Accessing Spectrum Databases Using Interference Alignment in Vehicular Cognitive Radio Networks

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***Abstract*—Cognitive radio (CR) vehicular networks are poised to opportunistically use the licensed spectrum for high-bandwidth intervehicular messaging, driver-assist functions, and passenger entertainment services. Recent rulings that mandate the use of spectrum databases have introduced additional challenges in this highly mobile environment, where the CR-enabled vehicles must update their spectrum data frequently and complete the data transfers with roadside base stations (BSs) in very short interaction times. This paper aims to answer two fundamental questions: 1) when to undertake local spectrum sensing, as opposed to accessing spectrum database information at a finite cost overhead; and 2) how to ensure correct packet receptions among the multiple BSs and CR vehicles using fewer slots than the messages that need to be transmitted. The contributions of this paper are twofold: First, we introduce a method of qualifying the correctness of spectrum sensing results using out-of-band 2G spectrum data using experimental results. Second, to the best of our knowledge, this is the first work on applying the concept of interference alignment (IA) in a practical network setting, leading to dramatic reduction in message transmission times. Our approach demonstrates significant reductions in the overhead of direct database queries and improvement in the accuracy of spectrum sensing for mobile vehicles.**

***Index Terms*—Cognitive radio (CR), correlation, interference alignment (IA), spectrum database.**

I. Introduction

The landmark Federal Communications Commission ruling in November 2011 in the USA mandated the use of spectrum databases, with rules of access for stationary and mobile cognitive radio (CR) nodes [1], as well as the consideration of specific capabilities such as geolocation [2]. These databases release information on the spectrum usage in the vicinity of the requesting node, which must be periodically refreshed to maintain updated information. However, the FCC also allows for local spectrum sensing, although such unassisted and unilateral sensing by a node must adhere to strict performance metrics. Identifying spatial regions or duration periods in which 1) the local sensing is likely to yield reliable and repeatable results (i.e., less random fluctuations on the signal imposed by the channel) and when 2) accessing spectrum databases is a must remains an open challenge.

In CR vehicular networks, where high-bandwidth communication is required by fast-moving nodes, the exchange of spectrum information must be undertaken in the shortest possible extent of time [3]. This allows the spectrum knowledge to remain current and relevant to the specific location of the vehicle. Moreover, given the large number of vehicles that traverses the road, this reduces the channel usage time per vehicle. Thus, the wireless spectrum is more efficiently utilized even during the spectrum querying process, mitigating the risk of congesting the channel used to disseminate the spectrum queries.

The work described in this paper is focused on answering the following two questions: How and when must a node rely on spectrum databases versus relying on self-generated measurements? When spectrum database query is the only solution, how do we ensure that the exchange of a large amount of information and control feedback between the neighboring base stations (BSs) and the querying nodes is accomplished in minimum possible time? To address these concerns, we make the following contributions in this paper.

A. Exploring Signal Correlation Between 2G and TV Channels

Signals from transmitters that are located in nearby areas are likely to experience a strong similarity in coarse channel behavior, owing to the common set of reflection, absorption-causing objects, and the large-scale path loss. We explore an interesting concept through an experimental study, where we establish that at certain locations, the behavior of the received signal strength in cellular channels can be used to predict the accuracy of spectrum sensing for certain channels in the TV whitespace (WS). In some cases, the TV transmitter and one or more cellular transmitters (operating on totally different bands) are located near each other, and when the signals from these two are received at a common location, we detect a strong correlation in the received signal strength indicator (RSSI). Thus, any sudden change in the TV spectrum usage in such locations can be verified by comparing with the corresponding fluctuations in the cellular channels. This provides an additional layer of check and reduces misdetection and false alarm. Of course, such a close correlation occurs only for limited duration periods and

Manuscript received January 7, 2014; revised March 20, 2014; accepted April 9, 2014. Date of publication April 22, 2014; date of current version January 13, 2015. The work of A. K. Al-Ali was supported by Qatar University under a Ph.D. scholarship fund. This work was supported in part by the U.S. National Science Foundation under Research Grant CNS-1265166 and the Office of Naval Research under grant number N000141410192.

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Digital Object Identifier 10.1109/TVT.2014.2318837

at specific locations (based on the relative distances and the presence of these two different transmitter types), but it can potentially offset costly spectrum database queries at these times.

B. Practical Demonstration of IA

The method of *interference alignment (IA)* allows separation of the useful signals and the interference signals arriving at a node into orthogonal planes. Recent work presented nonintuitive results for a case of two transmitters and two receivers, each of which is enabled with two antenna modes [4]. This allows four messages to be transmitted in three time slots. We further enhance this scenario with three concurrent transmitters and extend the basic formulations for a full-duplex case with simultaneous transmission and reception. To the best of our knowledge, we make the first scenario-specific use of the emerging technique of IA.

The rest of this paper is organized as follows. We describe the related work and provide background information on FCC database ruling in Section II. Section III presents the network architecture and overview of the approach, followed by experimental findings that motivate our work in Section IV. The database querying strategy exploiting the correlation among TV WS and 2G spectrum, as well as the IA setup for efficient channel access, is given in Section V. We undertake comprehensive performance evaluation in Section VI, and finally, we conclude in Section VII.

II. Related Work and Background

A. CRs and Vehicular Networks

In [5], the authors devise a spectrum sensing framework for CR-enabled vehicles. These vehicles send their data to a roadside BS, which, in turn, forwards it to a processing unit (PU). The PU then infers which channels the vehicles are allowed to use based on the aggregate sensing information and finally broadcasts this information to vehicles passing by the BS. Belief propagation techniques are used in [6], where vehicles combine different observations from surrounding vehicles, and spatial correlation is used to decide on channel availability. In [7], a framework for coordinated spectrum sensing method is proposed in the absence of any roadside BS. Instead, some vehicles are temporarily assigned the role of a "master" vehicle that coordinates the sensing and schedules the transmission activity of surrounding vehicles. In [8], a cooperative sensing framework called *Cog-V2V* is devised, where each node aggregates information it receives from surrounding vehicles to determine which channel to use in the current and future locations alongside the vehicles' path. In [9], a major interstate freeway in the State of Massachusetts (I-90 Interstate) is studied for free spectrum availability along its length. The authors argue for a use of a centralized database that vehicles can use to access the free spectrum information. An algorithm is also proposed on how to reliably populate such a database based on the sensing measurements. A vehicular cloud computing paradigm is explored in [10], where vehicles produce and consume content with a spatial and temporal locality, and the types of requests and responses drive the routing decisions. In [11], the benefits of a BS-assisted vehicular network over completely distributed scenarios are shown.

