When Vehicles Meet TV White Space: A QoS Guaranteed Dynamic Spectrum Access Approach for VANET

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***Abstract*—Vehicular ad hoc network(VANET) is an emerging wireless communication scenario and has caught the attentions of both academia and industry. However, some challenges still exist, one of which is the spectrum scarcity problem, especially for the throughput-demanding downlink infotainment services. In this paper, we present a solution to the problem by introducing the state-of-the-art cognitive radio technology, namely the exploitation of TV white space(TVWS). First, we give an overview of the compositions of this new networking paradigm. Then, taking into account the characteristics of both VANET and TVWS, we develop a novel TVWS resource model tailored for the system. After that, we focus on the dynamic spectrum access problem and formulate it as a matching between vehicles/requests and available channels. Both the throughput of the network and the guarantee of QoS are considered during the calculation of preference lists. Furthermore, an algorithm is also brought forth to implement the matching process. It is proved that after the execution of the algorithm, the matching is *stable* and *vehicle-optimal*. Numerical results demonstrate the feasibility and efficiency of our system.**

I. INTRODUCTION

Ubiquitous Internet access has always been one of the ultimate goals for wireless communication technologies, and it is naturally extended to the vehicular scenario where people spend a significant amount of time, not to mention the demand coming from intelligent cars[1]. This new communication paradigm is referred to as vehicular ad hoc networks(VANETs)[1]. Extensive works have been done on this topic by not only scholars but also engineers from industry, because of the potential economic benefits lying in the applications such as road safety information dissemination and real-time navigation.

Typically, VANET supports two modes of communication, namely vehicle-to-vehicle(V2V) and vehicle-to-roadside(V2R), both of which have their own characteristics. V2V has no time or location constraints on connection but the data rate is relatively low and the latency is high, mainly because of multi-hop transmission. On the contrary, V2R is capable of providing higher bandwidth whereas the communication is restricted to the coverage area of certain infrastructures called roadside units(RSUs). Numerous researches[2][3] about information downloading and distribution have been done on both modes, either separately or jointly. This paper mainly focuses on V2R communication.

Spectrum access problem is one of the primary challenges that VANET/V2R is facing and needs to be solved effectively. Two mainstream wireless access methods(3G/4G and Wi-Fi) have both been considered to implement V2R. However, their limitations can easily be foreseen. On one hand, with the ever growing mobile phone users, the cellular bands become highly congested, which will degrade the user experience of VANET services. More important, V2R is usually more attractive and promising during a long-distance journey such as driving on the inter-city or inter-state highways. Most of these highways are located in suburban areas where there may be no 3G/4G services. On the other hand, the effective transmission range of a Wi-Fi access point(AP) is typically hundreds of meters. In order to achieve a complete coverage, a large number of APs should be deployed along the roads, which is economically unsound. Furthermore, considering the high speed of vehicles and MAC contention, the actual connection time per vehicle is too short to support broadband applications.

Fortunately, the emerging cognitive radio(CR) technology is a feasible solution to the spectrum-related problems. With the help of dynamic spectrum access(DSA), namely exploiting the temporally or spatially unused spectrum resources in the licensed bands in an opportunistic manner, the spectrum efficiency is improved considerably. Recently, studies[4][5] mainly focus on utilizing these spectrum holes in the TV broadcasting bands, or TV white spaces(TVWS). Due to the global trends of digital TV switchover, a large amount of TV bands are released for secondary access. Organizations such as U.S. Federal Communications Commission(FCC) and IEEE 802.11 working group have already released related regulations and standards[6][7]. In this TVWS exploitation paradigm, a geolocation database is established to provide channel availability information services for secondary users. TVWS has been envisaged to have significant usages in

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[1] In the four-day consumer electronics show(CES) from Jan.7, 2014 in Las Vegas, NV, automakers such as Audi and Chevrolet attended and presented their ideas of next-generation cars featured by telematics and self-driving.

many scenarios, from femtocells to rural broadband access. However, the VANET situation is seldom considered until recently[8][9][10] although these TVWS channels are inherently suitable for V2R. For one thing, they lie in the relatively low VHF/UHF bands(e.g. from 54MHz to 698MHz in U.S.), which means larger coverage area and less infrastructure deployments. For another, the frequency resources are much richer than cellular and ISM bands, especially in suburban areas where terrestrial TV signals are relatively sparse.

