Vehicular Communication

Enhanced Networking Through Dynamic Spectrum Access

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In this article, the viability of performing dynamic spectrum access (DSA) in vehicular wireless communication networks is presented using actual spectrum occupancy measurements of broadcast television (TV) channels, as well as a custom-written computer simulation software package designed to evaluate at-scale vehicular networking deployments. In a world that is extensively dependent on access to information, reliable wireless communications serve a vital role in facilitating everyday activities taken for granted by modern society. Activities such as financial transactions, public safety operations, educational

Digital Object Identifier 10.1109/MVT.2013.2268659
Date of publication: 25 July 2013

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programs, national defense, and social interactions require some form of wireless communications to enable information exchange. One sector that is increasingly employing wireless communications is the automotive industry. Whether it is vehicle-to-infrastructure (V2I) or vehicle-to-vehicle (V2V) information exchanges, innovations in enabling vehicular wireless communications have the potential to enhance the driving experience, especially with respect to increasing driver awareness and situation perception to ensure overall vehicular safety [1].

All forms of wireless communication, including those used to perform vehicular communication, require access to electromagnetic spectrum. However, given the finite amount of this spectrum and the rapidly growing number of wireless applications and end users, many sectors are beginning to experience the effects of spectrum scarcity. On the other hand, it has been shown via several measurement campaigns that this spectrum scarcity issue is artificially generated because of the inefficient utilization of this limited natural resource [2], [3]. As a result, DSA has been proposed as a solution for accommodating the growing demand for wireless spectrum, enhancing spectral efficiency, and providing greater wireless access [4], [5]. As opposed to the conventional spectrum allocation paradigm, which focuses on static licensed spectrum assignments where the license holders possess exclusive transmission rights, the proposed DSA paradigm enables unlicensed devices to temporarily borrow unused licensed spectrum while ensuring that the rights of the incumbent license holders are respected. One technology capable of achieving DSA is cognitive radio, which employs autonomous and flexible communications techniques implemented via a software-defined radio (SDR) programmable wireless communications platform [6], [7].

Currently, the number of vehicles possessing the ability to perform wireless communications is only a small fraction of the total market. Furthermore, the spectral bandwidth requirement of the wireless communications employed by these vehicles is relatively low compared to wireless applications deployed in other commercial sectors, such as cellular telephony and broadband wireless Internet. Several frequency bands have already been allocated specifically for V2V and V2I communications, such as the 760-MHz band in Japan and the 5.8–5.9-GHz band worldwide. Furthermore, several standards supporting vehicular communications have already been designed around these bands, e.g., IEEE 1609 [8] and IEEE 802.11p [9].

Conversely, it is expected that the level of V2V and V2I information exchanges enabled by wireless communications will significantly increase in the near future because of a growing number of wireless-enabled vehicles, vehicular communication applications/standards, and high-data-rate traffic flows [10]. Consequently, the wireless spectrum scarcity issue currently experienced by several sectors within modern society will soon affect the automotive industry. Therefore, innovative techniques are required to enable more efficient usage of wireless spectrum by vehicular communication networks. One solution for accommodating this growing demand is vehicular DSA (VDSA), where vehicular wireless communication systems can temporarily borrow unoccupied radio-frequency spectrum to perform V2I and V2V information exchanges while simultaneously respecting the rights of the incumbent licensed transmissions [11]–[14].

When applying the DSA concept to vehicular networks to create a VDSA framework, the wireless spectrum used to support these transmissions must possess either a static or slow time-varying occupancy characteristics when viewed from a fixed geographical location. This requirement is because of the high level of mobility within the network, where the spectrum occupancy characteristics from the perspective of the vehicles appear to be changing in relation to the direction and speed of the vehicle itself. Consequently, TV spectrum has often been identified as a suitable candidate for realizing unlicensed wireless communications within licensed frequency bands [15]–[17]. This is especially true for VDSA networking, where the TV spectrum possesses the advantage of having relatively slow spectral occupancy variations over large distances and time periods. It should be noted that the frequency bands corresponding to other wireless services also may be potentially utilized to achieve VDSA. However, as mentioned previously, a wireless band such as the digital TV (DTV) frequency range, with relatively static channel occupancy characteristics, is better suited to the geolocation database-type approach that we have adopted.

In this article, we present an assessment regarding the viability of using TV spectrum within the context of a VDSA network. We conducted a TV spectrum measurement campaign along the entire portion of interstate I-90 in Massachusetts. Based on these measurements, we describe a quantitative model that accurately characterizes the spectrum occupancy behavior of a DSA-based vehicular communication network as a function of distance. Moreover, an associated computer simulator implementation from [18] is presented, which can be used to analyze the performance of a large-scale VDSA network to obtain a better understanding and insight on the behavior of these types of networks. To the best of the authors' knowledge, no wireless spectrum measurement campaigns have been conducted from the perspective of vehicular communications. More importantly, despite the fact that the geolocation database approach is a well-known method to identify the unused channels in a geographical region [16], we do not believe that a study using geolocation database information in conjunction with actual field measurements to identify vacant licensed channels exists in the published literature. Consequently, the conclusions that we have drawn are supported by the information concerning actual licensed transmitters, which is traditionally omitted by energy detection-based approaches.

TV SPECTRUM HAS OFTEN BEEN IDENTIFIED AS A SUITABLE CANDIDATE FOR REALIZING UNLICENSED WIRELESS COMMUNICATIONS WITHIN LICENSED FREQUENCY BANDS.

TV White Spaces: A Viable Spectral Option for VDSA Communications

Although several licensed frequency bands could facilitate VDSA communication networks, the DTV spectrum ranging 470–698 MHz has often been identified as a primary candidate because of its relatively static frequency channel usage by incumbent TV broadcasters, whose transmission frequencies are well documented and can be readily observed via simple spectrum-sensing techniques. With the transition of TV spectrum by the U.S. Federal Communications Commission (FCC) completed on 12 June 2009, a substantial amount of wireless spectrum white space was made available, which could potentially be used by vehicular networks via DSA.

