IMPLEMENTATION AND EVALUATION OF DISTRIBUTED CONTROL AND DATA CHANNEL COORDINATION ALGORITHMS FOR V2V DYNAMIC SPECTRUM ACCESS

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ABSTRACT

Dynamic spectrum access techniques are expected to play a vital role in future vehicular communications systems. In this paper we present a cyber-physical proof-of-concept lab implementation of our previously developed control and data channel assignment schemes for vehicle-to-vehicle communications. Specifically, vehicles coordinate data channels after agreeing on a virtual control channel on which they share relevant spectrum and position information. Both control channel(s) and data channels are determined in a distributed fashion. Our implementation is an integration of spectrum sensing and distributed channel coordination functions working on GNU Radio/USRP platform and simulation of primary user "appearances" both based on probabilistic event generation and on actual TV band white space measurements.

1. INTRODUCTION

Vehicular networking, typified by vehicle-to-vehicle (V2V), vehicle-to-roadside (V2R) and vehicle-to-infrastructure (V2I) communications, is envisioned to enable numerous applications involving vehicles, drivers, passengers, pedestrians, and traffic flow. These applications, in addition to improving road traffic efficiency, have significant potential to increase safety and convenience of transportation systems. Spectrum requirements of future vehicular networking applications are yet to be understood, however, one can expect that with the proliferation of new vehicular applications, spectrum scarcity may soon be a reality for vehicular networks. With this speculation, we advocate the use of dynamic spectrum access (DSA) techniques in vehicular networks, in addition to the already assigned spectrum bands for Intelligent Transportation Systems (ITS) applications. DSA techniques, or cognitive radio networks in a narrowly defined way, enable detecting spatial and temporal ”holes” in spectrum and allocating those unused portions of the spectrum to communicating entities dynamically on a secondary usage basis while ensuring that the rights of the incumbent license holders are respected.

In previous work [1], we developed a distributed and autonomous dynamic spectrum coordination method tailored for vehicular environments where two 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 changes. Vehicles in this method make use of each other's temporal and spatial proximity relationships to autonomously agree on channels. Moreover, in [1], we evaluated the coordination method via computer simulations by injecting probabilistic primary user “appearances” on a road segment. Furthermore, in [2], we investigated the spatial dependencies in selecting such an appropriate vacant channel for multi-hop V2V communications by taking into account several factors, such as the distance between the vehicles, channel bit rate, vehicle velocities and propagation distances of candidate channels. Again, we evaluated those methods by emulating primary users via independent exponential distributions. Also in previous work [3], we looked into the problem of detecting spatial and temporal spectrum holes, aka spectrum sensing, based on energy detection. In addition to the above, in [4], we reported quantitative and qualitative results obtained from a TV spectrum measurement campaign. We used those measurements to characterize vacant TV channels along a major interstate highway (I-90) in the state of Massachusetts, USA. Also in [4], by characterizing the availability of vacant TV channels in the 470-806 MHz frequency range, we showed the trends in the availability of vacant channels from a vehicular dynamic spectrum access perspective.

In this paper, we focus our attention on the cyber-physical proof-of-concept lab implementation of the method we proposed in [1] for distributed and autonomous coordination of control and data channels between vehicles. In the rest of the paper, we will first describe the channel coordination algorithm followed by the description of the lab prototype implementation using the GNU Radio [5] software radio platform with USRP (Universal Software Radio Peripheral) [6] hardware. Our implementation is an integration of spectrum sensing and distributed channel coordination functions working on GNU Radio/USRP platform with simulation/emulation of primary user "appearances" both based on probabilistic event generation and on actual TV white space measurements.

2. DISTRIBUTED AND AUTONOMOUS CONTROL AND DATA CHANNEL COORDINATION

Dynamic spectrum access for vehicular communications is expected to open up new frontiers as one can make use of the differences in characteristics of individual channels within a broad range of available radio frequencies. For example, the single-hop communication distance becomes longer as the frequency becomes lower if the same transmission power and modulation scheme are adopted. On the other hand, higher frequencies are suitable to realize higher bit-rate data transmission because relatively wider bands can be aggregated and used as a data channel. In a dynamic spectrum access inter-vehicle communications scenario, the control information will require a reliable, real-time, and sometimes longer-distance “connectivity” to be able to exchange small messages periodically. On the other hand, requirements for application data exchange vary widely. Safety-related applications will most likely need a real-time, continuous, but relatively low bit-rate pipe, while large file transfer applications will need a reliable, high bit-rate, but possibly non-real-time communications.