We note that the task of buliding the system by integrating TVWS and VANET is not trivial. Thus many challenges are still there to be dealt with. This paper mainly puts emphasis on the following aspects. First, an appropriate TVWS resource model is needed for this new scenario. Second, traditional media access methods like CSMA/CA in 802.11 can not be adopted directly when taking into account the new characteristics such as vehicle mobility, channel multiplicity and different QoS requirements. Therefore, a new DSA/resource allocation scheme is required to cope with these issues.

The contribution of this paper is summarized below:

- We develop a novel TVWS resource model tailored for the system, which takes into account the characteristics of both VANET and TVWS. The model is both intuitional for understanding and easy for analysis.
- We formulate the resource allocation process as a matching[11] between multiple channels and multiple requesting vehicles and propose a resource matching algorithm(RMA) to implement the matching.
- We set the objective of the resource allocation process by giving the definition of stability and optimality and prove that RMA can fulfill the objective. We also give numerical results to demonstrate the feasibility and efficiency of our system.

The paper is organized as follows. Section II describes the system model and problem formulation. In Section III, the resource matching algorithm is presented, together with the related analysis. Simulation results are given in Section IV. Finally, we conclude the whole paper in Section V.

II. System Model and Problem Formulation

A. System Model

The most important rule to exploit TVWS is to ensure the protection of incumbent users. This is achieved mainly by avoiding their operating hours and locations. As a consequence, the availability of TVWS channels is variant on both time and space scales. At a certain location, a channel is available for secondary uses if and only if the location is outside the protection region of every ongoing primary users occupying the same channel at this time. As mentioned before, this channel availability information is stored in a geolocation database, which is managed by FCC-authorized companies(in the U.S.) to keep its validity. Therefore, secondary users equipped with GPS devices can acquire the information easily.

Fig. 1 shows the overview of the system, which is generally the same as a common VANET scenario except for some new features. First, RSUs are connected with the geolocation database through backhauls to get the information on the available channels. They also synchronize periodically with the geolocation database to keep the information valid. Second, both the RSU and the on-board unit(OBU) own some CR functionalities. The RSU is capable of operating on different channels simultaneously. The OBU is the radio equipment on vehicles and it is able to work on a series of frequencies by reconfiguration of RF front ends. Finally, common control channels(e.g. DSRC channels), which are available at every location, are necessary for the control and requesting sessions between RSUs and vehicles.

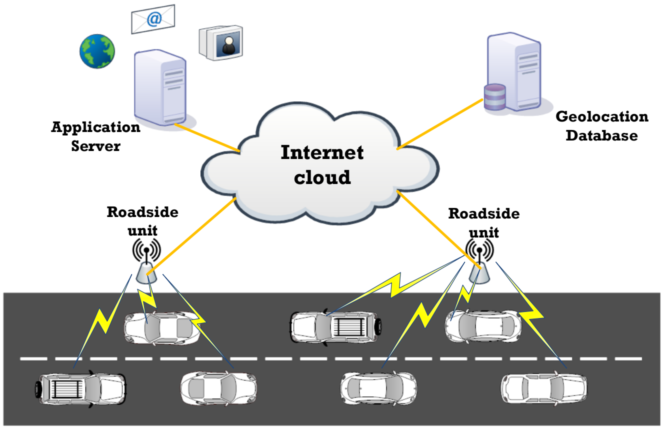

Fig. 1. Integrating VANET and TVWS

Due to the time and space variant properties, a new TVWS resource model tailored for the system is required. The temporal variation of TVWS is largely due to the unpredictable usage of wireless microphones, which are seldom in the rural highway scenario, hence we do not take it into account in this paper. In order to reflect the spatial property of TVWS, we project the availability of channels onto a location-frequency plane and get the available location of channels. An example is shown in Fig. 2, where each color stripe represents the available location of a certain channel. Suppose vehicle A and B are requesting at their current location. Their QoS requirements could be met if allocated the red and blue channel respectively, provided they could finish their requests within the corresponding available locations. Basically, this allocation is actually a matching between vehicles/requests and channels, hence we can formulate the resource allocation process as a matching problem.