However, given the mobility aspect of a vehicular communication network, the spectrum occupancy across a range of frequencies starts to become a time-varying phenomenon due to the vehicles either moving into range or out of range of a TV broadcasting site, even if their transmission ranges are on the order of tens of kilometers. Consequently, a quantitative model based on spectrum measurements of the DTV spectrum, such as those conducted in [12], can be used to accurately characterize the spectrum occupancy behavior of a VDSA wireless communication network as well as define the operation of such a network under these conditions when prioritizing emergency and other types of communications. These quantitative models could be deployed in the VDSA-enabled vehicles in the form of a geographical spectrum occupancy database, allowing the vehicles to make informed decisions about which frequency bands can be used for VDSA transmission and for how long before the vehicle comes into the transmission range of another DTV broadcast in an adjacent geographical area. It should be noted that certain wireless bands whose channel occupancy characteristics are extremely dynamic in nature may render a VDSA-enabled communication system impractical because of the numerous hops that are needed over several vacant licensed channels. Furthermore, the number of licensed transmitters using those wireless bands in a large geographical area (such as Massachusetts) and the parameters that need to be taken into consideration might potentially make a feasibility analysis for VDSA extremely cumbersome, if not impossible. In this respect, the manageable number of licensed transmitters in Massachusetts along with their static occupancy characteristics makes DTV channels a reasonable compromise for both data collection and analysis.

Hence, the first step in developing any VDSA solution is to accurately characterize the spectrum occupancy characteristics over distance and vehicular velocity. In the next section, our characterization of DTV spectrum across the length of Interstate I-90 located in Massachusetts is presented. However, without loss in generality, many of the analytical techniques used in the quantitative characterization of the DTV spectrum for VDSA communications, as well as some of the experimental findings, can be applied to other stretches of highway infrastructure.

TV White Space Assessment for VDSA Networks

This section describes the validation process conducted regarding the use of DSA in vehicular networking applications. The aim of this phase of the project consisted of the collection of spectrum measurements across the TV spectrum, which was accomplished in June 2009. By collecting these TV spectrum measurements, it is expected that new insights and knowledge will be derived that will help the research community further understand the usage of TV white space for DSA within the United States as well as around the world.

Measurement Configuration

The first phase of the spectrum measurement campaign was conducted on 7 and 11 June 2009 across 55 locations between Boston and West Stockbridge, Massachusetts. A frequency resolution of 20 kHz was selected, and ten sweeps were collected per site. Since the goal of the project is to characterize DTV spectrum over several locations along Interstate I-90 in Massachusetts, most sites were chosen to be within one-half mile of I-90 for the purpose of avoiding potential vehicular issues with nearby traffic. The locations were also selected such that they were spaced approximately two miles apart. The map of the measurement sites is shown in Figure 1. The measurement setup to collect spectrum measurements in the TV band consisted of an Agilent N1996A spectrum analyzer (SA) with an operating frequency of 100 kHz–3 GHz. This equipment was then connected to a laptop installed with the spectrum query utility interface for real-time radio electromagnetics (SQUIRREL) software package via an Ethernet cable. SQUIRREL is an

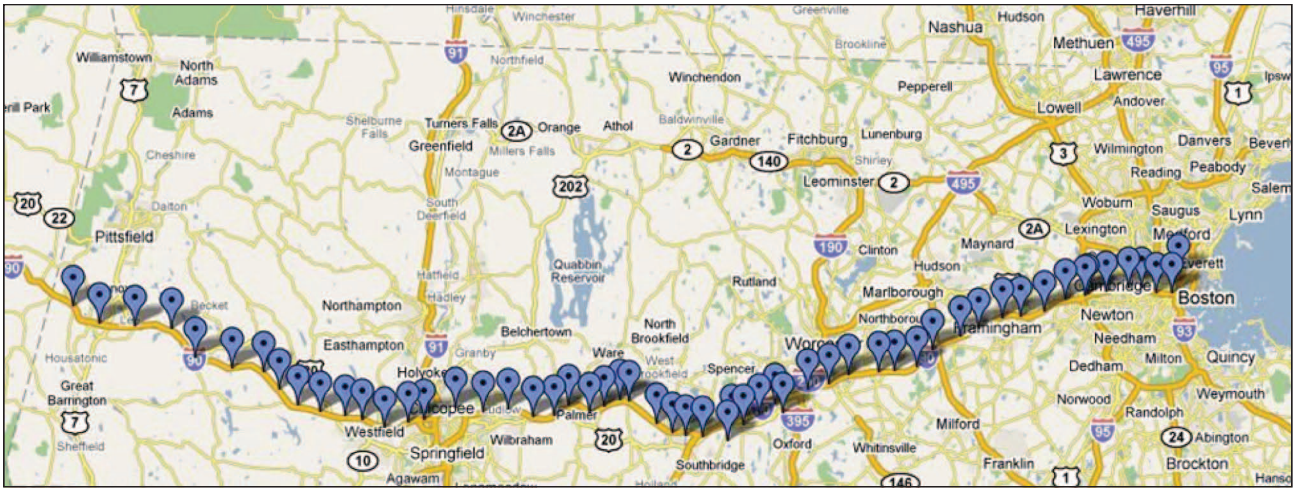

FIGURE 1 A map of the 55 locations close to Interstate I-90 between Boston and West Stockbridge, Massachusetts, over which spectrum measurements were collected on 7, 11, and 12 June 2009.

in-house software tool that communicates with the spectrum analyzer using tool command language (TCL) over transmission control protocol/Internet protocol (TCP/IP). A Diamond D-220 mini-discone antenna with an operating frequency range of 100–1,600 MHz was connected to the SA via a coaxial cable. The antenna was fixed to a bike rack mounted on the trunk of a car to make the entire setup portable.

