrum dedicated to time-critical applications. However, applying the dynamic spectrum access concepts to highly mobile environments brings additional challenges due to the mobility of the participating hosts. All of the existing standards center around a fixed or nomadic base station (or access point) in which a master-slave relationship exists. In vehicle to vehicle communications, this type of architecture becomes less relevant since most of the communications occur among vehicles in a geographically confined but continuously moving area.

Relatively static channel utilization of the broadcast television spectrum makes it one possible candidate for dynamic spectrum access in vehicular environments. In order to opportunistically access the unused spectrum, vehicles must be aware of their spectral environment. Two approaches being considered for spectrum awareness are incumbent user signal sensing and geolocation database lookup. Both approaches have advantages and drawbacks in vehicular environments. More specifically, neither of these approaches individually can provide sufficient incumbent protection from interference that might be created by vehicular cognitive network nodes [3].

Towards merging spectrum sensing with geolocation database lookup, a representation method of white space vectors customized for high mobility environments is studied in [4]. Once the spectrum holes are detected, the next step is to coordinate and agree with the other vehicle(s) on the channels that are suitable for communications. One of the first studies that looked into the potential of using white spaces for vehicular communications is [5]. In [5], a distributed and autonomous dynamic spectrum coordination method tailored for vehicular environments is proposed. Vehicles coordinate to agree on a control channel, to subsequently setup data channels, and from there to further exchange information on spatial and temporal spectrum variations. Vehicles in this method make use of each other’s temporal and spatial proximity relationships to autonomously agree on control and data channels.

In [6] we reported and demonstrated the first ever field tests of vehicle-to-vehicle communications over TV white space between two moving vehicles. Furthermore, [7] investigates the spatial dependencies in selecting an appropriate vacant channel for multi-hop vehicle-to-vehicle communications by taking into account several factors, such as the distance between the vehicles, channel bit rate, vehicle velocities, statistical information of channel utilization and propagation range of candidate channels. In [8] and [9] we described a combination and extension of the work in [6], with the distributed and autonomous control and data channel selection algorithms tailored for a group of vehicles and multi-hop communications which can work in an unknown spectral environment were developed and demonstrated. The system relied on limited spectrum sensing capabilities of the emulated TV signals in the field test area.

Moreover, the study in [10] looks into the feasibility of performing vehicular dynamic spectrum access across vacant TV channels via a queueing theory approach. It leverages actual quantitative measurements obtained from a wireless spectrum measurement campaign conducted along a major interstate highway in Massachusetts. The results show that in most rural and suburban areas, TV white space is a feasible resource for vehicle communications, satisfying performance requirements assuming that the sensing and channel switching functions are performed sufficiently fast. Work in [11] further advances the concept of vehicular dynamic spectrum access by employing artificial intelligence methods such as machine learning, to make a vehicle gradually learn from the past spectral experience and hence quickly converge into the best performing channel depending on the application requirements. In [12] we presented an assessment regarding the viability of using TV spectrum within the context of a vehicular dynamic spectrum access network.

Finally, complementing the system in [8] and [9], in [13] we extended the system design so as to include dual use of sensing and database information. We presented the general design and operation principles of a vehicle to vehicle communications system in which the TV white space information is obtained from a centrally authorized white space database. In the following section we will briefly review that architecture as well as the system operation, and describe implementation of the middleware that governs the flow of events.

3. OVERVIEW OF SYSTEM ARCHITECTURE AND OPERATION

Centrally authorized geolocation database is recently being ruled as the preferred method of primary user protection in certain markets. The secondary user of the spectrum must be location aware, and must periodically access the database querying the information regarding available white space. In centralized network topologies, base stations and access points can query the database on behalf of individual users. In an ad-hoc vehicle-to-vehicle communications setting, additional wireless connectivity to query the database would be necessary in each vehicle. Additionally, and depending on the market, the regulators require that a mobile node performs a database query whenever it moves more than 100 meters. If this rule is adopted for vehicular networks, a vehicle traveling at 100 km/h would create one database query every 3.6 seconds. A better way of accomplishing this could be to have one vehicle act as a proxy to obtain information from the database and distribute it among its peers, not only for the current location but also for "future" locations by taking hints from the neighboring vehicles' velocity vectors.

3.1 Dual Use of Geolocation Database and Spectrum Sensing

Since the centrally authorized geolocation database is (at least at present) the preferred method of primary user protection [14][15], the vehicles must be able to identify their location and query the database for available white space. In addition to the database access, we allow for spectrum sensing as the fallback option in case that the database access is lost, owing to high mobility of the network nodes (Figure 1).