This paper reconciles the previous approaches not only by using the BS support when needed but by relying on local coordination to enhance spectrum sensing accuracy as well.

B. IA and Full-Duplex Wireless Communication

While the concept of IA emerged in the seminal work in [12], it has seen limited explorations in the networking domain. In [13], the authors improve on classical IA through a technique called *blind IA*, where no channel state information is required. This is in contrast to previous works where a use of offline calculations or a backchannel connection (e.g., Ethernet) is used to exchange information among participating nodes [14].

In [4], the first real-time implementation of blind IA based on a 2×2 model, which becomes the starting point of our investigation, is presented. In [15] wireless systems operating in full-duplex mode, where transmitters and receivers work concurrently using antenna separation and interference cancelation techniques, are demonstrated.

Different from the previous paper, this paper aims at sharing spectrum sensing correlation results between two different TV and cellular channels among nodes to *improve the accuracy* of local sensing. This is in contrast to previous works where nodes cooperate to *choose* a certain channel for communication. We also offer, to the best of our knowledge, the first practical scenario-specific usage of IA in combination with full-duplex technology. This combination allows for an accurate, cost-effective, and efficient utilization of TV WS channels using both database management and local sensing.

C. FCC Database Management

The FCC recently authorized three types of devices to access available TV spectrum for communication. *Fixed* devices are required to register with a database and retrieve 48 h of spectrum availability information. *Mode I*: Devices operating in this mode do not have any geolocation capabilities. They are required to query Mode II or fixed devices to obtain spectrum information at least once every 60 s. *Mode II*: These devices are equipped with geolocation capabilities such as a GPS device. They are required to obtain spectrum information from one of the approved FCC databases once every 24 h if stationary, or if either condition holds true: 1) They moved more than 100 m since the last query, or 2) 60 s elapsed since the last update. Finally, sensing only devices may sense and utilize channels that they perceive as unoccupied, once approved for use by the FCC. They may not, however, share this spectrum information with any other device.

On January 26, 2011, the FCC approved nine applicants as TV bands database administrators. These applicants are Frequency Finder Inc., Google Inc., KB Enterprises LLC and LS Telcom, Key Bridge Global LLC, Neustar Inc., Spectrum Bridge Inc., Telcordia Technologies, and WSdb LLC. Later that year, on July 29, 2011, the FCC approved Microsoft Corporation as the tenth administrator.

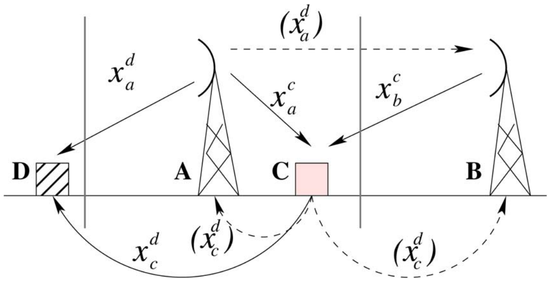


Fig. 1. Network architecture with two BSs A and B that have spectrum database access, and two vehicles C and D moving from left to right in a horizontal plane. The dotted lines indicate an overheard message.

III. Network Architecture and Overview

The overall network architecture is shown in Fig. 1. A and B are two fixed BSs that have access to the spectrum database. Each BS can only provide reliable readings in a limited extent of space, as shown by the boundary lines separating them. Each query to the database incurs a finite cost, i.e., both monetary and in protocol overhead. CR-enabled vehicles move along a straight line path from left to right, and two such nodes are indicated by C and D.

- *New incoming vehicle* D: Node D enters a new region serviced by A. At this junction, BS A sends message x_a^d, which includes BS A's ID, coordinates, and transmission power. Node D becomes aware of this BS and may use it for future database querying requests. This beacon message x_a^d is also overheard by BS B (more on this in the next section).
- *Fixed BSs* A *and* B: BS A sends its beacon information to $D(x_a^d)$, which D may use to query for the upcoming journey through the region served by A. x_a^d includes A's ID, coordinates, and transmission power, which is also overheard by BS B. This information can be used, for example, so that the BSs minimize the overlap region of their coverage area by dynamically adapting and coordinating their transmission power. As per the FCC ruling, a mobile node operating in *Mode II* must request a new set of spectrum availability readings after moving 100 m from its initial query point, or within a minute, whichever occurs earlier. Thus, a vehicle that has moved further into A's territory (as shown by vehicle C) beyond the first 100 m must re-obtain the spectrum usage information. Vehicle C sends a preamble to synchronize the BSs in range and to request spectrum availability information. BS A sends this information (x_a^c), which contains spectrum information for the remainder of the journey in A's region. At the same time, BS B, which is synchronized on hearing the message preamble from C, provides the spectrum usage (x_b^c) to vehicle C, as it is likely to enter B's new service area next.
- *Vehicle* C *within BS* A *'s service region*: The decisions taken by vehicle C and the subsequent messaging that follows form the core contribution of our work. C first determines if there exists correlation among the 2G spectrum and TV WS using experimental data (see Section IV) and, if so, sends out a broadcast (x_c^d) mainly intended for the incoming vehicle D. A high degree of correlation implies that the cellular channel can be a reliable metric to quantify the likelihood of sensing errors. This message (x_c^d) is also overheard by both BSs A and B. This overheard message indicates which channels are correlated and therefore can be used for future spectrum query replies. For example, a BS can prioritize the usage of vacant channels that it knows vehicles on the road are not using (due to the absence of any overheard correlation information by the BS). In turn, when D reaches the location currently occupied by C, it undertakes local spectrum sensing using the cellular and TV signal correlation (see Section V-A). If vehicle C's measurements indicate that a spectrum update is necessary, then it issues a preamble similarly to vehicle C previously and both the BSs send the updated query information to vehicle D. The IA approach (see Section V-C) ensures that all the message exchanges involving vehicle C and the BSs are completed in fewer slots that the number of messages.