In Figure 2, the data collected on 7, 11, and 12 June 2009 at 55 locations along Interstate I-90 in Massachusetts is presented. Essentially, Figure 2 shows the energy spectral density plot for the TV bands in the higher frequency

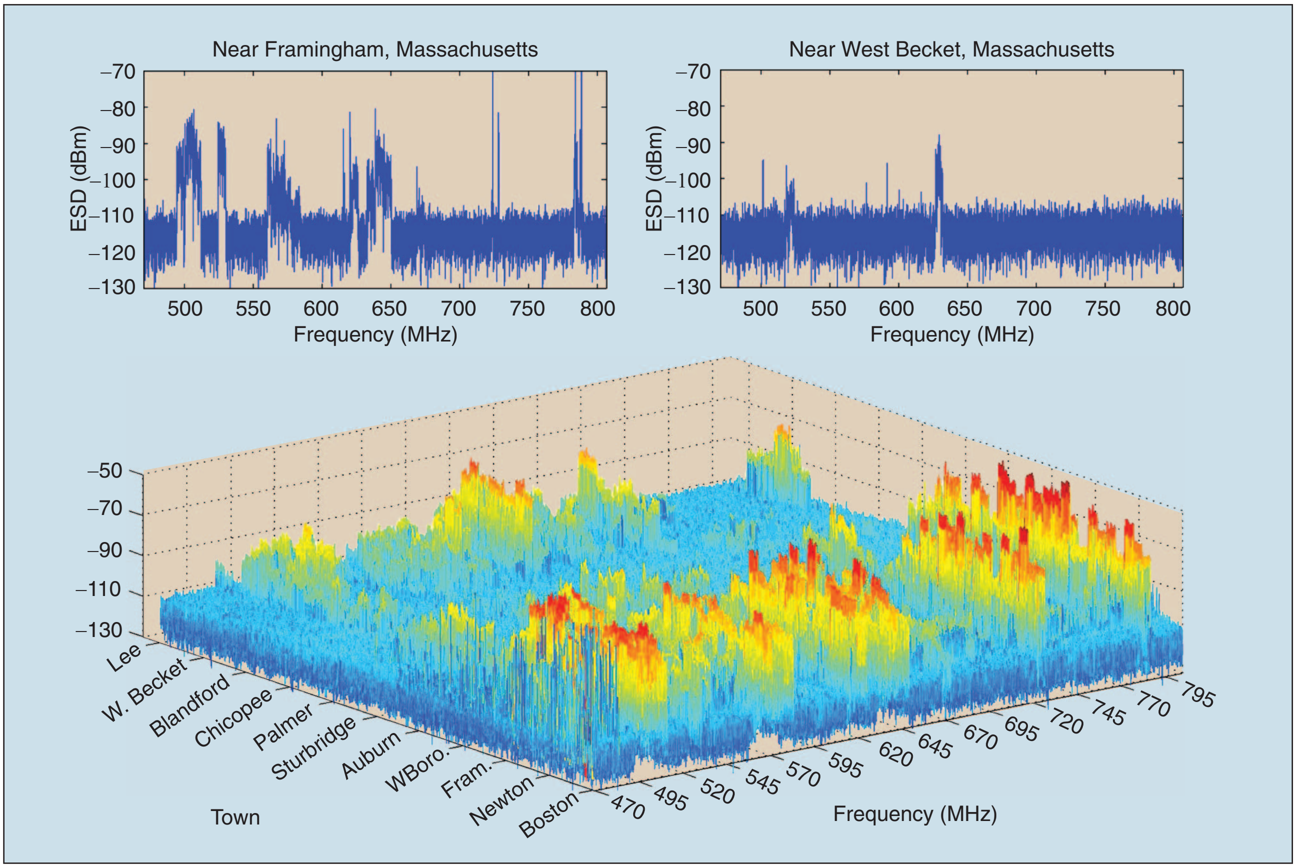

FIGURE 2 Spectrogram plot for the TV frequencies in the frequency range of 470–698 MHz over 550 time sweeps on I-90 between Boston and West Stockbridge, Massachusetts. Two-dimensional (2-D) plots corresponding to sweep numbers, Framingham, Massachusetts, and West Becket, Massachusetts, are also shown on top. (WBoro. = Westborough; Fram. = Framingham.)

range, which is the frequency region primarily identified as suitable for DSA. The eastern-most point in our study was Boston, and the western-most point was West Stockbridge. We observed strong signals on the order of –60 dBm at measurement locations close to Boston. This is consistent with the fact that Boston is a densely populated metropolitan area with many TV channels servicing the surrounding vicinity.

Postprocessed Results

Once the measurement data have been collected, a look-up table of the TV transmitters in the area of interest was compiled, and the protected contours based on [19] were identified. Note that the minimum required parameters are the effective radiated power (ERP) of the TV transmitter, its height above average terrain (HAAT), its location in global positioning system (GPS) coordinates, and the type of transmission, i.e., analog/digital and full-power/low-power. In our analysis, a look-up table was created consisting of 47 TV transmitters located within Massachusetts as well as five transmitters located within Connecticut, two transmitters located within New York, and one transmitter located within Rhode Island. These transmitters were considered because of their proximity and significant impact on the coverage of Interstate I-90 in Massachusetts. (Because of space constraints, the list consisting of these 55 TV transmitters has not been included in this article.)

Then, the desired points of interest along Interstate I-90 were located, and their distances from the TV transmitters under study were calculated. This distance calculation was performed using the polar-coordinate flat-earth formula

$$D(i, j) = R\sqrt{\theta_i^2 + \theta_j^2 - 2\theta_1\theta_2 \cos(\Delta\lambda)}, \qquad (1)$$

where $D(i, j)$ is the distance between the ith TV transmitter and the jth measurement site, R is the radius of the earth ($R = 6{,}371$ km), $\theta_i = (\pi/180)(90 - \text{latitude}_i)$, $\theta_j = (\pi/180)(90 - \text{latitude}_j)$, and $\Delta\lambda = (\pi/180)$ $(\text{longitude}_i - \text{longitude}_j)$.

If $D(i, j)$ is less than the protected contour of the transmitter, i, then the channel number corresponding to i is unavailable at measurement site, j, and the allowed transmit power level of the TV white space device (WSD) corresponding to j and i is zero. Otherwise, the channel number corresponding to i is available at j. However, this result does not yet provide any information on the power constraints imposed on a WSD when using a particular channel.