In our previous study [1], by considering those differences, we separated the control channel(s) for periodical reliable control information exchange and the data channel(s) for various types of application data exchange. More specifically, vehicles initially agree on the control channel from within a relatively narrow range of lower frequencies in a distributed and autonomous fashion, and later decide on the data channels by negotiation over the control channel so as to use frequencies suitable for the application requirements.

2.1. Control Channel Coordination

Hereinafter a single-hop communications scenario between two moving vehicles is considered. To communicate with each other, two nodes need to recognize a common channel to be used at the same time instance. However, in a dynamic spectrum access environment, spectrum sensing of the possible range of available frequencies might take a prohibitively long time if nodes try to simply coordinate a single channel from among a wide range of candidate frequencies. In order to promptly agree on the control channel between two nodes in a vehicular ad hoc network, we have proposed a distributed and autonomous scheme which makes use of the spatial and temporal proximity of two nodes.

We assume that each node is equipped with a Global Positioning System (GPS) receiver to periodically obtain the current time and location information. Each node uses this information to “infer” a short time slot and a small geographical area (referred to as a granule) it belongs to at that specific point in time. Nodes employ a common hash function that generates an index from the pair of the current time (time slot) and the current location (granule) information input. Each index corresponds to a (set of) channel(s) within a range of candidate control channels. Note that, since the control channels require relatively simple properties such as long-distance propagation and reliable information exchange, this possible range can be common and predefined within low frequency bands.

In this setting, when a node enters a new granule or a new time slot, the node selects one particular channel based on the index generated by the hash function, and obtains "the control channel candidate set" as n-successive channels staring from the selected channel (e.g., n=5). This is a small set of the channels implicitly shared by all nodes in the same granule at the same time slot. Subsequently, to find the currently available candidate channels and to avoid interference to the primary users, the node starts spectrum sensing periodically over this channel set. Since the number of channels in the control channel candidate set is limited, the sensing time can be reduced in order to achieve prompt channel coordination. A sender who wants to establish a control channel sends probe packets on each of the currently available candidate channels, while a receiver (passive) node “waits” for probe packets in a synchronized manner. If two nodes successfully exchange probe packets on one or more channels, the lowest frequency channel among them is eventually selected as the control channel between those nodes. If two nodes fail to communicate on all the candidate channels, another common hash function is used to obtain the next control channel candidate set.

Previous studies in the literature generally agree on separating the data plane and the control plane, however most of the work implicitly accept the idea of having a pre-defined, previously assigned control channel. Having a specifically assigned control channel definitely makes the coordination task easier, however, the assumption of having such a stable and constant channel might not be realistic in a vehicular scenarios, which triggered this study.

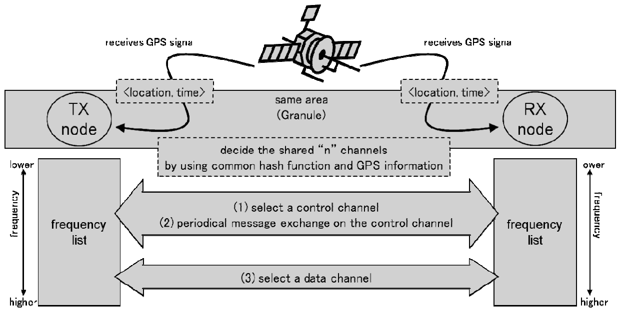

Fig.1. Distributed channel coordination scheme.

2.2. Data Channel Selection

In a vehicular ad hoc network with dynamic spectrum access, the availability of frequencies for data communications varies rapidly because of the movement of vehicles and the change in primary user activities. In selecting data channels for an application, therefore, both the channel environmental changes and the application requirements should be taken into consideration. This is more a complex task compared to the control channel coordination.