B. Problem Formulation

We use x to represent location and x^i_λ to represent the location of the ith RSU λ_i, with coverage area X^i_λ. The whole TV band channels form a set $\mathcal{C} = \{c_1, c_2, ..., c_j, ..., c_N\}$, where c_j is the jth channel and N is the number of total TV channels. The availability of c_j can be expressed as a piecewise function of x:

$$y_j = \begin{cases} 1, & x \in X_j \\ 0, & x \notin X_j \end{cases} \tag{1}$$

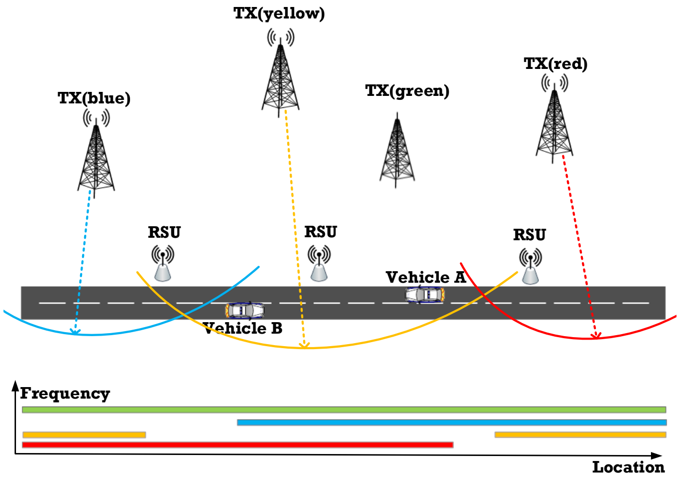

Fig. 2. An illustration of the TVWS resource model(the green TX is temporally not working

where X_j denotes the available location for channel c_j. A TV channel becomes unavailable either because it is occupied by primary users or allocated to other vehicles. Therefore, without loss of generality, at a certain time, the channel resources at λ_i can be described as a set of resource tuples *(channel,available location)*, namely $\mathcal{R}^i = \{(c_j, X_j^i) : j = 1, 2, ..., N\}$, where the available location $X_j^i = X_j \cap X_\lambda^i$, which may be not continuous. The data transmission rate γ on channel c_j at location x within X_λ^i is expressed in the following equation:

$$\gamma(x)_j^i = y_j W \log_2 \left(1 + \frac{P_\lambda^i}{\xi(\left|x - x_\lambda^i\right|)(P_N + P_I)}\right) \tag{2}$$

where W is the bandwidth of a channel, P_λ^i is the transmit power of λ_i, P_N and P_I represent the noise floor and interference from adjacent channels(if they are occupied), and $\xi(\cdot)$ is the path loss function. An example of path loss function(in free space) is given below:

$$\xi_{free}(\Delta x) = 20 \log_{10}\left(\frac{4\pi \Delta x}{\lambda_{wave}}\right) \quad (dB) \tag{3}$$

where Δx denotes the distance between transmitter and receiver and λ_{wave} is the wavelength of the carrier frequency. From above, it is clear that the data rate is inverse proportional to the distance between a vehicle and a RSU. In practice, a more realistic path loss function can be adopted, such as Okumura-Hata model.

We formulate the resource allocation process as a matching between channel resources and requests from vehicles. We use the expression $C : A \succ B$ to denote “C prefers A to B” and $A \sim B$ to denote “A is matched to B”. Each vacant channel has a preference list(PL) about requesting vehicles and vice versa. The sequencing of the PLs are based on predefined rules for the sake of improving network performance. The rule for channel resources is that it sorts the requests according to the instant data rates at the locations of requesting vehicles. Mathematically,

$$\begin{array}{ll} & c_j : V_r \succ V_s \\ iff & \gamma(x_V^r) > \gamma(x_V^s) \\ or & \gamma'(x_V^r) > \gamma'(x_V^s) \ when \ \gamma(x_V^r) = \gamma(x_V^s) \\ s.t. & x_V^r, x_V^s \in X_j^i, \ X_j^i \neq \emptyset \end{array} \tag{4}$$

This will maximize the total throughput of the whole network to some extent.

For a vehicle V_r, it has to assure that its request could be satisfied if it chose a certain channel. Here the requests can be classified into two categories with different QoS requirements. Category I is modeled as a file downloading process, with the file size Φ^r. Music(mp3 files), web pages or emails are some common examples of the files. The QoS requires that the requesting file should be downloaded completely so as to be used. Category II is modeled as a continuous connection process, which represents applications like video streaming. In this case, the QoS requires that a certain connection time τ^r and a minimum connection rate γ_{min}^r should be satisfied.