This cycle repeats as vehicles move in a straight line path, ensuring reduced spectrum update overhead and improved local sensing capability.

IV. Experimental Study of Correlation Between 2G and TV Channels

To study the correlation between the RSSI in the cellular 2G frequencies and the TV channels, we gathered a comprehensive set of measurements in the city of Boston over the span of one month.

A. Experimental Setup

We used two devices to collect data simultaneously. A universal software radio platform (USRP) was used to sense digital TV channels 21–51 [16], and an Android Samsung Galaxy S3 smartphone was used to gather the following information: 1) RSSI values of nearby 2G cellular towers; 2) current GPS coordinates; and 3) the true TV spectrum availability queried at 60-s intervals. We used Spectrum Bridge [17] by writing an Android application that directly accessed their proprietary application programming interfaces (APIs) to return the available/occupied channels and the signal strengths in the area of study. These devices were placed in a car, and the actual path traversed is shown in Fig. 2(a). The path progresses along a counterclockwise direction, starting and ending at Northeastern University campus (at the bottom).

B. Methodology and Observations

The RSSI samples gathered by the moving car were stored and analyzed offline to detect whether a level of spectrum cross-correlation exists in any 40–220-s moving window among the 2G spectrum and the TV channels. The points in Fig. 2(a) show the locations where the spectrum correlations were between 85% and 95%. Understandably, these correlations were detected at low-building-density areas: a) bridges, b) suburban low-building-density areas; or c) in broad street intersections,

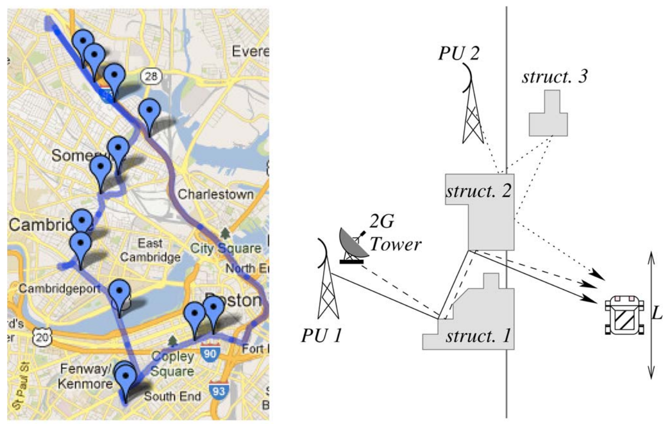


Fig. 2. Traversed path in our measurement experiment with markers indicating locations of (a) high RSSI correlation between TV channels and 2G spectrum and (b) explanation for the correlation.

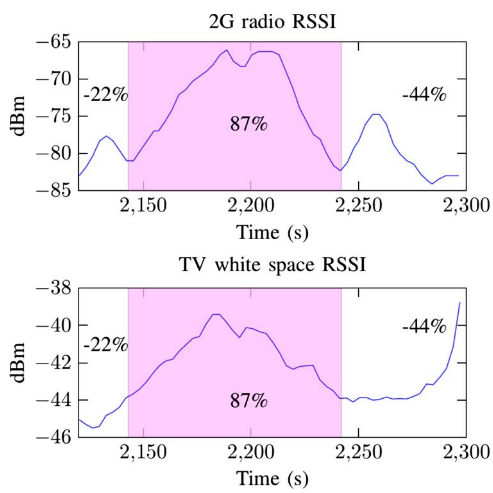


Fig. 3. Spectrum correlation between one TV channel band and one 2G radio tower RSSI values.

where the random multipath effects resulting from the neighboring structures were comparatively small.

In Fig. 2(b), we see that, as the vehicle moves along a direction from the bottom to the top, there are specific regions for which the TV transmitters (or PUs) in certain channels and the 2G spectrum towers are nearby, and their respective signals follow a somewhat similar propagation path. This scenario exists for PU1 and the 2G tower. At this time, the signal from PU2, on a different TV channel, encounters an altogether different multipath environment. Thus, the signal fluctuations between 2G and PU1 towers are likely to be correlated in a small window of the traversal path, as shown by L and totally uncorrelated at other times when the structural neighborhood changes. Thus, on observing sudden changes in the subset of highly correlated TV channels and matching these changes with the channel behavior of the 2G spectrum, the CR vehicle can identify if these are caused by multipath effects or due to PU activity.

Fig. 3 shows a randomly selected location point with two RSSI measurements plotted against time, i.e., one from a 2G cellular tower and the other from channel number 46 in the TV band, with intervals where strong correlation exists. The upper plot is for measurements through the Android phone (i.e., measuring signals in the 2G spectrum), and the bottom plot is from the USRP (i.e., in the TV channel). A moving average filter with a set span 11 was applied to both RSSI values for smoothening before calculating the correlation. The correlation is obtained using the $crosscorr$ function, which is explained by

$$(f \star g)[n] = \sum_{m=-\infty}^{\infty} f^*[m] g[n+m]. \tag{1}$$

In this equation, f^* denotes the complex conjugate of f, and n is the lag of one set relative to the other. We use a default lag of $n = 20$ (i.e., from -10 to 10) and evaluate $\max(f \star g)$ as our maximum spectrum correlation value. We see in Fig. 3 that the shaded time interval has 87% correlation, whereas intervals immediately next to this segment are highly uncorrelated: The spectrum correlation yielded -22% and -44% for these time duration periods before and after the shaded region, respectively.