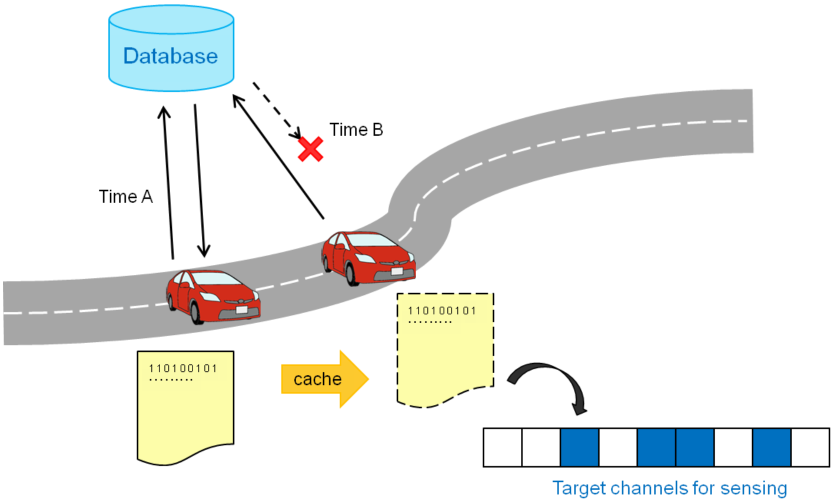

Figure 1. Conceptual view showing dual use of geolocation database and spectrum sensing.

When flipping to spectrum sensing as the method of spectrum awareness, the sensing subsystem obtains the list of vacant channels in the cache (effectively the last database access results) and builds a channel sensing plan by skipping those channels known as "occupied" at the time of switchover. If, for some reason, database access cannot be restored for a prolonged time, the system might end up starving spectrum in the worst case. This happens due to the sensing subsystem not visiting the previously occupied channels and continuously detecting other occupied channels as the vehicle changes location in time. To avoid spectrum starvation, we come back to the occupied channel list in the cache and select *n* channels randomly to include in the target channels for sensing list. Details of this scheme are explained in the flowchart in Figure 2.

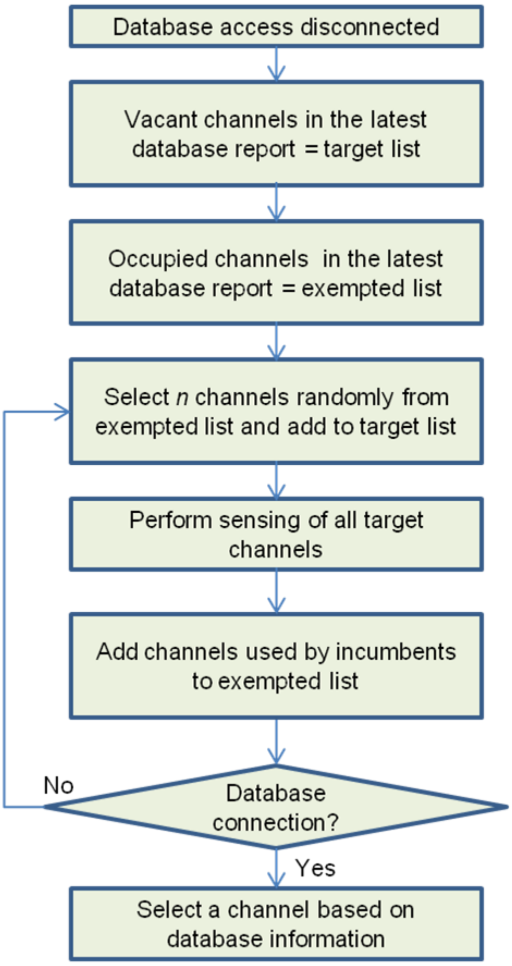

Figure 2. Database and sensing flip-over with spectrum starvation hedging.