In this paper, we adopt the Freeway Mobility Model[12]. Suppose at time t_0, V_r enters the coverage area of λ_i and V_{r+1} is the vehicle in front of it. Then the determination of the velocity of V_r at time t is given below:

$$\begin{array}{l} \overline{v}_r = \beta \overline{v}_{r+1} \\ v_r(t_0) = \overline{v}_r \end{array} \tag{5}$$

$$v_r(t + \Delta t) = v_r(t) + \eta a_r \Delta t \tag{6}$$

$$\begin{array}{ll} if \ v_r(t) < v_{\min} & then \ v_r(t) = v_{\min} \\ if \ v_r(t) > v_{\max} & then \ v_r(t) = v_{\max} \\ if \ \Delta x(t) < \Delta x_{\min} & then \ v_r(t) = v_{r+1}(t) - \frac{a_r}{2} \end{array} \tag{7}$$

where η and β are zero-mean random variables with uniform distribution, a_r is the acceleration, Δx is the distance between adjacent vehicles, v_{min}, v_{max} and Δx_{min} are constrains in order to make the model realistic. The average speed of V_r is $\overline{v}_r$, which is a reasonable characterization in the highway scenario, if no incidents(e.g. car crashes) happen. Further, the expectation of driving distance within time t and location at time $t_0 + t$ are respectively:

$$E\left[x_V^r(t_0 + t) - x_V^r(t_0)\right] = \overline{v}_r(t - t_0) \tag{8}$$

$$E\left[x_V^r(t_0 + t)\right] = x_V^r(t_0) + \overline{v}_r(t - t_0) \tag{9}$$

With the remaining distance within the available location of c_j denoted as $|X_j^{i-}|$, the data volume downloaded by using c_j is estimated as

$$\Phi_r^j = \int_{t_0}^{t_0 + \frac{\left|X_j^{i-}\right|}{\overline{v}_r}} \gamma[x_V^r(t_0 + t)]dt \tag{10}$$

Finally, the rule for Category I requests can be described as follows:

$$\begin{array}{ll} & x_V^r : c_j \succ c_k \\ iff & \Phi_j^r > \Phi_k^r \\ s.t. & \Phi_j^r > \Phi^r, \Phi_k^r > \Phi^r \\ & x_V^r \in X_j^i, x_V^r \in X_k^i \end{array} \tag{11}$$

Same as the analysis in Category I, the rule for Category II is drawn:

$$\begin{array}{ll} & x_V^r : c_j \succ c_k \\ iff & \left|X_j^{i-}\right| > \left|X_k^{i-}\right| \\ s.t. & \gamma(x) \geq \gamma_{\min}^r \; when \; x \in [x_V^r(t_0),\ x_V^r(t_0+\tau^r)] \\ & x_V^r(t_0) \in X_l^i, x_V^r(t_0+\tau^r) \in X_l^{i-},\ l = j,k \end{array} \tag{12}$$

After determining the PLs of both vehicles and channels, we need an objective for the matching, which is *stability*, as is given in the definition below:

Definition 1: The matching between channels and vehicles is stable if and only if the following conditions are not satisfied simultaneously for any j, k, r, s after the matching:

$$\begin{cases} c_j : V_r \succ V_s \\ V_r : c_j \succ c_k \\ c_j \sim V_s, c_k \sim V_r \end{cases} \tag{13}$$

This definition implies that when the matching comes to stability, there exists no way to benefit both channels and vehicles by changing the matching pairs.

III. RESOURCE MATCHING ALGORITHM

A. Resource matching Algorithm

Suppose at time t_0, the available channels at λ_i form a set $\mathcal{C}^i = \{c_j : X_j^i \neq \emptyset\}$ and the vehicles requesting for access form another set $\mathcal{V}^i = \{V_r : x_V^r \in X_\lambda^i\}$. The PLs of V_r and c_j are first calculated according to (11), (12) and (4) and denoted as vectors $\mathcal{L}_V^r$ and $\mathcal{L}_c^j$ respectively. A tie is broken by listing any one in the front, so $V_r : \mathcal{L}_V^r[1] \succ \mathcal{L}_V^r[2] \succ ...$ and $c_j : \mathcal{L}_c^j[1] \succ \mathcal{L}_c^j[2] \succ ...$ are satisfied. Thereby, the whole algorithm to find a matching between channels and vehicles is given in Algorithm 1.