C. *Motivation for Proposed Research*

In our proposed method, for certain locations and TV channels for which a strong correlation exists with the 2G spectrum, the CR vehicle may not require additional spectrum database updates to infer PU activity in these specific TV channels. Instead, it may rely on local spectrum sensing alone; as for these channels, it can track and attribute the cause of rapid signal fluctuations, thereby lowering the chance of false alarm and missed detection.

A vehicle that already has access to 2G RSSI values (effectively operating in *Mode II*) may be able to query the spectrum database directly without the need of a roadside BS or to perform local sensing. However, this is not always possible or optimal due to multiple factors.

1) Incursion by each vehicle is also reduced (e.g., when roaming). Moreover, a phone's service provider represents only a subset of the total RSSI values obtained, whereas a significant portion of the measurement data is gathered from towers that the phone cannot legitimately connect to (i.e., different High Speed Packet Access mobile carriers). 2) Having access to roadside BSs or local sensing, as opposed to querying the database directly, will save in the total overhead over the Internet given that a BS needs to query the database once every 24-h period. The BS can then mediate and share that information with passing vehicles saving on total traffic directed to the centralized database. 3) The latency to retrieve such spectrum information is reduced because the BS is much closer to the vehicles than an online database. 4) Given that the information is retrieved from the BS that queries the database once and then shares it at a fraction of a cost, the total cost per query incurred by each vehicle is also reduced.

V. Optimal Database Querying Strategy

Using the network architecture described in Fig. 1, we discuss here how a node decides whether spectrum database or local sensing needs to be undertaken, how to improve the local

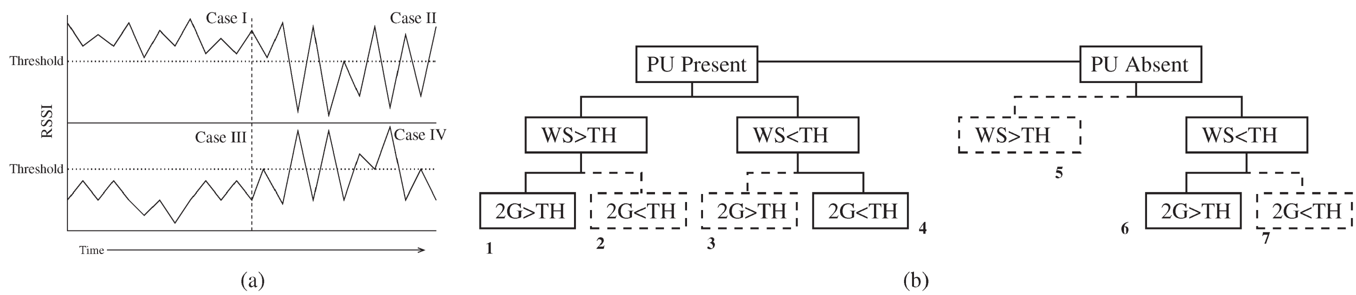


Fig. 4. (a) Four different types of RSSI readings performed by sensing. (b) Decision tree of the CR node. Solid lines indicate possible scenarios, whereas the dotted lines indicate impossible scenarios.

sensing capability, and how to undertake message transfers with reduced control overhead.

A. Exploiting Correlation Between 2G and TV WS

Node C collects the RSSI values of the 2G and WS towers' spectrum and analyzes it to determine if a high correlation exists between any pair of TV channels with those in the 2G band. We describe the four cases below that demonstrate the types of readings that C may obtain at any given point. The four cases are shown in Fig. 4(a).

- *Case I* occurs when the average RSSI values surpass a predecided sensing threshold λ [18].
- *Case II* occurs when the average RSSI drops below that threshold due to significant fading.
- *Case III* represents very low RSSI readings (well below threshold), which is the case for vacant channels.
- *Case IV* occurs when the average RSSI value is above the threshold, but the channel is really vacant. Case IV, however, can be minimized because contrary to current detection schemes that have a probability of false alarm rate due to uncertain noise power knowledge [18]–[20], in our proposed architecture, nodes can have perfect noise power knowledge by studying the RSSI values of channels that are indicated to be vacant by the database and setting the threshold to a value above the highest observed noise floor of the RSSI value. After minimizing the probability of false alarm in *Case IV*, vehicle C makes a decision based on which of the remaining three cases of RSSI readings it is currently observing.

Vehicle C uses the observed RSSI values (in the 2G spectrum and the TV WS), as well as the energy detection-based sensing threshold λ to infer whether a PU exists or not or whether the correlation information leads to indeterministic results. We use Fig. 4(b) to explain the possible scenarios using the decision pathways indicated by numbers at the endpoints in the figure. The following numerical list corresponds to these numbers. Note that this decision logic is used *after* correlation is detected by C between the 2G and the TV WS RSSI signals. The dotted lines indicate a state that is not feasible, whereas the solid pathways indicate a possible scenario.

1) WS RSSI $> \lambda$ *and* 2G RSSI $> \lambda$: This indicates that the PU is currently occupying the channel because a correlation exists, and both RSSI values are above the threshold λ.
2) WS RSSI $> \lambda$ *and* 2G RSSI $< \lambda$: This scenario is not feasible because the 2G towers do not have an on and off time and should remain constantly on at this location. Therefore, if a correlation existed between this pair previously, this scenario is not possible. If the 2G network is not present, then we expect the WS channel to also be vacant due to their previous correlation, but this is not the case. The node must query the database if it wishes to use this WS channel.
3) WS RSSI $< \lambda$ *and* 2G RSSI $> \lambda$: This scenario indicates that a PU is not present; the two signals were previously correlated (and correlation only happens when both channels are not vacant). If the 2G signal is still occupied while the WS signal is not, then this indicates that the PU is not present and the node may use this channel to transmit data. These two channels have a high correlation; therefore, if fading, shadowing, or multipath effects exist, it will affect both of the channels and not just one of them. This is not a possible scenario if the PU is present.
4) WS RSSI $< \lambda$ *and* 2G RSSI $< \lambda$: This is a possible scenario if the PU is present. The two correlated channels are below the threshold λ, which indicates a possible fading/shadowing/multipath effect that is affecting both channels. The read RSSI values are below the threshold, but we know from previous correlation that the two channels exhibit the same effects.
5) WS RSSI $> \lambda$: From our experiment results, if WS RSSI values are above the threshold λ, then this indicates that the PU is present. Therefore, this is not a possible scenario.
6) WS RSSI $< \lambda$ *and* 2G RSSI $> \lambda$: This is a possible scenario; see (3).
7) WS RSSI $< \lambda$ *and* 2G RSSI $< \lambda$: This is not a possible scenario because if the two channels are correlated, which indicates that they were previously both above the threshold λ, then the absence of the 2G RSSI network indicates the presence of channel effects (fading/shadowing/multipath) that is exhibited on both channels, and therefore, the PU is still occupying the channel.