In order to reduce the potentially high load on the wireless 3G/4G cellular network used to query the database, we implemented two procedures: 1) the vehicles which constitute the network swarm (described below in Section 3.3) select a proxy in charge of communication with the database and dissemination of the spectrum availability within the swarm; and 2) the proxy downloads spectrum availability information for multiple locations on the road in advance. The proxy is selected based on its *x*-*y* Cartesian coordinates. The area map is divided into a mesh. All vehicles compare their location within a square field in the mesh (which we call the “distribution area”) to the center of that area. A vehicle which is presently at, or close to the center of the distribution area implicitly assumes the role of a proxy and initiates a query to the database. The information received from the database is periodically announced on the distribution control channel (DCC). Since we assume congestion of the 760 MHz/5.9 GHz licensed bands, we do not choose those bands to distribute the database information. Thus, the proxy simply selects the white space channel which will be available for the longest distance, as the DCC. A careful selection of the DCC would help to distribute the spectrum information without the need to change it frequently which also allows vehicles within and outside a swarm to discover the channel availability. Nodes other than the proxy simply sequentially listen to all TV channels, starting from the lowest index, until they discover the DCC. There might be cases where two or more vehicles assume the role of proxy in the same distribution area at the same time. While this is not the ideal situation, it would nevertheless not cause ambiguity as long as the same information is delivered on the same DCC. Conveniently, this discovery procedure must be performed only in case of a “cold start”, or when a vehicle travels over to a completely new trajectory. This concept is outlined in Figure 3.

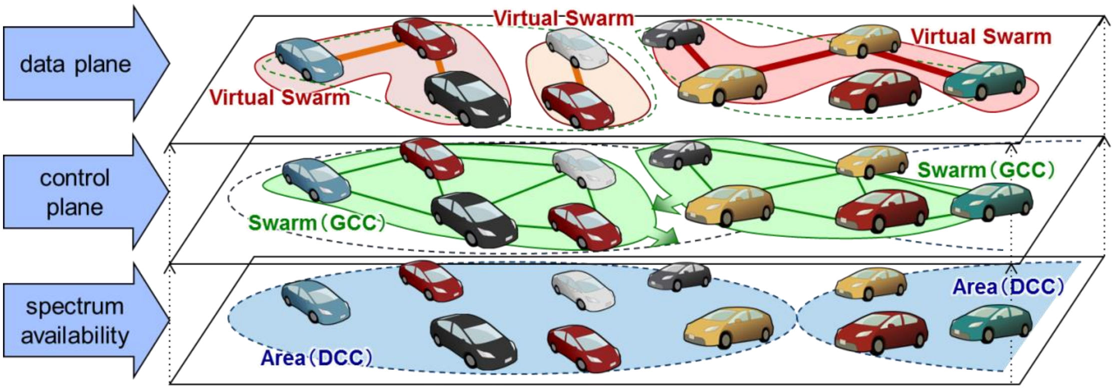

Figure 3. General concept showing the control and data plane separation with actual and virtual swarms of vehicles.

3.2 Proxy Database Access Modeling and Evaluation

When using a proxy vehicle to access the white space, the number of vehicles individually accessing the white space database would decrease with the increasing “distribution area” size. An appropriate size of this area can be determined by several factors to support fast distribution of the database information within the area. This, of course, depends on the transmission range of the Distribution Control Channel. Here we examine the impact of the proxy access with various sizes of the "distribution area" through a simple model evaluation. Model evaluation is conducted in a 15 km square area in which vehicles are randomly placed. We examine the relationship between the number of vehicles and the number of vehicles directly accessing the white space database, with and without proxies. We choose five different sizes of the "distribution area" (100 m, 200 m, 250 m, 500 m, 1000 m-square area) when using a proxy. Note that we here assume the DCC can reliably cover the distribution area.

Figure 4 presents the results of simple model evaluation. In the simplest case of individual access, all vehicles can obtain information from the database immediately. This comes with the price of linear increase in the number of database accesses. On the other hand, when using a proxy for database access, the average number of vehicles directly accessing the database can be calculated as follows

$$Average\ no\ of\ vehicles\ accessing\ database = N - \frac{(N-1)^n}{N^{(n-1)}}$$

where n is the number of vehicles and N is the number of distribution areas in the evaluation area. With use of proxies, the number of vehicles accessing the database ideally converges to N. This might prove especially beneficial in urban areas.

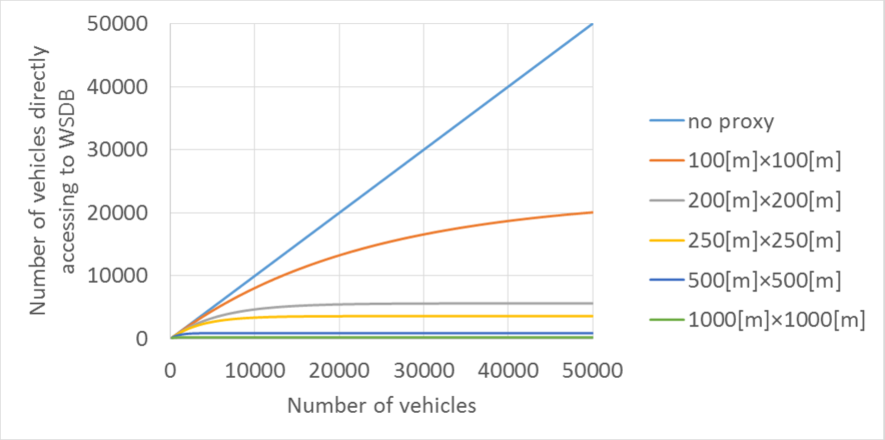

Figure 4. Number of total vehicles vs number of vehicles accessing the database with and without proxies.