We have previously proposed a distributed scheme for data channel selection in [1, 2]. In our scheme, two nodes periodically exchange the current channel environmental information through the control channel established as defined above. Next, based on the exchanged information, "the data channel candidate set", that is, the available channels suitable for the application requirements, are determined. Among them, the scheme selects one or more channels for an application.

Note that, while the bit-rate and the communication distance of individual data channels vary in reality, we use constant values for the bit-rate and the communication distance in this prototype system due to limitations of the hardware.

3. LAB PROTOTYPE IMPLEMENTATION DETAILS

Here, we briefly explain the design and implementation details of our proposed schemes of control channel and data channel coordination introduced in the previous section.

3.1. Spectrum Sensing Implementation

One of the key techniques required in dynamic spectrum access is spectrum sensing for prompt detection of all currently available frequencies depending on time and location from among a very wide range of potentially available frequencies. Ideally, this should be performed in parallel with the communications (information transmission) because the availability of frequencies changes dynamically requiring that secondary "users" should release the frequency being used when a primary (incumbent) user appears on that frequency.

In case of multi-antenna systems, some antenna(s) can be dedicated for spectrum sensing. However, in case of a single-antenna system, both the communication function and the spectrum sensing function should be implemented in a time-division manner on a single antenna. In our prototype implementation reported here, we use multiple daughterboards (RF front-end) on GNU Radio/USRP. For this, we have developed a module to manage multiple daughterboards to realize a multi-antenna system. Our spectrum sensing implementation is based on energy detection with an implementation similar to the one we described in [3] previously.

3.2. Control Channel Coordination and Data Channel Selection Implementation

We divided distributed control channel coordination and data channel selection (described in sections 2.1 and 2.2) into 6 MODEs, as shown in Figure 2. In MODE1, the sender and the receiver share "n" channels as a result of calculation of common hash function in which the pair of location and time information obtained from GPS is used as the input key. After that, they exchange probe and probe-ACK packets sequentially on each of the "n" channels. If these messages are successfully exchanged, the channel is listed as a candidate control channel. Then, the channel with the lowest frequency band among all candidate channels is selected as the control channel and the system shifts into MODE2.

In MODE2, the sender and the receiver exchange a pair of <location, time> information and a list of available channels with each other over the selected control channel. If the message exchange succeeds, each node changes its own status to MODE3. Otherwise, they judge that a control channel is unavailable and shift to MODE6.

The nodes in MODE3 individually select a common data channel based on the information exchange in MODE2, and then establish a connection over the data channel. More specifically, in MODE2, the sender and the receiver share the information in terms of available channels, location, vehicle velocity, thereby selecting an appropriate data channel in a distributed manner. However, for simplicity, our implementation selects a channel with the highest channel number among all available channels, and probe/probe-ACK packets are exchanged on the selected channel. If this step is successful, the two nodes select the channel as a data channel and then change their states to MODE4. Otherwise, they exchange probe/probe-ACK packets over a channel with the second highest data rate (i.e. highest channel number in this implementation) again.

Afterward, the sender and the receiver periodically exchange information including a list of available channels, location, and vehicle velocity with each other over the control channel. Each node checks the status of control and data channels every time these messages are exchanged. If a disconnection of the control channel is detected, each node enters MODE6 and tries to establish a new control channel. On the other hand, when a disconnection of data channel is detected, they change their states to MODE3 and try to find a new data channel.

Note that although communication between the sender and the receiver may be interrupted due to the start of a primary user's communication, their detection timing is different from each other due to the spatiotemporal characteristic of primary user's activity. Therefore, when a node detects the disconnection of the data channel, it changes its own state to MODE5 and then informs the corresponding vehicle about the disconnection. After the notification, both nodes move to MODE 3 and then select another data channel again.

In contrast, if the selected control channel is interrupted by a primary user, vehicles choose another channel from among the candidate control channels, and try to reconnect on that channel. If all candidate control channels obtained at MODE1 become unavailable, they re-select the shared "n" channels based on subsequent GPS information, that is, the system re-starts the state transition from MODE1.