B. Database Query or Local Sensing Decision

Here, we explain the querying process for a snapshot of the vehicles currently in the network and show in Fig. 1. We show how database querying is accomplished by vehicle C, resulting in low traffic on the channel. We then extend the discussion for

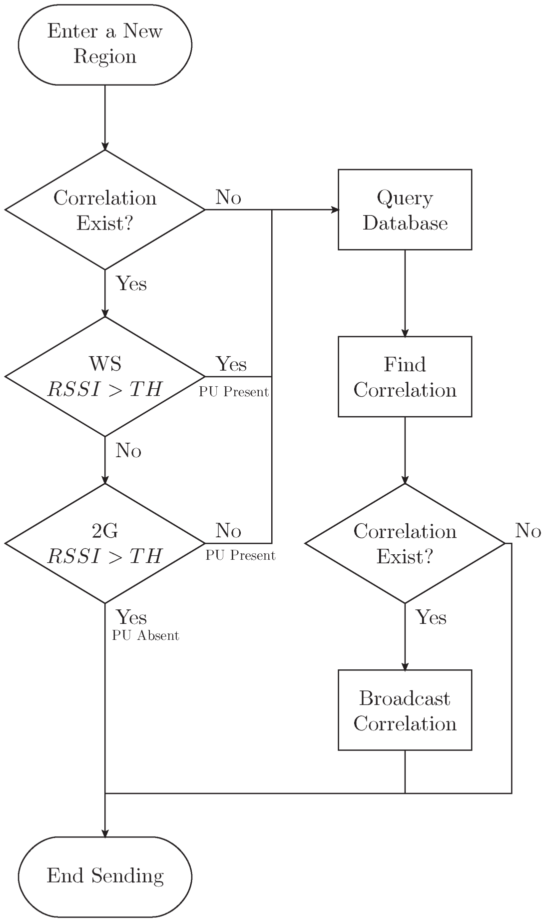


Fig. 5. Sensing versus querying decision flowchart.

vehicle D and then, finally, for any other general vehicle along the road.

- *Case for Vehicle C*: In this case, vehicle C follows the steps outlined in Fig. 5 to determine if it is able to come to a conclusion about the PU activity using the correlation and RSSI measurements. As vehicle C enters a new region, it checks to see if there is any prior knowledge of correlation between TV WS and 2G spectrum at its present location. If *no* (the decision flow moves along the right arm of the flowchart), it issues a spectrum query to the nearest BS. At this stage, it is in a position to measure the signal correlation itself and inform other vehicles in the downstream chain. If a spectrum correlation is found, it broadcasts that information to these vehicles, including node D. If no correlation is detected, it simply uses spectrum information from the database and concludes the algorithm. Note that the Query Database and the Find Correlation blocks can happen simultaneously; this key fact will be used in the subsequent section when querying the database and transmitting to the downstream vehicle happens simultaneously via *IA*.
- *Case for Vehicle D*: We describe this case for vehicle D using the left arm traversal of the decision logic in Fig. 5. We assume that it received prior confirmation of spectrum correlation at its present location (for example, by vehicle C). It then uses the reasoning described in Section V-A to determine PU presence. First, it checks if the TV WS RSSI readings are below the threshold. If so, it checks whether the 2G RSSI readings are also below the threshold. If both conditions are true, then it concludes that the PU is present. It arrives at this somewhat nonintuitive result as 1) the prior vehicle verified correlation exists; 2) the 2G spectrum has beacon signals that are always present at set intervals in time; and 3) it does not detect the 2G beacons, possibly lost due to multipath and fading, which indicates similar trends in the TV WS. On the other hand, if the 2G RSSI values are above the threshold, then [see path 6 in Fig. 4(b)] we determine that the PU is absent, and D may use that channel for data communication.

If, however, the WS RSSI is above the threshold λ, which indicates the presence of the PU, vehicle D completes the algorithm by moving to the right arm of the decision flow, i.e., it issues a query to the database. The rest of the steps follow exactly the procedure for vehicle C previously described.

The description of the steps for this network snapshot is applicable for any vehicle in the network. The overall actions of the vehicles along the entire length of the road allow each vehicle to extrapolate correlation information and, hence, serve as the source of spectrum correlation information for the remaining downstream vehicles.

C. Spectrum Updates Using IA

The overall aim of the database access phase, when it occurs, is to allow all the transmissions and packet exchanges to be completed in exactly three time slots. This results in remarkable efficiency of the channel usage. The modification to the classical IA scheme that is leveraged for this purpose is described next.

IA places the interfering signals along vectors oriented orthogonal to those of the useful signal [12]. It achieves this by allowing the receiver to switch antenna modes according to a preset pattern. The antenna mode can be altered by changing the antenna response parameters, reducing the height, or as we suggest in our case, simply use antenna 1 or 2, when the receiver needs to be in mode 1 or 2, respectively. Thus, IA demonstrates much improved resilience to signal losses by not attempting to cancel or limit the interference level at its location, which requires extensive transmitter side information.