Current FCC regulations require that a mobile TV white space device perform database query whenever it moves for more than 100 meters [14]. To act as a simple remedy for excessive queries to the white space database in case of high mobility of the nodes, the regulations allow for prefetching of data. As the trajectory of vehicles, at least until the next intersection, is highly predictable, the proxy can trade a number of per–point database queries for a single query addressing multiple locations. The query process can further be made efficient by filtering out the "cells" that the road curvature is clearly not passing through, thus decreasing the amount of information that needs to be shared with other swarm members. From another point of view, by excluding the irrelevant cells from the query, a longer "look ahead" in terms of available spectrum might be possible.

On the other hand, if a proxy is querying the database on behalf of the others, as in a swarm, then, a more comprehensive pattern which includes other vehicles' position and speed vectors is required. This relevant-cells-only concept for the case of three vehicles is illustrated in Figure 5.

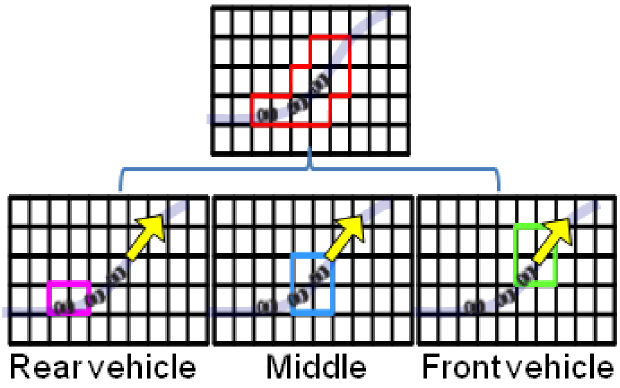

Figure 5. Look-ahead and relevant-cells-only database query area for a three-vehicle swarm.

3.3 Swarm Formation

In addition to querying the database, the information about location of nodes is needed to establish and maintain network topology. Conveniently, localization is already an important part of the licensed DSRC network design. To fulfill traffic safety assistance tasks, the vehicles broadcast their data including their identifier, location, speed, heading, and acceleration in the licensed 760 MHz or 5.9 GHz band. These messages are broadcasted periodically, for instance ten times per second, as defined in the SAE J2735 [16], the ETSI ITS [17], and the Japanese Advanced Safety Vehicle (ASV) Message Set specifications [18]. This inherent information exchange implicitly provides a tool for each vehicle to be aware of the network topology within its one-hop reach of broadcasts. Subsequently, from the information received about its neighbors, each vehicle can create and maintain a swarm table in which it stores one-hop neighbors' list and prunes out the data belonging to two-hop neighbors. If the vehicles are lined up as in a convoy, then it is probable that a vehicle will be listening to more than one vehicle's safety messages. This would lead to the multiple choices of swarm join probabilities. Whether a vehicle joins a swarm *k* or not is a decision taken by the vehicle itself by considering the following constraints: 1) the current member population of the swarm *k*; 2) whether the speed, direction, acceleration, etc vectors of elements of swarm *k* are similar to those of ego vehicle. The information related to the swarm operation is distributed over Group Control Channel (GCC). We do not assume that these swarm tables to be maintained with perfect accuracy, because high mobility of nodes causes frequent changes in the network topology as vehicles travel with different speeds and frequently merge and leave roads. We assume that the vehicles share the same view of regional maps so that they can synchronize on Cartesian coordinates. In the field experiments described below, all vehicles were preloaded with the same maps. Also, vehicles in the experiments were always part of a single swarm due to the very small number of participating cars.

Given that the role of DCC is to share (announce) channel availability information, and that padding of additional information on the DSRC broadcast packets is not in compliance with the relevant standards mentioned above (i.e., SAE J2735, ETSI ITS, J-ASV), the remaining issue is how to exchange swarm related information among the swarm members. A mechanism is needed on the application (data) plane to form "virtual swarms" of nodes which run a certain application and require data exchange. The virtual swarm nodes must congregate to the same white space channel and select a data route in the case of multi-hop exchanges. In our design, the necessary information is shared over the group control channel (GCC). Note that these control and distribution channels can be logical or physically allocated channels.