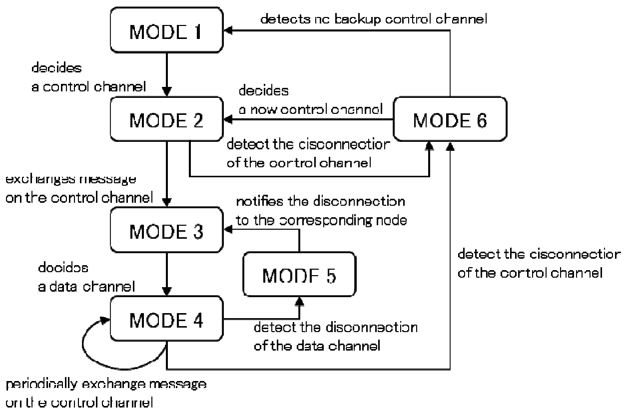

Fig.2 State transition in our implementation.

We developed several communication programs by referring to benchmark_tx.py and benchmark_rx.py, and tunnel.py, which are provided as sample codes for GNU Radio/USRP. More specifically, to decide the shared and continuous "n" channels, here we developed a "main_loop" function for providing a block of sending processes. The "main_loop" function determines the kind of information exchanged between the sender and the receiver according to the MODE status. For example, when the MODE status is 2 or 4, they exchange a file holding the information of available channels, location and velocity of vehicle. Furthermore, in MODE5, when the interruption of data channel is detected by one node, a specific string of characters is directly included into a packet (not a file format) and the packet is transmitted to the corresponding node. Otherwise, they periodically exchange probe/probe-ACK packets only, which do not include any payload (data).

Rx_callback function defines a block of receiving processes. In MODE 2 or 4, each node restores the received data strings to an original file and then utilizes the information included in a file to decide the next MODE of our system. In MODE 5, the corresponding node can detect the disconnection of data channel by extracting the specific characteristics through this function.

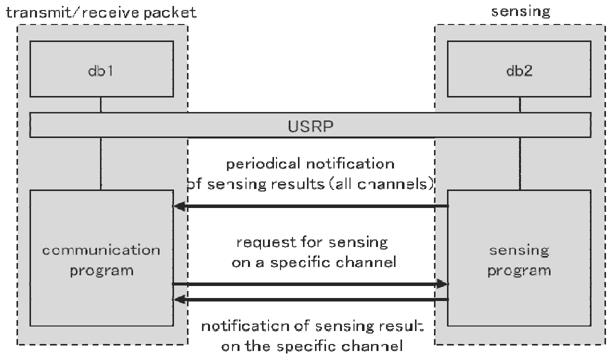

Fig.3. Relationship between communication and sensing programs.

3.3. Integration of Channel Sensing and Communication Functions

As shown in Figure 3, sensing program always performs sensing processes in parallel with the communication program, and periodically sends the sensing results of all channels to the communication program. Furthermore, to check the communication status of one specific channel from the view point of communication program, we developed an additional function in which the communication program asks the sensing program to check whether primary user exists or not. Note that the sensing program always checks the condition of all available channels one by one, thereby potentially causing a long sensing delay.

4. SYSTEM COMPONENTS AND EXPERIMENTAL ENVIRONMENT

Here, we implement our modules described in previous section into GNU Radio and conduct experiments by using the implementation. System components and experimental environment are described below.

4.1. System Components: USRP Motherboard and Daughterboards

We implemented our proposed schemes onto the GNU Radio platform as system modules. In the present paper, we employ RFX400 front-end that supports a half duplex communication in the range of 400MHz-500MHz, and XCVR2450 supporting half-duplex in the range of both 2.4GHz-2.5GHz and 4.9GHz-5.9GHz. Two sets of PC and USRPs with two daughterboards are employed in order to examine how the proposed scheme establishes control and data channels between neighboring two nodes. System components are illustrated in Figure 4. A USB cable is used to connect between PC and USRP, and two USRPs are connected by SMA-SMA cable (coaxial cable), which is used to emulate the wireless link between interfaces. Note that since there is no attenuation over the coaxial cable unlike real wireless link, an attenuator is inserted into coaxial cable to intentionally decrease the received signal strength (RSS) emulating a real wireless link. Moreover, two PCs are connected to a Network Time Protocol (NTP) server to achieve time synchronization between them.