Our extension to the 2×2 blind model of IA proposed in [4] is based on two important considerations. First, we use a full-duplex radio that can simultaneously transmit and receive, although it has only one transmitter and receive chain, respectively. Off-the-shelf USRP radios can be adapted to support this full-duplex operation [15]. Second, we depart from the traditional model of a cleanly separated set of transmitters and receivers. Instead, in our case, one of the receivers (i.e., vehicle C) switches its role into a transmitter to send a message to the second receiver (i.e., the downstream vehicle D). The individual alignment equations based on the received packets are described next for each node (see Tables I–IV), and the channel gains for the unidirectional transmissions are shown in Fig. 6.

1) Transmitter/Receiver-Vehicle C (Table I): CR Vehicle C changes its mode in the pattern 1–2–1, as indicated by switching

TABLE I
IA EQUATIONS FOR NODE C

Antenna Rx	Antenna Tx	Node C
1		$z^{[c]}(1) = (x_a^c + x_a^d)h_{ac}^{11} + (x_b^c)h_{bc}^{11}$
2		$z^{[c]}(2) = (x_a^c)h_{ac}^{12} + (x_b^c)h_{bc}^{12}$
1	2	$z^{[c]}(3) = (x_a^d)h_{ac}^{11}$

TABLE II
IA EQUATIONS FOR NODE D

Antenna Rx	Antenna Tx	Node D
1		$z^{[d]}(1) = (x_a^c + x_a^d)h_{ad}^{11} + (x_b^c)h_{bd}^{11}$
1		$z^{[d]}(2) = (x_a^c)h_{ad}^{11} + (x_b^c)h_{bd}^{11}$
2		$z^{[d]}(3) = (x_a^d)h_{ad}^{12} + (x_c^d)h_{cd}^{22}$

TABLE III
IA EQUATIONS FOR NODE A

Antenna Rx	Antenna Tx	Node A
2	1	$z^{[a]}(1) = (x_b^c)h_{ba}^{12}$
2	1	$z^{[a]}(2) = (x_b^c)h_{ba}^{12}$
2	1	$z^{[a]}(3) = (x_c^d)h_{ca}^{22}$

TABLE IV
IA EQUATIONS FOR NODE B

Antenna Rx	Antenna Tx	Node B
2	1	$z^{[b]}(1) = (x_a^c + x_a^d)h_{ab}^{12}$
2	1	$z^{[b]}(2) = (x_a^c)h_{ab}^{12}$
2		$z^{[b]}(3) = (x_a^d)h_{ab}^{12} + (x_c^d)h_{cb}^{22}$

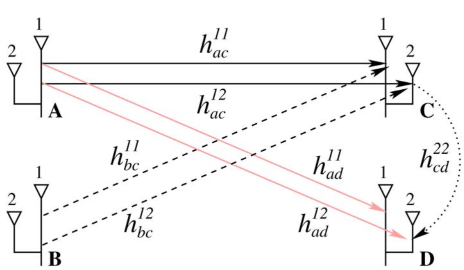


Fig. 6. IA with three transmitters (A, B, and C) and two intended receivers (C and D).

between antennas 1 and 2. It subtracts the third equation from the first to get two unknowns in two variables, by eliminating x_a^d, which is the message destined for D. The resulting set of linear equations can be solved to obtain x_a^c and x_b^c, respectively. These unknowns represent the spectrum database information C requested from A, and B for the subsequent journey toward B's control region. In the last transmission slot, C transmits its assessment of the feasibility of spectrum sensing to D using transmit antenna 2. This message, x_c^d, is also overheard by BSs A and B, which, as we previously noted in Section III, can be used for different quality-of-service channel prioritization in all subsequent queries.

2) Receiver- Vehicle D (Table II): CR Vehicle D subtracts the second equation from the first, for which it was in the same mode 1. This leaves the only unknown x_a^d, which is the beacon information that A intends to supply to D as it enters for the first time in its control region. This value is then subtracted from (3) to obtain x_c^d, i.e., the transmitted message from CR vehicle C to D. Vehicle D's transmitter antenna remains unused throughout the process.

3) Transmitter-BS A (Table III): BS A hears the transmissions from the neighboring BS B in the first two slots and the transmission from vehicle C to D in the final slot x_c^d. This last message also informs BS A what channels vehicle C found to be correlated and may use that information for subsequent queries in, for example, optimizing quality of service. While A does not switch operational modes, it does rely on the full-duplex ability to continuously transmit on antenna 1 and receive on antenna 2.

In the first slot, it transmits a summation of the messages $x_a^c + x_a^d$ to both the vehicles, whereas in the second slot, it only transmits x_a^c to vehicle C. These messages are received by the adjoining vehicles and BS B in the first two slots, respectively, subject to the channel gains from A to them.

4) Transmitter-BS B (Table IV): The operation of BS B is very similar to that of C. Subtracting the second equation from the first returns the message x_a^d sent to D from A. This is, in turn, substituted in (3) to obtain x_c^d, which informs B what channels vehicle C found to be correlated and may use that to improve subsequent queries' quality of service.

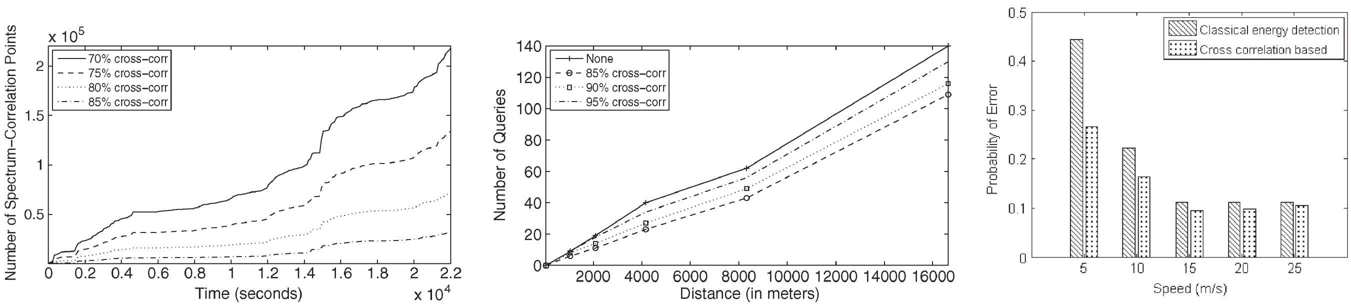
In summary, the information exchange equations are carefully constructed using IA while ensuring that the preference for local sensing or database updates is correctly communicated to the network entities.