3.4 Data Channel Selection

Data channel selection can also exploit the look-ahead and relevant-cells-only concepts employed in database query, this time to select the data channel from a set of available channels. The simplest way of doing this is apparently to consider the available channel(s) that would provide the longest availability (in terms of distance) without the need to switch to another channel. For this, the vehicle trajectory and the channel availability information are overlapped for each channel and the resulting "longest" channel is chosen as the data channel. This simple solution, however, may lead to channel collisions as the number of communicating pairs of vehicles selecting this longest one as their preferred channel of data transfer increases. A number of schemes that further look into the application types of each pair can be conceived of which would go beyond the scope of this paper. In the field tests described below, we simply selected the longest available channel as the data channel among the set of vehicles participating in the experiments.

3.5 Database Design

The database used during the field tests is developed and implemented by the National Institute of Information and Communication Technology (NICT) of Japan. It was implemented in such a way that divided the entire Japanese archipelago into cells of 100m x 100m resulting in approximately 550 million cells in which the incumbent TV station information is calculated per channel. Cells were identified by their latitude and longitude identifiers in addition to a cell number. The database was located in Yokosuka City, approximately 900 km away from the test site, and was accessed via the 3G/LTE networks.

4. EXPERIMENTAL EVALUATION AND RESULTS

We obtained experimental licenses for five TV channels, through channel 13 to 17 of 5.7 MHz of width each, centered at 473, 479, 485, 491 and 497 MHz. The license was effective for several weeks, covering a 5 km stretch of the public roads in Miyazaki, southwestern Japan. The power limit for the TV band devices was approximately 80 mW over these five channels. TV band devices employed OFDM without channel bonding. Relevant parameters are summarized in Table 1. A schematic outline of the field tests is given in Figure 6.

Location	Misatocho, Miyazaki
Channels	TV Ch 13 to 17 (470-500 MHz)
Bandwidth	5.7 MHz/channel
Output Power	79 mW
Modulation	OFDM 64QAM
Database	NICT-Yokosuka, access via 3G/LTE

Table 1. TV band device operation parameters.

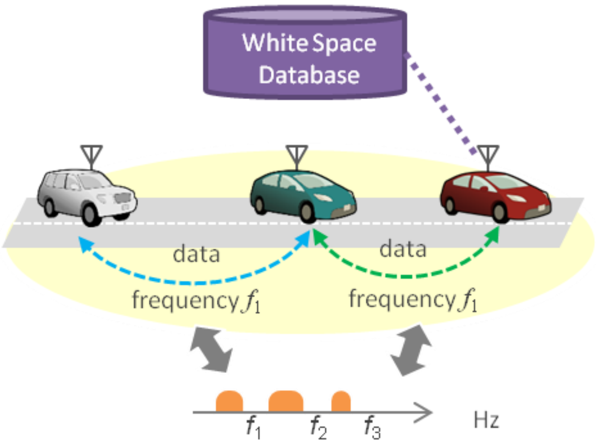

Figure 6. Outline of the field tests.

The tests involved three vehicles with a camera installed on the headrest of one of them as shown in Figure 7. An application that transferred real-time video images from the car with the camera to other vehicle(s) was implemented and used during the tests. Vehicles traveled at or below 40 km/h, the speed limit for the public roads in the experimentation area. Note that, while the camera is installed in only one of the cars, the sequence of the vehicles need not be as shown in Figure 7 as the location based routing scheme implemented in the middleware core uses a so-called georouting algorithm. In other words, depending on the position of the source and destination(s) of the application, the routing scheme builds and maintains a route that takes into account the actual coordinates of the vehicles. This scheme was also tested by changing the sequence of the vehicles without changing the source and destination of the application to confirm that the position of the source (car with video camera) triggers a makeover of the routing table in all cars.

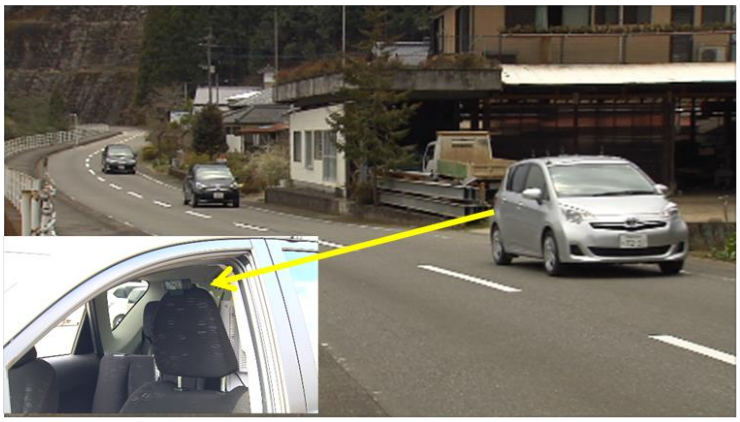

Figure 7. Field tests with a front-view camera installed in the lead car feeding real-time video images to others.