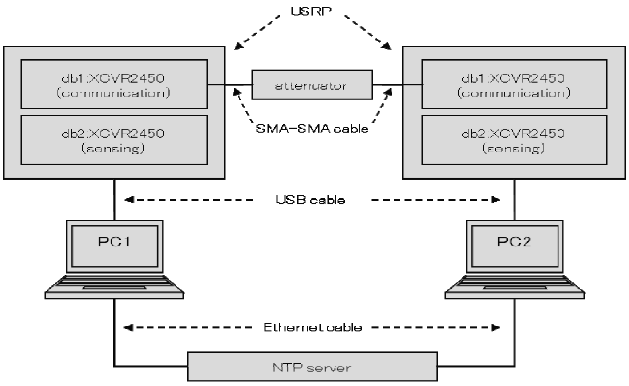

Fig.4. System components.

4.2. Experimental Environment

Hereinafter, to examine the effectiveness and validity of our implementation, we conduct two experiments: (1) performance evaluation of sensing capability in a real wireless environment and (2) evaluation of communication performance in a dynamic spectrum access environment emulated by using actual measurement results on TV channels. In the following two experiments, we assume that primary user starts communication on the data channel only (never appears on the control channel), and that data rates provided on each channel increase in proportion to channel ID. Moreover, the transmission power is fixed and velocities of the vehicles are stable at 40 Km/h. All experimental parameters used for the performance evaluation of sensing capability are listed in Table1.

Table 1. Experimental parameters (sensing capability)

Daughterboard	XCVR2450
Number of channels	100
Frequency range	2.400125GHz - 2.499125GHz (1MHz bandwidth)
Primary user signal	Randomly occurs on the data channel

Table 2 lists all experimental parameters used in the performance evaluation of communication using the results reported in [4], which investigated the TV channel vacancies along I-90 in the state of Massachusetts, USA. Note that, in these experiments, we set bandwidth of individual channels to 1MHz, which is different than the actual TV channel bandwidth (6MHz).

Table 2. Experimental parameters (communication performance)

Daughterboard	RFX400
Number of channels	5ch: assumption of 29-33ch in VHF band on TV channel
Frequency range	428MHz - 432MHz (1MHz bandwidth)
Control channel	29ch (fixed)
Measurement points	49.5mile - 81.6mile (away from Boston city)

5. EXPERIMENTAL RESULTS

First, we show the basic effectiveness (validity) of our implementation. In section 5.1, we examine the sensing capability of the implementation system in a real wireless environment. Then, in section 5.2, we use actual measurement data sets to represent primary users, and illustrate how the prototype system dynamically switches the communication channel in response to the change in the available communication channels. Note that since we assume that both vehicles move at the same velocity, channel switching due to change of distance between these nodes never occurs. Channel switching depending on the distance between the nodes is currently being implemented onto the present setup. Testing of this behavior will also require the emulation of velocity difference, as long as the current setup is tested in the lab.

5.1. Performance Evaluation of Primary User Detection

Using the experimental environment described in section 4.2 and the parameters in Table 1, we employ the following two performance measures for examining the sensing capability of our system.

1. Detection probability: Detection probability of primary user signal
2. Detection time: Time interval from the start of primary user's communication to its detection.

We run 50 experiments and examine the performance of our implementation system.

Table 3. Detection probability.

	Detection probability [%]
True detection	70
False detection	22
Un-detection	8

We classify the detection probability into three categories: true detection rate, false detection rate, and un-detection rate. Note that false detection indicates that primary user's signal is detected as a signal on a different channel, while un-detection means that primary user's signal cannot be detected at all. In Table 3, we demonstrate that our implementation system limits the true detection rate to 70%. Due to hardware limitations our implementation may end up with a false detection of 22%, thereby decreasing the detection probability.

Next, we investigate the average detection time of primary users signals in all success cases (35 experiments). In our system, each of two interfaces is devoted to sensing and communication, respectively, and the sensing interface scans all of 100 channels one by one. Therefore, we can suppose that the maximum detection time is equal to entire sensing delay of entire 100 channels, and the average detection time is half of the entire sensing delay due to random arrival of a primary user signal. Through experiments, we confirmed that the average detection time is 1.12 sec, which is approximately half the maximum sensing time (2.04 sec).