Duplicate entries of the available channel information were deleted for each of the TV transmitters that use the same channel but are geographically separated by a sufficient distance. Furthermore, the closest transmitter, requiring smaller ERP values to conform to the FCC guidelines, was noted, and a reduced set of available channels was created. If the current channel is a cochannel to the nearest incumbent transmitter, the allowed WSD transmit power corresponding to j and transmitter k (from the reduced set) defined by [19] is calculated. That is, for a fixed value of HAAT, the $F(50, 10)$ curves are employed [19] to identify the ERP on the secondary transmitter that interferes with the incumbent receivers on the edge of the protected contour at 50% of the locations for 10% of the time. Consequently, this value is the allowed ERP on a secondary transmitter without violating the FCC's directives on using DTV spectrum on a secondary basis. Note that the value of $D(k, j)$, i.e., the distance between the kth TV

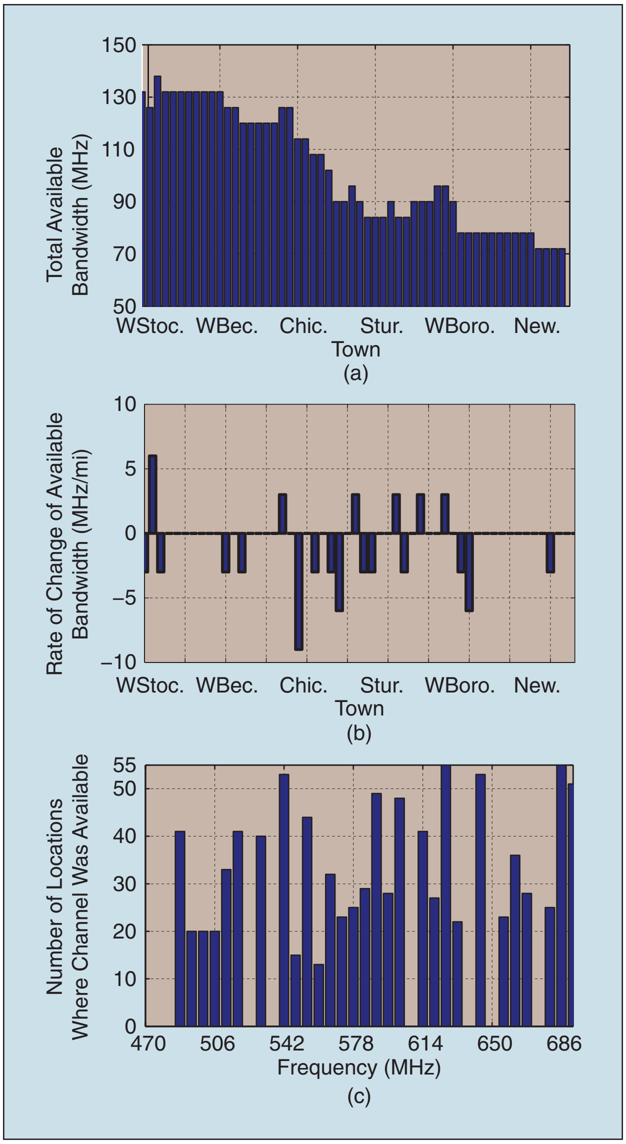

FIGURE 3 Processed results pertaining to the available bandwidth from Western Massachusetts to Boston along I-90. (a) The total available bandwidth from along I-90. (b) The rate of change of the available bandwidth along I-90. (c) The availability of each channel along I-90. (Wstoc.: West Stockbridge, WBec.: West Becket, Chic.: Chicopee, WBoro.: Westborough, New.: Newton.)