4.1 Throughput and Delay

We first measured the throughput of the system without the relay car in between the source and destination (i.e. single hop). The values vary depending on the distance between the cars, however the average is roughly 5 Mbps. When the relay car is introduced in between the source and destination (i.e. two hops) the average throughput drops to around 2 Mbps. This is a well known issue stemming from the shared media access of more than two nodes. Theoretically, end-to-end throughput can be maintained the same in multi-hop structures if each hop uses a different channel, however this requires extra hardware and/or other sophisticated schemes such as full-duplex radio. The throughput results for TCP and UDP, as well as the packet loss percentage and end-to-end delays are summarized in Table 2 for a packet size of 1470 bytes. The distance between the cars in the single hop measurements was around 140 meters, and was 185 meters in total with two hops.

	Throughput (TCP)	**Throughput (UDP)**	**Packet Loss (UDP)**	**End-to-end delay**
One hop	4.64 Mbps	6 Mbps	-	3.1 msec
Two hops	2.24 Mbps	2.7 Mbps	1%	7.2 msec

Table 2. Throughput, delay and packet loss performance results for single hop and two hops.

Figure 8 presents a snapshot of the display inside the rear car showing the near real-time video feed being received from the lead car. It is worth noting that the video codec delays in these tests were much more significant than the packet transmission delays (2 seconds versus 7 msecs). Figure 9 zooms into the user interface inside the rear car showing real-time operating parameters. Upper portion shows the data route active in between the cars, middle portion shows the spectrum sensing results, and the lower portion shows database query results coming from the proxy car overlaid onto the actual map of the test area. More will be said about sensing performance below.

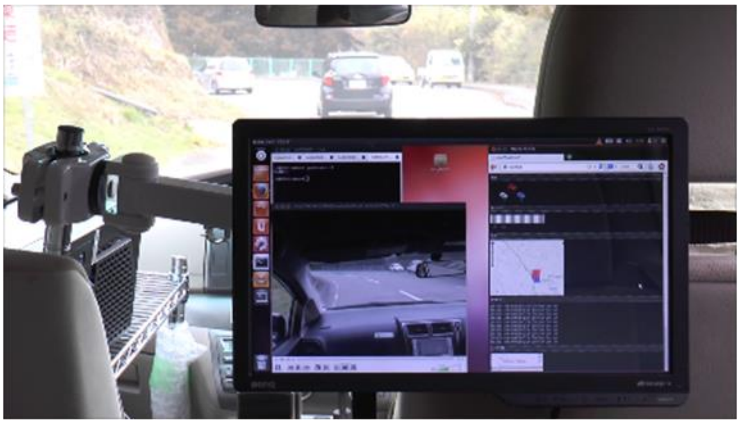

Figure 8. Snapshot of the view inside the rear car showing video feed from the lead car.

Figure 9. User interface inside the rear car showing routing, sensing and database overlay.

4.2 Incumbent Sensing

We implemented a cross-correlation method that looks into a single segment of the 13-segment Japanese digital terrestrial broadcast scheme (ISDB-T) to perform incumbent sensing. In ISDB-T, HDTV broadcast signal occupies 12 segments, and the remaining single 428 KHz segment is used for mobile terrestrial digital audio/video and data broadcasting (the so-called “1seg” service). Our sensing implementation was tuned to detect signals on this 1seg service band which sits in the center of the TV channel. Sensing capability of the TV band devices was -108dBm/430KHz (-111.3dBm/200kHz). Figure 10 presents results pertaining to detection probability of the 1seg signals. These results were obtained when the vehicles were stationary. For comparison, we provide spectrum analyzer screen shots of the corresponding channels in Figure 11. We also observed false alarm rates of 15%, 7% and 1% for channels 43, 44 and 46, respectively. The false alarm usually spreads to other channels too when the vehicles are not stationary.