Algorithm 1: RESOURCE MATCHING ALGORITHM

```
Input: $\mathcal{C}^i, \mathcal{V}^i, \mathcal{L}_V^r, \mathcal{L}_c^j$
Output: Matching result
1  for every $V_r \in \mathcal{V}^i$ not kept by any channel do
2      if $\mathcal{L}_V^r \neq \emptyset$ then
3          $V_r$ applies for $\mathcal{L}_V^r[1]$
4      else
5          $V_r$ stops applying
6      for every $c_j$ receiving applications do
7          $c_j$ keeps the applying vehicle highest in $\mathcal{L}_c^j$
8      each rejected vehicle removes $\mathcal{L}_V^r[1]$
9  for every $V_r \in \mathcal{V}^i$ do
10     if $V_r$ is kept by a channel or stops applying then
11         each channel is allocated to its keeping vehicle
12     else
13         jump back to step 1
```

The stability of the matching generating from RMA is guaranteed by the theorem below:

Theorem 1: The matching that comes out from RMA is stable.

Proof. The proof is by contradiction. Suppose after the algorithm terminates, $c_k \sim V_r$ and $c_j \sim V_s$. If the matching is not stable, then we can assume that $V_r : c_j \succ c_k$ is true. According to the algorithm, V_r must have applied to c_j before it applied to c_k. Since it is accepted by c_k now, we can easily know that it has been rejected by c_j, which means that at least $c_j : V_s \succ V_r$ is true. Hence, the matching is stable, which is contradicted with our assumption before. ■

Discussion: As mentioned in the last section, equation (11) and equation (12) guarantee that the request of vehicles are satisfied; equation (4) assures that the throughput is to some extent maximized. Therefore, from the process of RMA, we know that if a vehicle allocated a vacant channel, its QoS could be guaranteed. Furthermore, by Definition 1 and Theorem 1, we can conclude that the resources are allocated to the vehicles in a manner that considers the benefits of both the channels and the vehicles.

B. Optimality of the Algorithm

The optimality of a stable matching is given in the definition below:

Definition 2: A stable matching is vehicle-optimal if it can not be better off for any of the vehicles under any other stable matchings.

One property related to it is described in the theorem below:

Theorem 2: A vehicle-optimal matching is unique if it exists.

Proof. The proof is by contradiction. If there were two vehicle-optimal matching, then at least one vehicle would be better off in one matching than the other(because the preference list has no ties). Hence, according to Definition 2, one of them is not vehicle-optimal, which is contradicted with our assumption. ■

Then we will demonstrate the existence of vehicle-optimal matching by proving that the matching coming from RMA is vehicle-optimal, as is given by the following theorem:

Theorem 3: The matching that comes out from RMA is vehicle-optimal.

Proof. The proof is by induction. We use the expression $c_j \simeq V_r$ if $c_j \sim V_r$ does not happen in any stable matching. Assume at a certain time during the RMA, each rejection happened corresponds to a conclusion, for example, c_j rejects V_r corresponds to the conclusion $c_j \simeq V_r$. At this moment, suppose V_r is rejected by c_j, who is keeping V_s now, then we must prove that $c_j \simeq V_r$. For V_s, we know by assumption that a channel c_k that has rejected it corresponds to the conclusion $c_k \simeq V_s$. Now imagine that $c_j \sim V_r$ in a stable matching, then V_s must be assigned to another channel c_l that is less desirable than c_j. From the analysis above, we can see that $c_j : V_s \succ V_r$ and $V_s : c_j \succ c_l$ while $c_j \sim V_r$ and $c_l \sim V_s$, which is the same as in equation (13) and thus leads to instability. Thus, $c_j \simeq V_r$. Finally, according to the procedure of the algorithm, each vehicle applies for the channels from the top of its preference list to the bottom. So we can make the conclusion that the matching generated from the resource allocation algorithm is vehicle-optimal. ■

Discussion: At this point, by Definition 2 and Theorem 3, we can draw the conclusion that RMA insures that each vehicle gets its best possible resource. In other words, instead of maximizing the total throughput of the network, the QoS of vehicles is placed on a higher position.