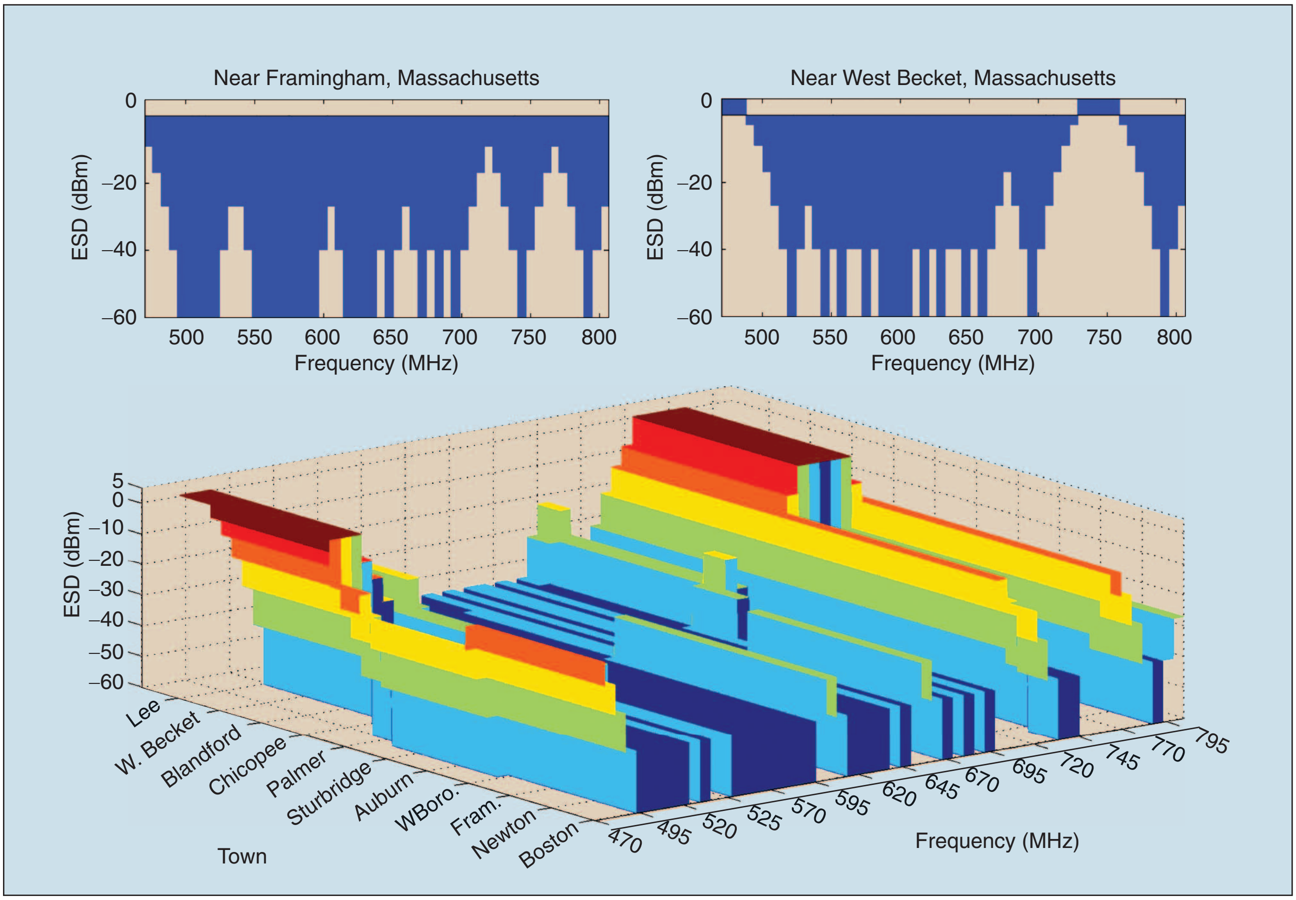

FIGURE 4 WSD power constraints of the available TV channels at different locations along Interstate I-90 located within Massachusetts. (WBoro. = Westborough; Fram. = Framingham.)

transmitter and the jth measurement site, is employed when performing this calculation. If the current channel is an adjacent channel to the nearest incumbent transmitter, the allowed WSD transmit power corresponding to j and k is calculated via the aforementioned procedure but using the *DU* ratios from [19, Table II].

The algorithm described earlier was implemented for all the locations visited along Interstate I-90 for this project. Figure 3 describes the processed results for the measured data, whereas Figure 4 shows the overall WSD power constraints on the available TV channels at different locations along Interstate I-90 located within Massachusetts. A bar graph showing the total available bandwidth across all the measurement locations is shown in Figure 3(a). As noted earlier, because of the presence of several TV transmitters within the Boston metropolitan area, we noticed that the total available bandwidth for secondary usage decreases steadily as one travels from western to eastern Massachusetts. For instance, the available bandwidth in West Stockbridge is almost twice the available bandwidth in Boston. We then studied the rate of change of bandwidth availability with respect to the distance along I-90 in miles. We consider the rate of change of bandwidth availability between any two consecutive points along I-90 to be equal to the difference in the available bandwidth for VDSA calculated based on the algorithm described in [12] divided by the intersite distance. A unit of intersite distance is approximately 2 mi throughout the data-collection process.

Figure 3(b) shows the results corresponding to this analysis. From this figure, it can be readily observed that across several locations, the amount of bandwidth available remains constant over a maximum distance of about 25 mi. However, across certain locations, this value varies by as much as 12 MHz, which is the equivalent of two TV channels. These results highlight the need for the secondary devices to vacate certain channels to the primary users and transmit in other channels, which might become available as the vehicle moves in and out of coverage areas pertaining to different TV transmitters. To further analyze our results, we looked at the number of locations along Interstate I-90 where each of the 38 6-MHz channels across 470–698 MHz are available. These results are shown in Figure 3(c). From this figure, we see that although the total bandwidth at any given location on Interstate I-90 is known from Figure 3(a), several channels may be unavailable and the remaining would need to be accessed in a noncontiguous fashion.

Computer-Driven Experimentation of At-Scale VDSA Networks

Since developing multiple radios and testing them in real-world situations can be both costly and technically challenging, we developed a lightweight computer-based traffic simulator to evaluate the performance of VDSA networks operating at scale under mobile highway conditions [18].

We have three design goals in the development of this traffic simulation tool. The first goal is to perform a spectrum analysis, which generates data based on incident reporting to understand how much spectrum is required to broadcast alert messages. The second goal is to determine the blocking percentage of incident broadcasts based on broadcast bandwidth requirements. Blocking percentage represents alert messages that cannot be sent because of the lack of bandwidth to send messages. The data gathered from this simulator will help assess the feasibility of certain propagation methods based on spectrum usage and the number of vehicles on the road at any given time. The third and final simulation goal is to provide graphical representation of the number of vehicles on the road and the number of vehicles that are broadcasting information throughout the execution of the simulation. This graphical user interface tool will also visually show spectrum utilization for secondary users and the relationship between the number of vehicles and the number of broadcasts.

Platform and Functionality

Using Java, a collection of classes that represent both vehicles and the highway were devised, where each vehicle was created based on invoking the corresponding class. In addition to the classes used to create and control the vehicles and the highway, code was written that enabled the generation of random variables to represent the behavior of the vehicular communications within the VDSA network. Finally, to enable the end user to fully understand the behavior of VDSA networks operating at scale over distances on the order of miles, the computer simulation possessed a visualization front end that displayed the simulated traffic flow and spectrum utilization by all the vehicles involved in the experiment (see Figure 5).

Since the proposed computer simulator had to provide sufficient variability and unpredictability similar to the actual motion experienced by the vehicles on a highway, specific simulation parameters, such as the instances when the vehicles enter the highway, the ramp through which they enter the highway, and the traveling speed of the vehicles were randomly simulated. After the random variables have been initialized for both the vehicles and the highway, a clock begins to increment. At each increment of the clock, the simulator checks to see if there are any vehicles that have an assigned "enter the highway" time equal to the current clock time. If there is such a vehicle, it enters the highway. After all the vehicles have been checked, any vehicles that are on the highway are moved based on the speed they have been assigned during the initialization period. During this time, any potential collisions resulting in the faster-moving vehicles approaching slow-moving vehicles are avoided through the process of lane changing and the decrease of vehicle speed. The flow chart in Figure 6 shows an overview of the major blocks of the code.

After all the vehicles have been instantiated, the proposed simulator checks to see if any vehicles have reached their final destinations. Each vehicle is assigned an on and off ramp to enable it to enter and leave the highway. If there are any such vehicles that have reached their destinations, they will be removed from the highway. Once this has been completed, a quick check is done to see if all the vehicles have completed their specified trips. After checking, the clock is incremented, and the simulator returns to checking for any new vehicles that are entering the highway.