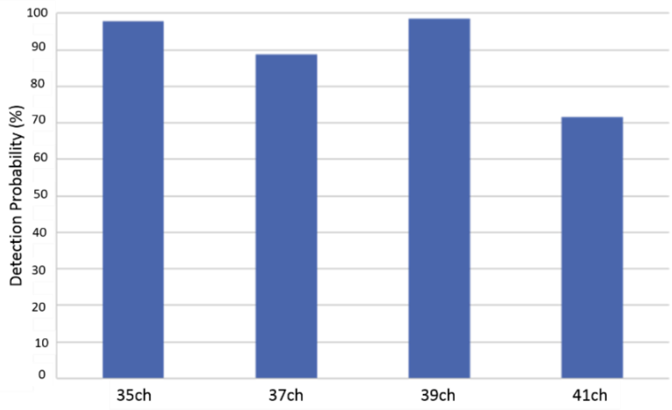

Figure 10. Incumbent detection probability for channels 35, 37, 39 and 41.

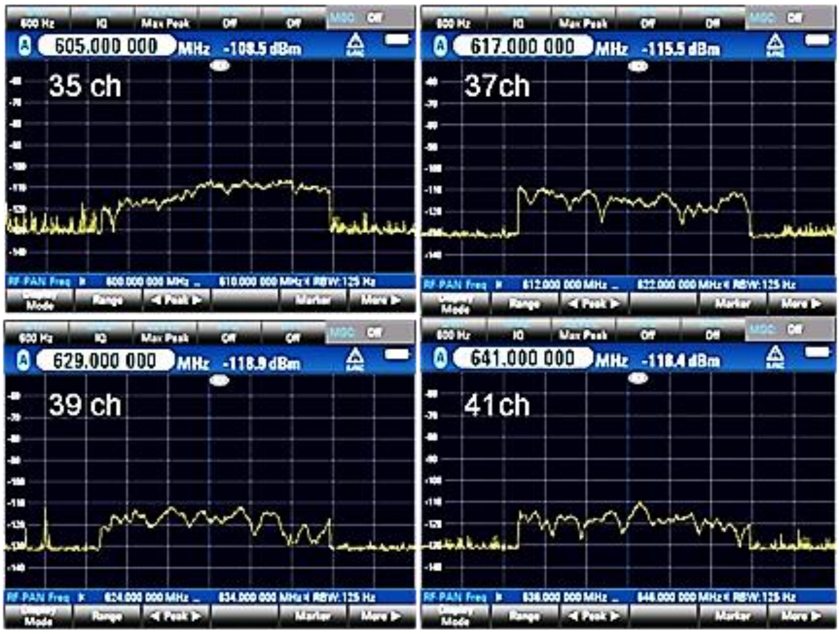

Figure 11. Spectrum analyzer screen captures of the corresponding channels in Figure 10.

4.3 Database Access Latency and Channel Switching Latencies

When accessed over 3G cellular, database access takes 9 seconds for cold start. This includes connection setup times. The same cold start access time over LTE is 0.3 seconds. For the subsequent queries, response time decreases to 0.4 seconds for 3G and to 0.12 seconds for LTE on average per query. As the vehicles traveled from an area with no incumbent signal on the borrowed channel, to another area with incumbent activity on that channel, they switched channels by negotiating over the group control channel (GCC). We measured the time to switch in between the channels. Vehicles traveled at approximately 40km/h and with 40-50 meters of separation during channel switchover tests. Switchovers were performed for the following patterns: Ch 14 → Ch 16, Ch 16ch → Ch 15, Ch 15 → Ch 16, Ch 16 → Ch 14. The time that the channel on the first hop change from a soon-to-be occupied channel to a vacant one, on the average, is 2.69 seconds and the time it takes for both hops change the channel is 2.70 seconds. Most of this delay comes from the radio to “settle” on a new channel.

4.4 Delay Jitter Evaluation

While average end-to-end delay time is a valuable performance metric, for most applications the analysis is incomplete without delay jitter evaluations. Here we present results of delay jitter analysis. As mentioned previously, end to end delay times are 3.1 and 7.2 msec for one-hop and two-hop scenarios, respectively. Jitter varies similarly for both topologies. Average jitter in single hop topology is 2.35 msec and that of two-hop topology is 5.88 msec. Corresponding distribution patterns of the jitter for one-hop and two-hop topologies are given in Figure 12 and Figure 13. Note the wider distribution with two humps in case of the multi-hop topology.