All of the analyses above are done within a single RSU. However, RMA can be extended to the case where serial RSUs alongside the highway allocate their spectrum resources collaboratively, provided RSUs have TVWS information of their neighbors. This condition can be easily met since RSUs are all connected to the same geolocation database.

IV. SIMULATION RESULTS

We have done extensive simulations via MATLAB to validate the feasibility and efficiency of our system. Some of the arguments and their values are listed in Table I.

TABLE I
ARGUMENTS AND VALUES IN SIMULATION

Arguments	Value
Tot. channel Num.	38($470-698$MHz)
Ava. channel Num.	20
Bandwidth	6MHz(5.33MHz in calc.)
TX power	36dBm
Noise floor	-105dBm
Min. SNR	8dB
RSU cov.	$\{4,5,6\}km$
Alloc. period	$\{1,2,3\}$s
Time span	1000s
Time slot	1s
RSU loca.	center of cov.
Min. veloc.	60km/h
Max. veloc.	120km/h
Min. dist.	15m
Acceleration	$1m/s^2$
File size(Cat. I)	$[10,100]$MB
Min. rate(Cat. II)	$[20,40]$Mbps
Min. connec. time(Cat. II)	$[5,25]$s

The randomly generated available location of TVWS is illustrated in Fig. 3, in which each green bar represents an available channel. In the simulation, we use the more realistic Hata Model in suburban areas to calculate path loss. Fig. 4 shows the variation of data rates of four evenly selected frequencies between 470 and 698MHz. As the distance away from RSU increases, the data rate decreases(higher frequencies decrease faster) because the SNR is dropping. It finally becomes zero when the SNR is below the minimum value required by the receivers. Fig. 5 snapshots the location of vehicles driving in left direction and their requesting status at a certain time slot.

In order to prove the effectiveness of RMA, we also emulate two other channel access methods in our system model. In the first method, each available channel randomly selects the requesting vehicles within its coverage area in each allocation period. This random allocation scheme is regarded as a baseline of the system. In the second method, we extend the basic idea of CSMA into this scenario. Specifically, each requesting vehicle randomly selects a white channel and listens to it in each allocation period. If the channel has not been occupied yet, the vehicle will take use of it to complete its request. Otherwise, it attempts to access in the next period. Fig. 6 shows the aggregated transmitted data bits by using three different access methods. As we can see, the cumulated throughput of random allocation and CSMA is with the same level, which lies below that of RMA(77% of RMA at $t=1000s$). In Fig. 7, the succeeded and failed requests of the three methods are shown respectively. Again, RMA presents a 29% increase in number of succeeded requests and a 90% decrease in number of failed ones(at $t=1000s$). This outcome is predictable since RMA guarantees the QoS of requests when calculating PLs by applying an "admission control" mechanism virtually, according to the analysis above.

Next we will do some analysis on the parameters that have impacts on our system. The first parameter is the allocation period, and we set three different values(see Tab. I). As we can see, increasing the allocation period will lead to underutilization of spectrum resources, which reflects the slight decrease of throughput and negligible drop in succeeded request percentage in Fig. 8 and Fig. 9, respectively. The second parameter is the coverage area of a RSU and we also choose three values for comparison. Intuitively, as the coverage area of RSU gets larger, the data rate becomes lower and finally zero, according to Fig. 4. Therefore, the percentage of succeeded requests will descend as well as the average data rate while the number of failed requests will ascend. Fig. 10, Fig. 11 and Fig. 12 demonstrate these phenomena. Nonetheless, smaller coverage area also means more RSU deployment and essentially more cost, thus a compromise is required here.

V. CONCLUSION

In this paper, we discuss the system by integrating VANET and TVWS, which is a promising solution for the spectrum scarcity problem existing in VANET/V2R scenario. We propose a novel TVWS resource model tailored for the system and it proves to be both intuitional for understanding and simple for analysis. Taking into account the differences with existing systems such as vehicle mobility, channel multiplicity and different QoS requirements, we bring forth a new resource/channel allocation method, which formulates the problem as a matching process between vehicles/requests and available channels. The method considers both the throughput of the whole system and the QoS of vehicles/requests during the calculation of PLs. We also present an algorithm, namely RMA, to implement the matching. We give the definition of stability and optimality of matching and proved that RMA reaches a stable and vehicle-optimal matching. It means that the resources are allocated to the vehicles in a manner that considers the benefits of both the channels and the vehicles and each vehicle gets its best possible resource. Simulation results demonstrate the feasibility and efficiency of our system. Our future work may cover the topics like finding the compromised solution of RSU deployment, user experience and system cost.