5.2 Evaluation of Communication Performance by Using Actual Measurement Results on TV Channels

Bu using the experimental environment described above and the parameters in Table 2, we examine how a data channel is switched in our implementation. Note that our implemented system selects a data channel with the highest data rate among all of available channels, i.e., the highest channel ID. Figure 5 shows the utilization condition on TV channel band at several points extracted from results in [4]. Black-colored boxes indicate the existence of primary user (TV broadcast) on the channel at this area, while white-colored boxes indicate an available channel. With consideration of our data selection policy, we can estimate an appropriate data channel in this environment beforehand. Boxes along an arrow represent the appropriate channel.

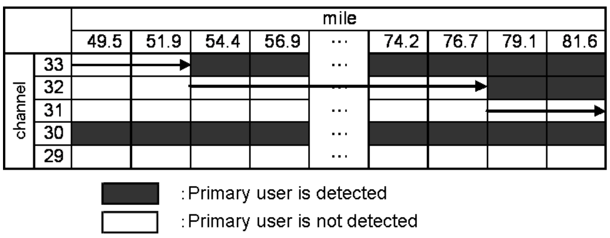

Fig.5 Measurement results of TV channels [4].

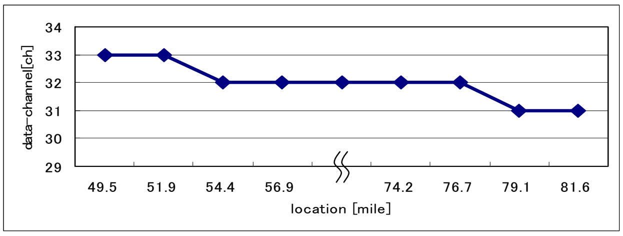

Fig.6 Change of the selected data channel.

Figure 6 illustrates how our implementation selects a data channel in response to the results in Figure 5. By comparing Figures 5 and 6, we show that the prototype can dynamically switch the data channel to an appropriate channel from among all of available channels. More specifically, our system operates on channel ID:33 until mile 51.9. After that, since the primary user's signal is detected at 54.4 mile point, our system changes the data channel to channel ID:32 appropriately. Similarly, the data channel is changed to channel ID:31 after the detection of primary user on channel ID:33 at 79.1 mile point.

In addition to the actual TV channel vacancy data, our prototype operates with simulated primary user appearances which assign an independent exponential distribution with arbitrary mean values to each channel. We used RFX2400 daughterboards for that set of experiments where we artificially divided the bandwidth into 100 channels. The primary user activity simulation on each channel is synchronized with the USRP operation to test the dynamic switching capability of the system. Our results showed that allowing a channel switch time of around 100msec for the daugtherboards will comfortably handle the rather unrealistically harsh primary user appearances emulated by the exponentially distributed activity.

6. SUMMARY AND CONCLUSIONS

In this paper, we presented a cyber-physical proof-of-concept lab implementation of the method we proposed previously for distributed and autonomous coordination of control and data channels between vehicles. We described a lab prototype implementation using the GNU Radio/USRP platform. Our implementation is an integration of spectrum sensing and distributed channel coordination functions working with simulation/emulation of primary user "appearances" both based on probabilistic event generation and on actual TV white space measurements. Current hardware limitations force our implementation to work either with "recorded/emulated" primary user activity to illustrate the control channel coordination followed by data channel selection; or to work with a constant virtual control channel to illustrate the sensing functionality with data channel switching. An ideal implementation would consist of three "daughterboards", i.e. a full-time dedicated spectrum sensing module, and two full-duplex RF frontends, one for the control channel and one for the data channel. Currently, this system is being transported onto USRP2 where we expect to add the three simultaneous RF front-end functionality by integrating three USRP2 modules as a single node. Furthermore, we intend to repeat these tests in the field by using vehicles and radio waves (instead of SMA cables) over vacant TV channels in a rather isolated geographical area in Japan. This will require a couple of regulatory permissions which we are presently working towards.

7. REFERENCES

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