VI. PERFORMANCE EVALUATION

Here, we first provide trace-driven simulation studies to demonstrate the feasibility of exploiting the spectrum correlation approach described in Section IV. Then, we provide quantitative results on the efficiency of the channel utilization by using the IA scheme from Section V-C through a simulation study in MATLAB.

A. Improvements Due to Spectrum Correlation Exploitation

We use traces from the experimental setup described in Section IV, where a USRP radio is placed inside a moving vehicle. The Android phone accesses the 2G spectrum, maintains a history of the path traveled via the inbuilt GPS capability, and queries the Spectrum Bridge Inc. database through software APIs every 100-m traversal, or when 60 s elapsed, whichever is earlier. The traces were collected over a total of five runs on the same path in March 2011 as indicated by Fig. 2(a). As a subsequent check, all measured sensing results obtained via energy detection through the USRP are validated with offline verification through the database at the end of the experiment. A subsequent trailing vehicle may schedule its own query, unless the vehicle ahead transmits a beacon that informs it to cancel the database query and rely on local sensing using the procedure adapted from Section V. The observed signal fluctuations in the 2G spectrum and the TV WS are saved on a laptop



(a) (b) (c)

Fig. 7. (a) Number of spectrum correlation points as the time of the experiment increases, (b) number of queries for various spectrum correlation percentages, and (c) accuracy of sensing.

computer, and correlations are calculated via a continuously running MATLAB program.

B. Improvements Through IA

Fig. 7(a) shows the number of spectrum correlation points as the vehicle moves along the map shown in Fig. 2(a). In this figure, we can see that the number of these points is higher when the correlation level is set at 70%, as compared to 85%, by about four times. This demonstrates the tradeoff that exists between higher accuracy (imposed by higher correlation demands) between the 2G spectrum and TV WS, and total number of correlation points where this approach can be actually used.

We list the total number of database queries that a vehicle engages in the path that was traversed to collect the spectrum information in Fig. 2(a). As the distance traversed increases, the number of queries that have to be performed also increase. In Fig. 7(b), we plot the number of queries that are undertaken by the CR vehicle if no spectrum correlation information is leveraged, as opposed to when it utilizes the spectrum correlation information to reduce the number of direct queries. The lower the allowed spectrum correlation percentage, the fewer the number of queries that the vehicle will undertake. In the case of correlation level set to 70%, the vehicle only needs to query the database 108 times, instead of 140 without our proposed scheme. This results in a saving of up to 23%. This number can be easily scaled with appropriate multipliers, such as the monetary cost of spectrum usage time imposed by carriers, the channel utilization, and resulting data congestion, among others, to obtain tangible impacts of reducing the number of database queries.

In Fig. 7(c), we plot the probability of error with P^x_{err} and without P^c_{err} our proposed scheme where

$$P_{\mathrm{err}} = \frac{\text{number of times the query resulted in misdetection}}{\text{total number of queries}}. \tag{2}$$

We first calculate P^c_{err} by assuming Rayleigh fading over a period of time for the RSSI measurements to check whether the latter that are obtained over the sensing time t_s are above or below the threshold λ. Here, we chose $t_s = 0.022s$, and λ was empirically observed over the total simulation time [18] to be -0.5 (amplitude dB). We then calculate the fraction of times that the average RSSI value is below the threshold over the total number of sensing intervals to give us the classical energy detection probability of error P^c_{err}. This is, in turn, plotted against P^x_{err}:

$$P^x_{\mathrm{err}_j} = \left(1 - \frac{x_j}{X}\right) \times P^c_{\mathrm{err}_j} \tag{3}$$

where x_j is the number of spectrum correlation matches that occur at speed j, and X is the total number of such correlations obtained over the entire experimental duration. One can observe that the probability of error decreases as the speed of the moving vehicle increases for both the classical energy detection and the correlation-based approach. However, the error in the latter is always less at all the measured speeds. This is because the RSSI may stay below the threshold for longer periods of time when the speed is slower, resulting in the sensing errors when $t_s = 0.022s$ [18].

C. Improvements Through IA

Here, we simulate the scenario in Fig. 1 where the entire distance traversed is 2 km and BSs A and B are located at 500- and 1500-m distances, respectively, with the coverage radius of each BS set to 500 m. We vary the interarrival rate of vehicles that arrive from left to right in the figure (read vehicle density) and the vehicle speed and determine the performance gains in channel utilization and number of queries. We compare the performance of different scenarios: a) Pure query: In this case, vehicles do not leverage any spectrum correlation information. Vehicles entering will query the database whenever 60 s has elapsed or 100 m was traversed. No carrier-sensing algorithm is implemented here; hence, the queries may collide causing interference. b) Carrier sense multiple access (CSMA): In CSMA, vehicles back off when a collision is detected based on 802.11 standards. c) Without IA (w/o IA): This scenario has vehicles using spectrum correlation information to save database query costs but does not exploit IA for channel utilization gains and d) with IA (w/ IA), where vehicles send data using IA after exploiting any spectrum correlation information. In all simulations, we use the RSSI traces that we obtained in our March 2011 experiment (see Section IV).