Simulation Parameters

As mentioned previously, individual vehicles can be assigned different speeds, making the simulated traffic environment appear similar to an actual stretch of highway. Moreover, each instance of a vehicle creates a new set of parameters that need to be handled by the simulator. The vehicular operating parameters that make the proposed simulation realistic are the highway entry locations and times for each vehicle. These parameters are assigned from a discrete set of "on" ramps and a continuous set of simulation time values. Assigning each vehicle a time when it will enter the highway enables each of them to enter at different locations and different times throughout the simulation, thus making the proposed simulation similar to actual highway conditions. Both vehicular operating parameters are generated using the process defined in Figure 6.

Simulation, Implementation, and Functionality

With the design goals discussed earlier, our current implementation of simulation tool can perform the following functions. First, it can realize a wireless transmission environment for vehicular networks operating under the highway conditions by using the actual spectrum occupancy measurements obtained in the "TV White Space Assessment for VDSA Networks" section. Second, it can randomly generate the highway incidents and the creation of a VDSA-based alerting approach (dynamically choose available frequency to broadcast alert messages) for relaying this incident information to nearby automobiles. Third, the assessment of reaction timing performance within the vehicular network with respect to the vehicles avoiding collisions using information can be made available within the VDSA network. Reaction time represents an important factor in avoiding collisions, since human reaction time varies based on driver capabilities, while alert messages received over the wireless channel help significantly improve the reaction times.

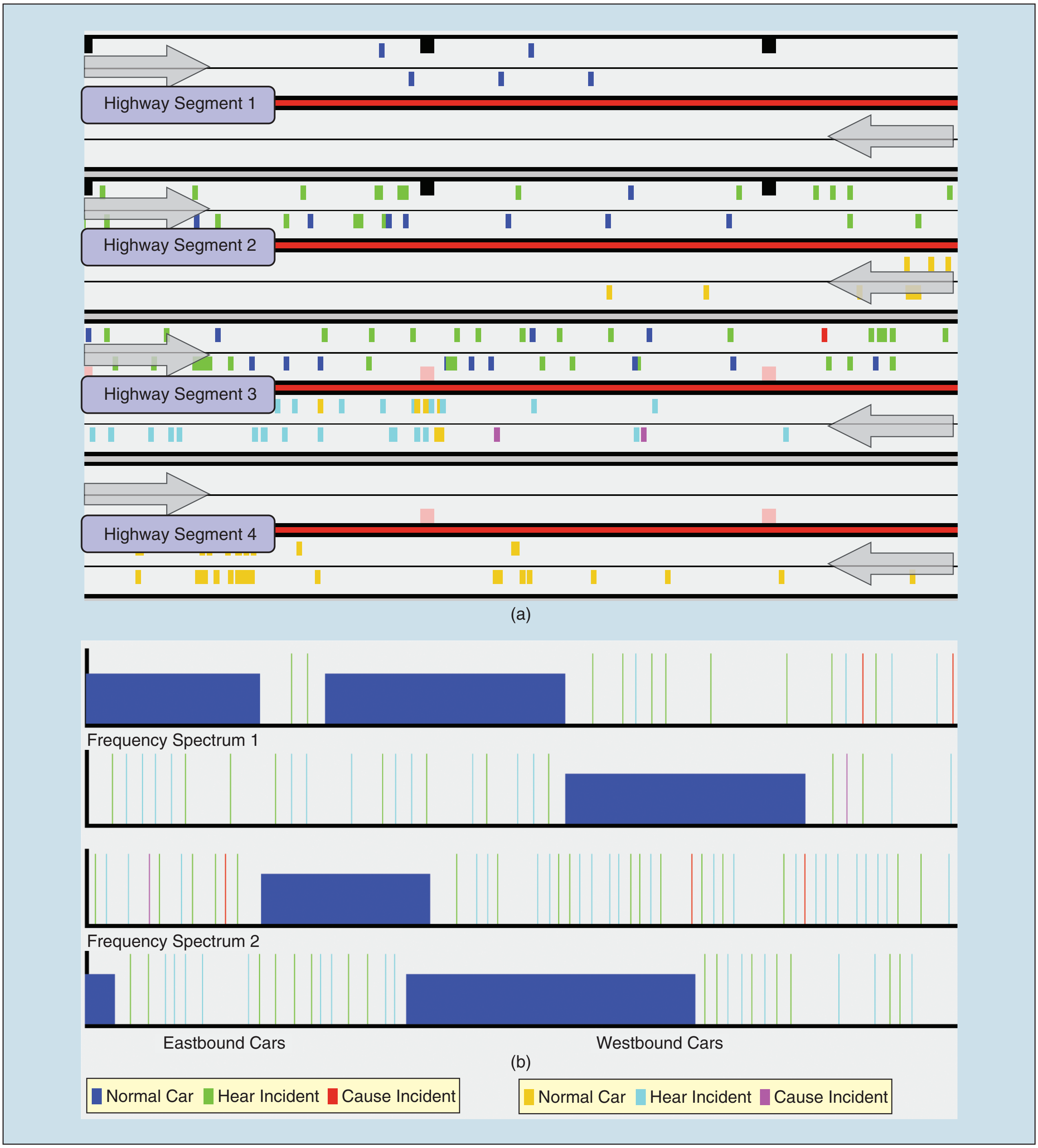

FIGURE 5 A screen capture of the visualization front end of the proposed VDSA-based computer simulation software for an experiment involving 10 mi of highway traffic. Notice that the top portion of the visualization front end shows four 2.5-mi lengths of two directions of a two-lane highway (a total of 10 mi), while the bottom portion shows the spectral occupancy across the TV frequency bands, where the large blue blocks represent the frequency locations of active TV channels, while the other blocks represent VDSA transmissions. (a) Close-up view of individual vehicles operating under highway conditions within the proposed VDSA-based computer simulation software. (b) Close-up view of individual VDSA wireless transmissions occurring across TV spectrum resulting from the vehicles operating in highway traffic conditions.

In Figure 5, we observe a section of the visualization front end, possessing both the vehicular traffic flow [highlighted in Figure 5(a)] and the spectral occupancy resulting from the VDSA-based transmissions [highlighted in Figure 5(b)]. In Figure 5(a), the vehicles travel along a stretch of highway, which is represented in this case as four lengths of contiguous highway portions of equal distance. When a vehicle travels along one of these highway segments and reaches the end of one length, it automatically moves to the next corresponding highway segment and continues traveling. Since this is simulating the vehicles traveling in both directions, each highway segment has two lanes heading in opposite directions.