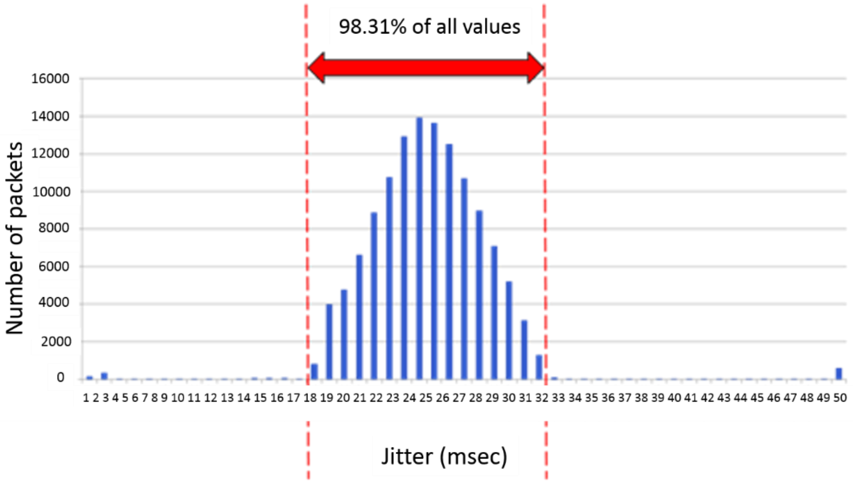

Figure 12. Jitter distribution for one-hop topology.

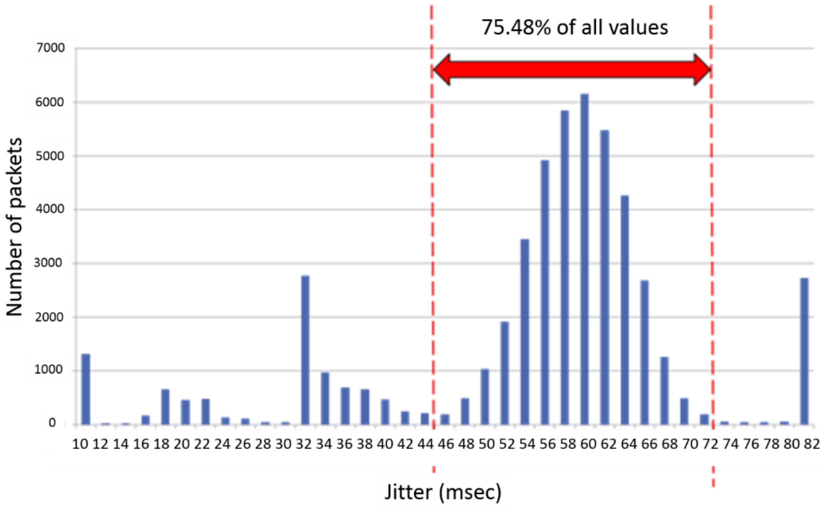

Figure 13. Jitter distribution for two-hop topology.

5. SUMMARY AND CONCLUSIONS

We have presented an architecture that makes use of a centralized TV white space database to determine the spectrum opportunities for V2V communications. We have also implemented a spectrum sensing subsystem which complements the database-oriented operation. We implemented and tested the system in the field by using licensed TV channels and presented results pertaining to throughput, sensing, channel switchover, database access latencies, end-to-end delays and jitter. Future work would look into scalability of the inter- and intra-swarm schemes with proxy elements distributing the database information.

ACKNOWLEDGEMENT

Part of this work was supported by the “FY2012 Revised Budget for Research and Development into Expanding Radio Wave Resources” of the Japanese Ministry of Internal Affairs and Communications.

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Responses to the Comments

Before anything, we apologize for the extreme delay in preparing the revised version.

Please find below our responses to the reviewers' comments followed by the revised version of the manuscript. Thank you and kind regards.

On behalf of the authors,

Onur Altintas, Ph.D.
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Reviewer #1 comments:

The paper deals with a V2V communication system operating on TV white space. The architecture, the procedure to access the database and the sensing operation are clearly described. The only aspect that is not particularly clear is the swarm formation. How a vehicle decide to join a swarm or another? When is created a new swarm? Maybe some additional explanations and references to procedures used in the literature should be added. Finally the "proxy" is selected depending on its Cartesian coordinates. It means that the area is pre-mapped and all the vehicles have the same reference points?

Authors' response:

Thank you for the comments. Although the swarm formation was not a central component of this work, we agree that it was not clearly described. We added the description of the general principles of formation and how they were adapted in the field experiments in Section 3.3. Also, your assumption regarding the coordinates being pre-mapped as well as being available to all vehicles is correct. We added this point as well to the manuscript to be more specific.

Reviewer #2 comments:

All aspects of the systems have been clearly described. Comprehensive results are presented. Figure captions and axis labels need to be redone. They are not clearly readable. This makes the paper unsuitable for publication in a Journal.

Authors’ response:

Thank you for the comments. We have revised the graph axis labels, and if needed we will provide better quality figures in the production stage.

Reviewer #3: The paper is very well written and presents its results in a comprehensible way.

Authors’ response: Thank you for the comments.