1) Channel Utilization: Fig. 8 shows a comparison of channel utilization per vehicle (time slots) in various speed and density scenarios as the simulation is run for a duration of 1000 s. The results are averaged over 20 simulation runs. There

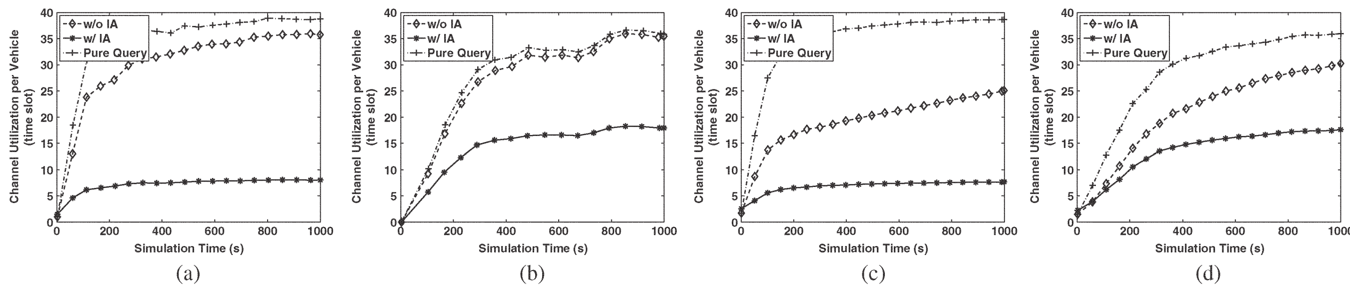


Fig. 8. Channel utilization per vehicle for no IA allowed, IA allowed, and pure query scenarios in (a) light density and fast-moving vehicles, (b) light density and slow-moving vehicles, (c) high density and fast-moving vehicles, and (d) high density and slow-moving vehicles.

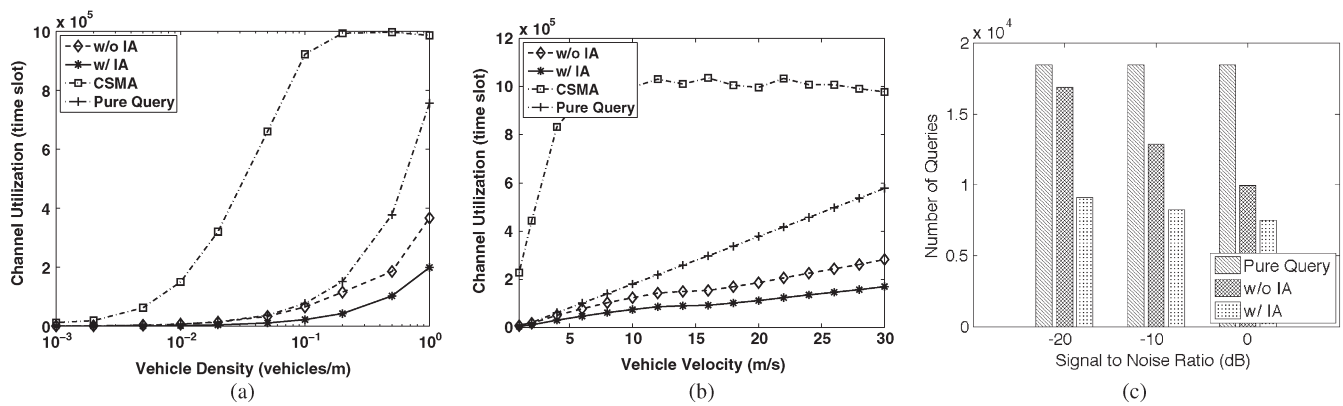


Fig. 9. (a) Channel utilization per vehicle for no IA allowed, IA allowed, and pure query scenarios. (b) Channel utilization as vehicle velocity increases. (c) Number of queries as SNR increases.

are a number of interesting facts that can be derived from the four figures. 1) IA outperforms both pure query and without IA, the channel utilization is improved through IA because a vehicle can obtain future spectrum information from tower B at the same instance it is also obtaining it from A for the rest of the duration in A (see Sections V-C and VI), whereas in the slower scenarios, the vehicles have expired spectrum information, which requires them to requery the database and hence incur higher channel utilization. 2) When density increases, without IA (w/o IA) scheme is significantly improved over pure query. This is because having more cars in the scenario leads to better chances of sharing (and exploiting) spectrum correlation information and, hence, less channel utilization. 3) In all scenarios, IA outperforms both pure query and without IA.

In Fig. 9(a), we vary the vehicle density (interarrival rate) while keeping the velocity constant. Conversely, in Fig. 9(b), we fix the vehicle density and vary the speed. We compare CSMA with pure query, no IA information leveraged, and full IA in the global utilization of the channel. In both cases, the CSMA reaches channel saturation early. This is because an increase in vehicle density and speed causes more collisions, leading to the channel being sensed for prolonged periods of time. We also see that when we increase the vehicle velocity in Fig. 9(b), the IA scheme results in slower increase in total channel utilization than that of pure query and without IA. Since we keep the average distance between vehicles unchanged, increasing the speed results in an increase in the number of cars entering the region at any given time, and thus, in all cases, total channel utilization increases. When we increase the vehicle density in Fig. 9(a), we see that CSMA attains maximum channel utilization before the three remaining schemes. Additionally, these competing schemes result in a faster increase in channel utilization as the vehicle density grows, as compared with the scheme with IA.

2) Number of Queries as the Noise Level Changes: In Fig. 9(c), we apply white Gaussian noise to the signals on the 2-km stretch of the simulation with increasing signal-to-noise ratios (SNRs). The plot shows that as the SNR increases, the number of queries decreases. This is due to having more spectrum correlation between the TV and 2G signals as the SNR increases leading to less reliance on the database to query for spectrum information.

VII. CONCLUSION

In this paper, we have described a new paradigm for spectrum database access, which allows querying the database only when needed. The resulting method exploits the correlation that exists among two entirely different spectrum bands at specific locations, thereby improving the performance of local sensing and reducing the costs associated with repeated database queries. Results reveal about 23% reduction of queries, making it attractive for practical spectrum database deployments. In addition, we also explored a real-world *IA* application that can reduce control channel utilization. We followed this by simulation runs to verify the performance gains using this approach. This nontrivial approach can potentially open up a hitherto unexplored direction in spectrum sensing, and future work will be focused on building the protocol suite that enables quick and efficient exchange of spectrum data between the vehicles and the BSs.

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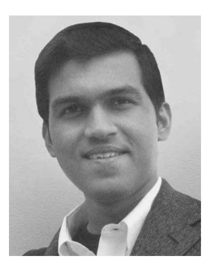

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