On the basis of events during the computer simulation, the vehicles will change color to indicate their current status. For instance, if a vehicle is traveling eastbound indicating a normal status and then suddenly causes a traffic incident, it will turn red. If this incident becomes obsolete, meaning that the duration of the event has passed, the vehicle will return to the normal state. The frequency spectrum [Figure 5(b)] is updated based on the broadcasting events of the vehicles on the highway and also follows the same color scheme. A normal car will not be broadcasting, such that there are no blue or orange spectra to indicate a normal broadcast. If a vehicle creates an incident, red spectra will be shown where the center frequency for an eastbound car is broadcasting, and maroon spectra will be shown for a westbound car. The same holds true for a vehicle that has heard about an incident and is now rebroadcasting the incident. Green spectra represent an eastbound vehicle that is broadcasting after hearing about an incident, and cyan spectra is associated with westbound vehicles. Figure 5(b) shows how the color association between the spectrum and the vehicles appears on the simulator screen. The proposed computer simulation code is available with the project report located online at [18].

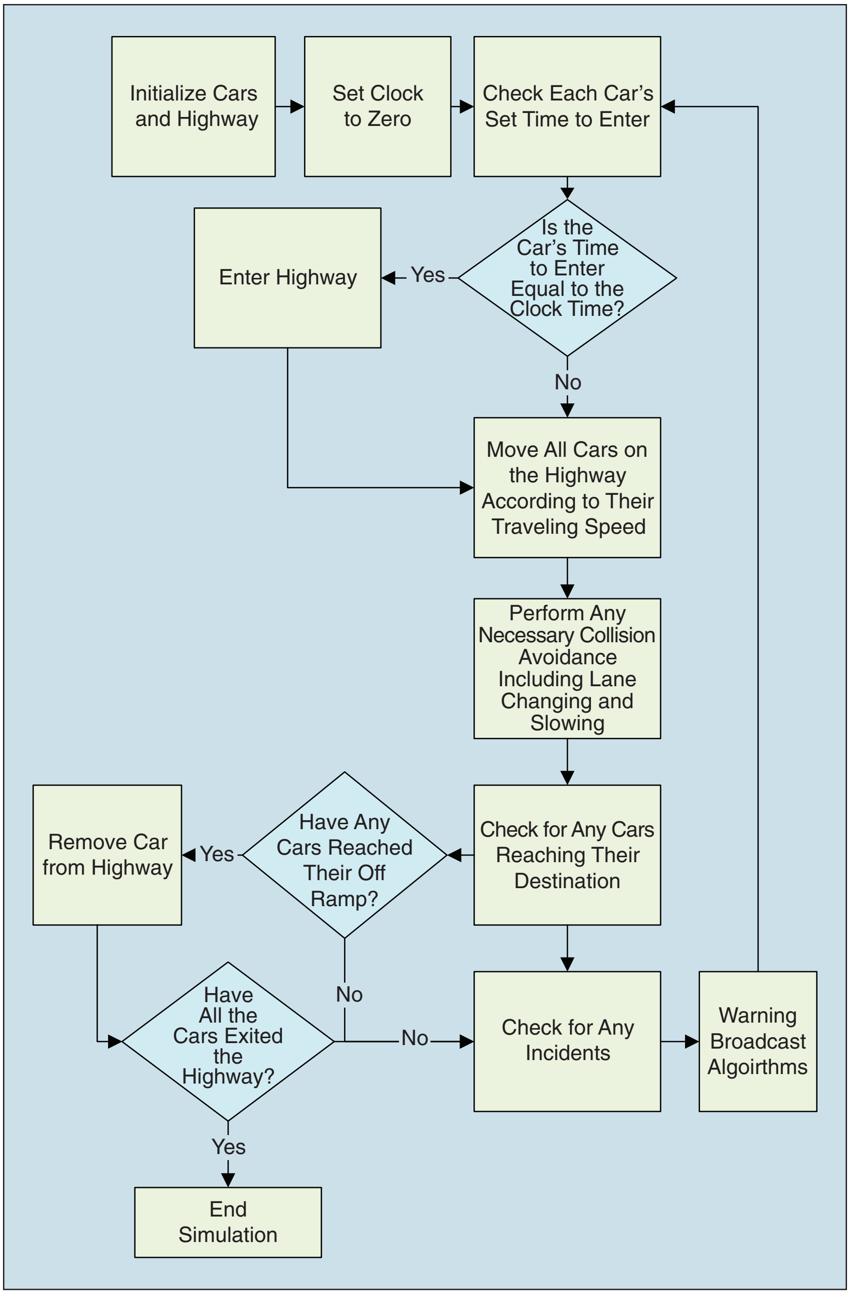

FIGURE 6 Major functional blocks of the proposed computer simulation software.

Alert Message Transmission

The propagation of alerting signals is done using the flooding broadcast method and is described in Figure 7. Since it is the fastest propagation method, it will be the most interesting when observing the propagation speed and the blocking percentages in the high frequency usage areas and the high broadcasting densities. In our current implementation, random cars create alert messages at random locations. When an alert message is created, the vehicle will start the broadcasting protocol. This includes finding the first available car behind it and passing on the information associated with the incident, including the location, the car that created the incident, and a time stamp. The cars that are alerted of the incident begin to broadcast the information after a short delay and continue broadcasting until the message has become obsolete. Next, the simulator introduces new algorithms for frequency selection to take into account possible bandwidth requirements for single broadcasts and uses real-world frequency spectrum data obtained from the frequency database created earlier in the project. During one execution of the simulator, each