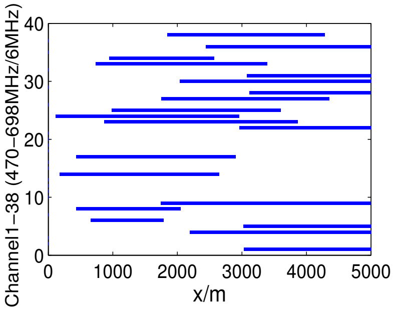

Fig. 3. Available location of TVWS

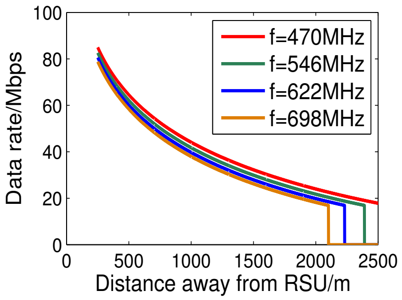

Fig. 4. Data rate of TVWS channels with different frequencies using Hata Model

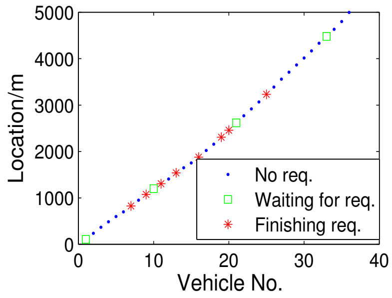

Fig. 5. Location and requesting status of vehicles on a one-lane road

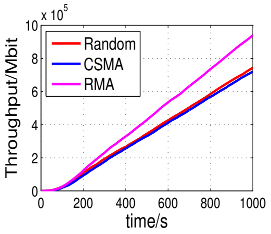

Fig. 6. Total throughput for different methods

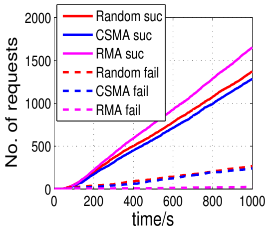

Fig. 7. Num. of succeeded and failed requests for different methods

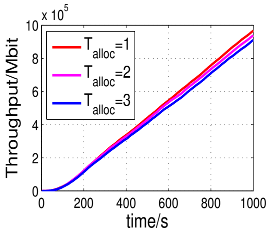

Fig. 8. Total throughput for different allocation periods

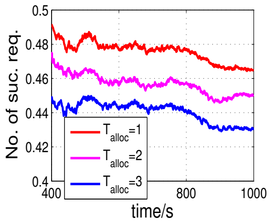

Fig. 9. Percentage of succeeded requests for different allocation periods

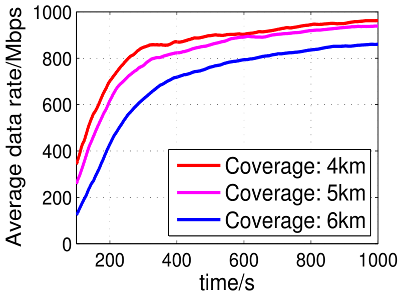

Fig. 10. Total average data rate for different RSU coverage

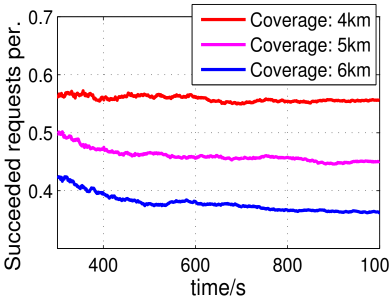

Fig. 11. Percentage of succeeded requests for different RSU coverage

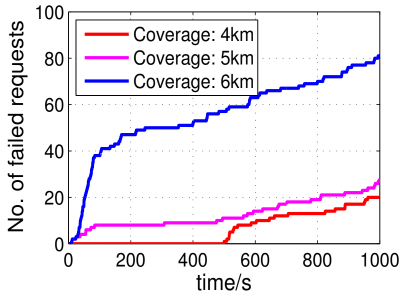

Fig. 12. Num. of failed requests for different RSU coverage

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