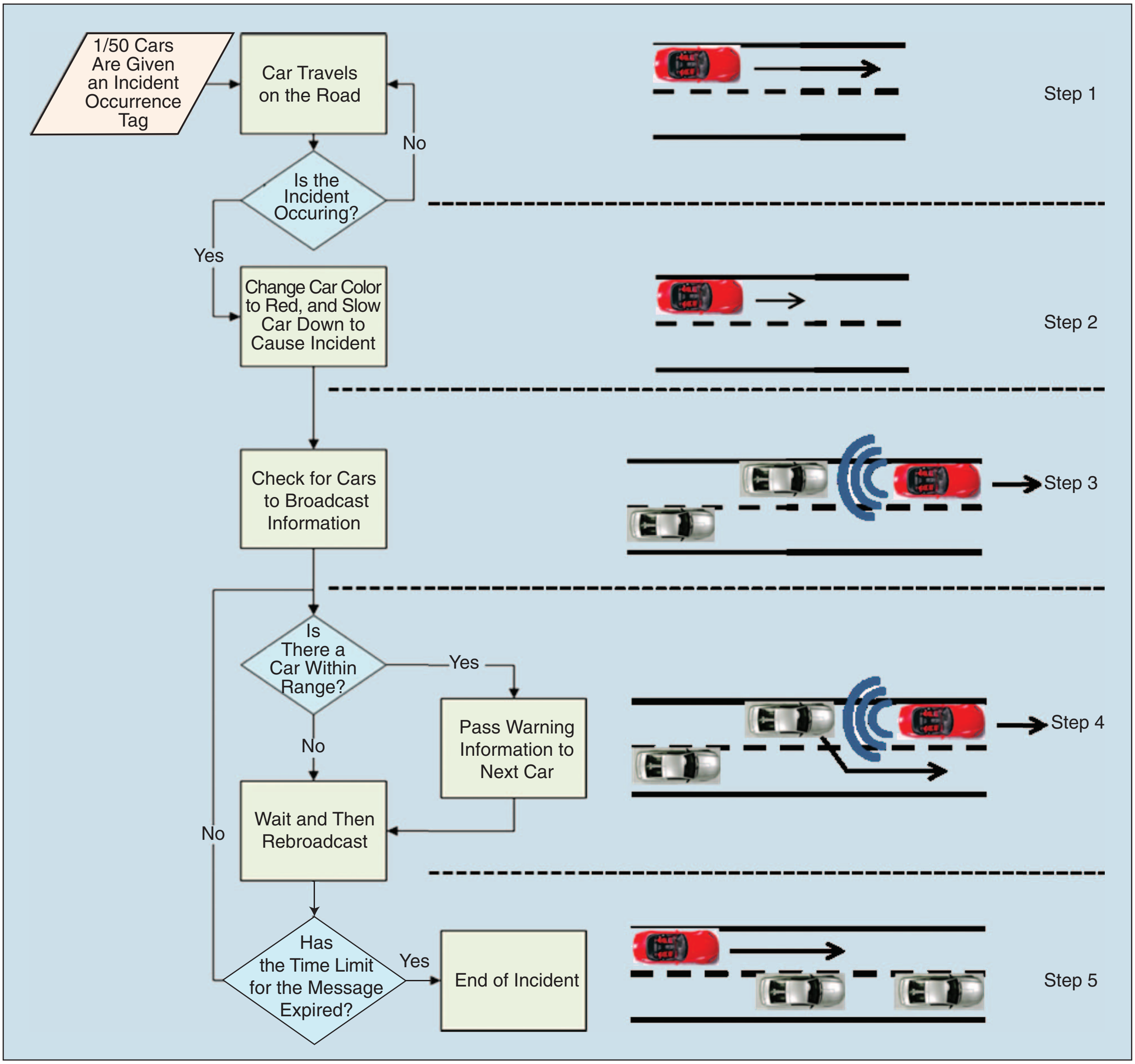

FIGURE 7 Flow chart of the car alert method. The car travels normally in step 1 until an incident is created in step 2. Once in step 2, the car slows down and proceeds to step 3, where it checks for cars in its local area to broadcast a warning. If a car is in the area, it will receive the warning and take action to avoid a collision, as in step 4. Once the incident is over, driving returns to normal (step 5).

broadcast will select a frequency in a way that separates broadcasts by the largest possible value. For example, if there is a 40-MHz section of the frequency spectrum that is currently not in use, the center frequency for a broadcast would be selected 20 MHz from the used frequency spectrum. Using this algorithm to select the broadcasting frequency ensures that the broadcasts are the farthest away from each other, providing the least interference between consecutive broadcasts. If there is no spectrum portion large enough, blocking occurs, and the broadcasting radio must wait before attempting another broadcast. We evaluate performance of various broadcasting protocols such as single broadcast, flooding, and controlled multicast to evaluate effective utilization of available spectrum to send alert messages.

Conclusion and Future Directions

Vehicular networking has enormous potential to enable diverse applications associated with traffic safety, traffic efficiency, and information provisioning. VDSA has been proposed as a possible solution to accommodate this rapidly increasing interest and growth with respect to vehicular wireless networking applications while simultaneously preventing the issue of spectrum scarcity. Moreover, TV spectrum appears to be a viable candidate for supporting VDSA-based communication networks because of its relatively well known propagation characteristics and static spectrum occupancy profile at fixed geographical locations. Consequently, it is possible to devise VDSA-based transceivers capable of performing DSA while minimizing the probability of spectral collisions with licensed transmissions by using a spectrum occupancy geographical database created from measurement data.

Future work in this area includes the need to develop a real-time decision-making process for a VDSA-based transmission device that is capable of selecting an appropriate channel when provided with multiple choices, perhaps accounting for factors such as the interference caused by several other VDSA-based devices in a certain neighboring channel (and hence choosing a channel with fewer VDSA-based devices in its adjacent channels), the geographical terrain obstruction at the location of operation (and hence choosing a channel in the lower frequency range), and the possibility of binding fewer contiguous channels versus several noncontiguous channels. Another topic is the creation of an analytical model for assessing the capacity of a VDSA network. In [13] and [20], a queuing theory-based framework for a vehicular communication network based on the allocation of unoccupied frequency spectrum to different vehicular wireless nodes was devised to accurately assess the capacity of these types of networks across a range of realistic scenarios. However, there is still much work to be done in devising an accurate analytical tool for VDSA network capacity in high-density traffic conditions, especially when unoccupied spectral resources are scarce, spectral access is rapidly time varying, and different VDSA-based wireless transmissions possess different priority levels, e.g., emergency/safety communications, infotainment, and Internet. Nevertheless, the future of enhancing vehicular wireless networks is at hand, and the ability of VDSA to make large amounts of bandwidth available for either V2V or V2I transmissions is quickly becoming a reality.

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